

ADVANCEMENTS IN **NANOMATERIALS** FOR **MODERN ELECTRONICS**

Design, Applications and Future Trends



Usama Afzal & Mamoon Riffat

SCOPUA

Advancements in Nanomaterials for Modern Electronics: Design, Applications and Future Trends

By

Usama Afzal and Mamoon Riffat

Book Title

**Advancements in Nanomaterials for Modern Electronics: Design,
Applications and Future Trends**

Author(s)

Usama Afzal 

School of Microelectronics, Tianjin University, Tianjin, China

Mamoona Riffat 

Lappeenranta-Lahti University of Technology, Finland

Publisher

**Scientific Collaborative Online Publishing Universal Academy,
Lahore, Pakistan**

Series Name

Books of Research Collection

Date of Publication

02 January 2026

Edition

1

ISBN: 978-627-7898-01-4

DOI: [10.64060/978-627-7898-01-4](https://doi.org/10.64060/978-627-7898-01-4)



This work is licensed under a Creative Commons Attribution NonCommercial NoDerivatives 4.0 International License. The publisher Scientific Collaborative Online Publishing Universal Academy (SCOPUA), the authors, and the editors assume that the advice and information in this book are believed to be true and accurate as of the date of publication. Neither the publisher nor the authors nor the editors give a warranty, expressed or implied, concerning the material contained herein or for any errors or omissions that may have been made. Publisher remains neutral regarding jurisdictional claims in published maps and institutional affiliations.

BISAC

SCI055000, SCI050000, SCI050000, SCI003000

THAMA

PH, PHF

BIC

PHFC, TGM, TBC

Authors Biography



Usama Afzal, PhD researcher at the School of Microelectronics, Tianjin University, China, is a multidisciplinary expert specializing in microelectronics, environmental science, material statistics and physics. His research primarily focuses on material science, nanotechnology, and statistical system analysis, particularly emphasising the design and fabrication of advanced sensors for heavy metal detection. Afzal's innovative work has been widely published in prestigious journals including "Sensors and Actuators B: Chemical, ACS Sensors and Environmental Science and Pollution Research, making significant contributions to the fields of sensor technology and environmental analysis. In addition to his journal publications, he has authored books and book chapters that are recognized for their groundbreaking perspectives. As a dedicated academic and passionate knowledge sharer, Afzal has earned a reputation as a respected leader in his field, inspiring future scholars and researchers through his commitment to excellence and advancing sensor technology. He also serves as a book editor for Elsevier and Cambridge Scholars Publishing, contributing to the growth of scientific literature.



Mamoon Riffat is a renowned researcher and physicist specializing in nano-materials and their applications. Currently pursuing her PhD at Lappeenranta-Lahti University of Technology, Finland, Mamoon has established herself as an expert in her field through her extensive research and training. Her work has taken her to various international destinations, including Germany and Scotland, where she has honed her skills in advanced characterization techniques. With her unique blend of academic rigor and real-world experience, Mamoon brings a distinctive voice and perspective to her writing.

Foreword

As a physicist with a strong research focus on nanomaterials and electronic device engineering, I feel deeply privileged and honoured to witness the completion of this valuable scholarly contribution by my student, alongside collaboration with distinguished researchers in the field. This work is both pioneering and timely, consolidating a wealth of critical insights on a subject that is rapidly gaining global significance as electronic technologies transition toward miniaturization, sustainability, and intelligent functionality.

The science and engineering of nanomaterials have progressed tremendously in recent years, yet their translation into reliable, commercial-scale electronic systems remain complex. Performance at the nanoscale is governed not only by fundamental quantum and thermodynamic phenomena, but also by stringent requirements of fabrication compatibility, structural stability, energy efficiency, and long-term reliability. The interplay between these factors shapes the future of transistors, sensors, memory, optical systems, and energy-harvesting devices. While technologically advanced regions have made notable progress toward integrating emerging nanomaterials within existing microelectronic infrastructures, many developing nations continue to face significant scientific, industrial, and economic barriers. Limited research facilities, high-cost fabrication, technology transfer constraints, and shortage of skilled personnel pose substantial challenges to the widespread adoption of nanomaterial-enabled electronics.

This book offers a comprehensive exploration of the scientific and technical challenges that must be addressed to unlock the full potential of nanomaterials in practical electronic applications. Issues such as surface instability, material–substrate incompatibility, thermal management, and manufacturing

scalability are not abstract academic concerns—they pose real risks of slowing or even obstructing technological progress in regions aspiring to join the global semiconductor and nanoelectronics landscape. The involvement of international research bodies and standardization agencies, such as IEEE, NIST, and ISO/TC 229, plays a crucial role in promoting unified fabrication standards, characterization protocols, and data-driven performance benchmarks.

Global consistency and collaboration are essential, as fragmented research standards and non-uniform fabrication methodologies continue to be major challenges in the field. The coordinated efforts of scientific societies and regulatory organizations will be vital in establishing cohesive technological platforms, enabling emerging nations to participate effectively in the global nanoelectronics market. This book highlights the scientific and engineering responses required to address these issues, including the development of universal material-characterization standards, CMOS-compatible fabrication pathways, and adaptive device-integration strategies capable of accommodating new classes of nanomaterials and hybrid architectures.

From a physics perspective, the importance of these efforts cannot be overstated. As nanomaterials continue to reshape the electronic ecosystem, research frameworks must balance technological advancement with energy efficiency, material sustainability, and environmental responsibility. The experimental case studies and analytical discussions featured in this book provide meaningful insight into how material science, quantum physics, and electronic engineering can collectively shape the next era of device innovation. They also offer practical guidance for laboratories and industries in both developed and developing regions, helping bridge the gap between fundamental research and scalable commercial deployment.

Ultimately, this book underscores the critical importance of global scientific collaboration, methodological harmonization, and research adaptability in enabling nanomaterials to drive the future of electronics. It will be of great value not only to academics and scientists, but also to engineers, technology developers, policymakers, and industry professionals working toward sustainable and high-performance nano-enabled electronic systems. The perspectives and knowledge presented herein will undoubtedly contribute to shaping the future direction of research and development in nanoelectronics, with a continued emphasis on responsibility, innovation, and societal benefit.

Associate Prof. Dr. Naveed Ahmad
University of Education, Lahore, Pakistan

Preface

Over the past two decades, nanoscience and microelectronics have converged in ways that were once unimaginable. What began as curiosity-driven exploration of matter at the 1–100 nm scale has matured into a powerful technological engine that is reshaping the entire electronics landscape—from atomic-level hardware to large-scale energy and communication systems. This book was developed as a timely and coherent roadmap of that evolution, linking the fundamental physics of nanomaterials with the practical engineering requirements of commercial electronic devices.

Our intention has never been to add another broad, high-level survey to the literature. Instead, we invited contributors to reflect on two central questions:

- What unique functionality do nanomaterials offer those conventional bulk materials cannot provide?
- How must device design, fabrication, and system integration evolve to translate that functionality into manufacturable, reliable, and sustainable products?

With these questions as a framework, the book presents a continuous narrative that spans the journey from fundamental scientific principles to real-world implementation. Topics include the synthesis and characterization of emerging nanomaterials; their incorporation into high-performance electronic, sensing, photonic, and energy systems; the transition toward flexible and wearable platforms; and the challenges of integrating novel materials within established silicon infrastructure. The broader implications of sustainability, safety, and regulatory standards are also examined, recognizing that the future of nanomaterial electronics depends not only on performance metrics, but equally on societal responsibility and long-term viability.

This book is intended for graduate students entering the field, industry professionals engaged in technology-transfer and product

development, and policy makers responsible for balancing innovation with risk management. Each chapter concludes with a concise “Key Take-aways & Outlook” segment that highlights what can be implemented immediately, what requires medium-term development, and what remains a long-term challenge.

We sincerely hope that this work serves as both a reference and an inspiration supporting continued progress toward scalable, responsible, and impactful nanomaterial-enabled electronics.

Dedication

Alhamdulillah by the boundless grace of Allah, this work has reached completion. We reverently dedicate it to the Beloved Prophet Muḥammad ﷺ, the eternal well-spring of light and guidance who illuminates every step of our journey. We also honour Mian Muḥammad Afzal, Advocate of the Lahore High Court, whose steadfast patience, wise counsel and meticulous refinement of our English carried us through the long hours of composition. Finally, we offer our deepest gratitude to our families and colleagues, whose unwavering support sustained us throughout.

Acknowledgements

Our sincere appreciation goes *Associate Prof. Dr. Naveed Ahmad, Prof. Dr. Jiran Laing* and *Prof. Keping Wang*, whose guidance and expertise were instrumental in shaping the research direction of this book. This book project did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this book.

Table of Content

Chapter No	Chapter Name	Page No
One	Fundamentals of Nanomaterials in Electronics	01
Two	Advanced Nanomaterials for Semiconductor Devices	17
Three	High-Performance Nanomaterial-Based Sensors	47
Four	Energy Storage and Harvesting Technologies Using Nanomaterials	67
Five	Flexible, Wearable and Stretchable Electronics	102
Six	Quantum and Nano-Optical Devices	119
Seven	Integration of Nanomaterials with Conventional Electronics	138
Eight	Challenges in the Fabrication and Commercialization of Nanomaterial Electronics	152
Nine	Emerging Trends and the Future of Nanomaterials in Electronics	162

List of Abbreviation

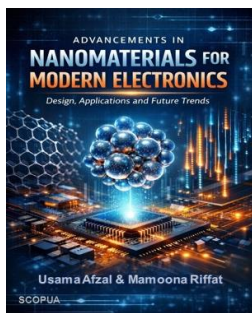
AI	Artificial Intelligence
ALD	Atomic Layer Deposition
BCPs	Block Copolymers
CNTs	Carbon Nanotubes
CVD	Chemical Vapor Deposition
CMOS	Complementary metal-oxide-semiconductor
DLW	Direct Laser Writing
DIW	Direct Ink Writing
DSA	Directed Self Assembly
DUV	Deep Ultraviolet
EN	Engineered Nanomaterials
EBL	Electron Beam Lithography
EUV	Extreme Ultraviolet
EPA	U.S. Environmental Protection Agency
ECHA	European Chemicals Agency
FETs	Field Effect Transistors
FTEs	Flexible Transparent Electrodes
GNRs	Graphene Nanoribbons
GHz	Gigahertz
GFET	Graphene Field Effect Transistor
h-BN	Hexagonal Boron Nitride
IoT	Internet of Things
ISO	International Organization for Standardization
ITO	Indium Tin Oxide
LEDs	Light Emitting Diodes
LIBs	Lithium-Ion Batteries
LSBs	Lithium-Sulfur Batteries
LTPS	Low-Temperature Polycrystalline Silicon
MEG	Multiple Exciton Generation
MIR	Mid-Infrared
MOS	Metal Oxide
ML	Machine Learning
MWCNTs	Multi-Wall Carbon Nanotubes
NFC	Near Field Communication
NIL	Nanoimprint Lithography

OLEDs	Organic Light-Emitting Diodes
OECD	Organization for Economic Co-operation and Development
Pb	Phosphorus
PCM	Phase-Change Memory
PENGs	Piezoelectric Nanogenerators
PSCs	Perovskite Solar Cells
QDs	Quantum Dots
QKD	Quantum Key Distribution
QDSCs	Quantum Dot Solar Cells
QLEDs	Quantum Dot-based LEDs
Rf	Radio-Frequency
rGO	Reduced Graphene Oxide
SADP	Self-Aligned Double Patterning
SAQP	Self-Aligned Quadruple Patterning
SOC	Spin–Orbit Coupling
SMEAs	Stretchable Microelectrode Arrays
SWCNTs	Single-Walled Carbon Nanotubes
TCO	Transition Conductive Oxide
TFTs	Thin-Film Transistors
TMDs	Transition Metal Dichalcogenides
TPL	Two-Photon Lithography
TMD-MO	Transition Metal Dichalcogenide–Metal Oxide
XAI	Explainable AI
ZT	Figure of Merit
2D	Two Dimensional
2DMs	Two-Dimensional Materials

CHAPTER 1

FUNDAMENTALS OF NANOMATERIALS IN ELECTRONICS

MAMOONA RIFFAT ^{1*}



Book Title

Advancements in Nanomaterials for Modern Electronics:
Design, Applications and Future Trends

Series Title

Books of Research Collection

Published On

January 02, 2026 (Edition 1)

Publisher

Scientific Collaborative Online Publishing Universal
Academy, Lahore, Pakistan

DOI: <https://doi.org/10.64060/978-627-7898-01-4-1>

Book ISBN: 978-627-7898-01-4

THIS WORK IS LICENSED UNDER A CREATIVE COMMONS ATTRIBUTION NONCOMMERCIAL NODERIVATIVES 4.0 INTERNATIONAL LICENSE. SCOPUA (SCIENTIFIC COLLABORATIVE ONLINE PUBLISHING UNIVERSAL ACADEMY) PUBLISHER REMAINS NEUTRAL REGARDING JURISDICTIONAL CLAIMS IN PUBLISHED MAPS AND INSTITUTIONAL AFFILIATIONS.

¹Department of Physics, LUT school of Engineering Science, Lappeenranta-Lahti University of Technology, Finland.

*Corresponding: mamoonna.riffat@lut.fi (M. Riffat)

Abstract

Nanomaterials represent a pivotal frontier in modern electronics, offering unprecedented opportunities to enhance device performance through their unique quantum, surface, and interface phenomena. Defined by at least one dimension within the 1–100 nm range, these materials exhibit distinctive electrical, optical, and mechanical properties that deviate significantly from their bulk counterparts. This chapter provides a comprehensive overview of the fundamental principles governing nanomaterials for electronic applications, encompassing their classification, synthesis, structural characteristics, and functional behaviour. Special emphasis is placed on carbon-based nanomaterials, graphene, carbon nanotubes, and fullerenes and on metal oxide systems such as TiO_2 , ZnO , and SnO_2 , which underpin major advances in transistors, sensors, and optoelectronic devices. The chapter also discusses hybrid and nanocomposite materials that integrate organic–inorganic interfaces to achieve tunable conductivity, enhanced charge mobility, and multifunctionality. Furthermore, state-of-the-art fabrication strategies, including both top-down and bottom-up methods, directed self-assembly, and nanoscale 3D printing, are evaluated in terms of precision, scalability, and sustainability. Collectively, the discussion illustrates how nanoscale engineering is redefining electronic materials, driving the development of next-generation devices that are faster, more efficient, and environmentally adaptive.

Keywords: *Carbon Nanotubes; Directed Self-Assembly; Energy-Efficient Devices; Flexible Electronics; Graphene; Hybrid Nanocomposites; Metal Oxides; Nanofabrication; Nanomaterials; Quantum Confinement; 3D Nano-Printing*

1.1. Introduction

Nanomaterials have emerged as foundational elements in the rapidly advancing fields of nanoscience and nanotechnology. These materials have at least one dimension in the nanometer range, typically between 1 and 100 nanometers [1]. They exhibit novel physical, chemical, and electronic properties that differ significantly from their bulk forms. These distinct characteristics make them excellent options for the upcoming generation of electronic devices, which will improve performance, reduce size, and enhance energy efficiency. Advanced



nanomaterials are new materials with improved properties designed to provide superior performance [2],[3].

Nanostructures sit at the crossroads of several scientific field's materials science, physics, chemistry, and engineering, all come together to explore this fascinating area. Over the last twenty years, research into these tiny structures has exploded, fueled by the global drive to turn nanoscale effects into real-world technologies. We're already seeing the impact: from more intelligent sensors and more efficient memory devices to energy-harvesting systems and bendable electronics, nanomaterials are pushing the boundaries of what's possible in tech, making it faster, smarter, and greener [2],[3].

Fundamentals of nanomaterials in electronics explores the essential principles behind nanomaterials, covering how they're made, how we study them, and how they're used, especially in the context of electronic devices and systems [4]. This book explores the diverse landscape of nanomaterials transforming electronics, from carbon-based nanomaterials like graphene and carbon nanotubes to metal oxides, quantum dots, and emerging 2D materials.

This book is crafted for students, researchers, and industry professionals who want to bridge the gap between theory and real-world applications. It offers insight into how nanostructures affect electronic properties; how specific nanomaterials are tailored for roles and the hurdles and breakthroughs involved in bringing these materials into everyday technology. Whether exploring new designs or refining existing ones, the knowledge shared here inspires and informs your work. As electronics enter an exciting new phase, shaped by advances at the nanoscale, this book opens the door to understanding the science behind next-generation devices that are more powerful, compact and efficient than ever imagined.



1.2. Basic Principles and Properties of Nanomaterials

The dimensions of nanomaterials divide them into different categories, such as 0D (nanoparticles), where all three external dimensions are confined to the nanoscale (Figure 1.1), 1D (nanowires, nanotubes), having one dimension at the nanoscale, for example, the diameter of nanowires ranges between 1 to 100 nm. Another category is 2D (graphene, MoS_2), having dimensions in the nanoscale in two directions, forming thin layers or sheets, and 3D Three-dimensional NMs are characterised by nanostructures with nanoscale dimensions in all three directions (bulk nanocomposites) [5]. Some nanomaterials exist naturally, such as volcanic ash, and the gases released during eruptions contain a variety of nanoparticles. While engineered nanomaterials (EN), which are created for and already utilised in several commercial processes and products, are of special interest. They are present in products like makeup, recreational goods, tires, electronics, stain-resistant apparel, and many other commonplace objects. They are used in medical imaging, diagnosis, and medication delivery [6],[7].

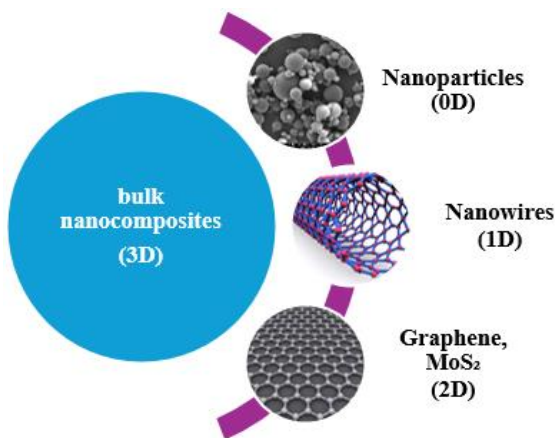


Figure 1.1: Categories of nanoparticles.

Engineered nanomaterials are resources created at the molecular (nanometer) level to benefit from their small size and



unique qualities typically absent from their traditional bulk counterparts [6]. One of the most unique features of nanomaterials is the concept of quantum confinement that emerges when the material's dimension is comparable to the wavelength of electrons. Electron transport is constrained in these situations, resulting in discrete energy levels instead of the continuous bands seen in bulk materials. The electrical, optical, and magnetic characteristics of the material are drastically changed by this change, opening new functionalities for next-generation electronic devices [8].

Another significant factor is the large surface area to volume ratio. When a particle's size decreases to the nanoscale, its surface area increases excessively in proportion to its volume. This shows that there are more atoms on the surface, which increases surface energy and the chemical reactivity of the substance. This feature is highly beneficial for sensor and catalysis applications, where surface interactions are crucial to performance [6]. Surface and interface effects are also quite significant at the nanoscale. Nanomaterials are controlled mainly by what happens at surfaces and interfaces between various phases or materials, as opposed to bulk materials, whose behaviour is dominated by the interior (bulk). These effects are important in devices like transistors and nanosensors, as they affect everything from charge transport to electronic band topologies. Tunnelling diodes and other nanoelectronics components are based on this characteristic, which is essential for creating circuits that are incredibly quick and energy efficient [9].

1.3. Key Types of Nanomaterials for Electronics

The remarkable capabilities of nanomaterials are reshaping the electronics industry. Among the most important are carbon-based materials, graphene with its ultra-thin yet robust structure, carbon nanotubes that act like tiny wires with extraordinary



conductivity, and fullerenes with their intriguing spherical shapes and electronic versatility. Metal oxides like titanium dioxide, zinc oxide, and tin oxide bring valuable semiconducting and sensing properties, making them key components in things like solar cells and gas sensors. Then, there are nanocomposites and hybrid materials, which combine the best traits of different substances to create smarter, stronger, and more adaptable materials. These nanomaterials aren't just improving electronics but making new devices possible [10],[11].

1.3.1. Carbon Nanomaterials: Graphene, Carbon Nanotubes (CNTs), Fullerenes

Traditionally, carbon was recognised in three primary forms: amorphous carbon, graphite, and diamond. However, the landscape of carbon-based materials changed dramatically with the 1985 discovery of buckminsterfullerene (C_{60}), produced through the laser ablation of graphite. This breakthrough quickly identified other fullerene structures, including C_{70} and C_{80} , which were synthesised using similar methods. Fullerene has a spherical carbon structure with unique electron-accepting properties relevant to organic photovoltaics, molecular electronics, and as charge carriers [12],[13].

Interest in fullerenes sparked further exploration into other novel carbon nanostructures, leading to the emergence of carbon nanotubes (CNTs). CNTs have cylindrical nanostructures with exceptional electrical, thermal, and mechanical properties. Used in field-effect transistors (FETs), conductive films, and nanoscale interconnects. Initially, multi-walled carbon nanotubes (MWCNTs) were observed, followed by the successful synthesis of single-walled carbon nanotubes (SWCNTs). While the two-dimensional carbon material graphene had been theoretically proposed for some time, it wasn't until 2004 that it was experimentally isolated and characterised using a simple mechanical exfoliation method,



commonly called the "Scotch tape" technique. Graphene is a single layer of carbon atoms arranged in a hexagonal lattice known for its high electrical conductivity, mechanical strength, and flexibility. Applications include transistors, sensors, and transparent electrodes [12].

C₆₀ and SWCNTs were commonly synthesised using laser ablation and arc discharge techniques. Over the past three decades, researchers have developed a range of advanced synthesis approaches for these materials. Among the most notable is chemical vapour deposition (CVD), which has become a prominent method for producing CNTs and graphene [14]. More recently, low-temperature organic synthesis routes have also been explored. The reader is encouraged to consult existing literature reviews for a comprehensive overview of the synthesis methods for SWCNTs and graphene [15].

1.3.2. Metal Oxides: TiO₂, ZnO, SnO₂

Nanostructured metal oxides such as zinc oxide (ZnO), tin dioxide (SnO₂), and titanium dioxide (TiO₂) have emerged as critical materials in electronics thanks to their versatile electrical and optical characteristics [16],[17],[18]. When engineered at the nanoscale, these oxides show distinctive properties that differ significantly from their bulk counterparts, enabling their use in transparent conductive electrodes, sensors, thin-film transistors, and photovoltaic devices [18],[19],[20].

ZnO is widely valued for its wide band gap (~3.4 eV) and high exciton binding energy, making it ideal for optoelectronic applications such as UV light emitters and transparent conductors [21],[22],[23]. When doped with group III elements like aluminium or gallium, ZnO exhibits enhanced electrical conductivity while maintaining optical transparency. Its abundance in the Earth's crust and relatively low production cost make it a strong candidate for



replacing more expensive transparent conductive oxides in large-scale applications [20],[22].

SnO_2 , another significant TCO material, is recognised for its robustness and chemical stability. Because of its resistance to extreme environmental conditions, it is appropriate for transparent electrodes in high-temperature or chemically hostile situations. Although its conductivity is slightly lower than that of ITO, SnO_2 has a long history of commercial use, particularly in applications where durability is essential, such as heated windows and gas sensors. Nanostructuring SnO_2 improves surface area and charge transport, especially in sensing technologies [20].

Though not a conventional TCO, TiO_2 plays a pivotal role in electronics, especially in dye-sensitised solar cells and photocatalytic systems. Its high refractive index, wide band gap (~ 3.2 eV), and excellent chemical resistance make it ideal for light manipulation and surface stability applications. TiO_2 provides enhanced electron transport and faster photo-response times in nanostructured form due to reduced recombination rates and increased surface area [20].

Integrating nanomaterials in electronics has revolutionised device performance by simultaneously enabling high conductivity, optical transparency, and mechanical flexibility. At the nanoscale, quantum effects, high surface-to-volume ratios, and tunable band gaps allow metal oxides like ZnO , SnO_2 , and TiO_2 to outperform traditional materials. Improving device efficiency and developments in synthesis methods like magnetron sputtering and sol-gel processing have made it feasible to regulate doping concentrations, crystalline quality, and film homogeneity [20].

1.3.3. Nanocomposites and Hybrid Materials

The use of nanocomposites and hybrid nanomaterials has significantly advanced modern electronics, enabling greater



performance, enhanced functionality, and design flexibility that was once difficult to achieve. These materials are engineered by combining different nanoscale components, each with unique physical or chemical traits, into a single, unified system. When integrated thoughtfully, the result is a material whose properties go well beyond what its individual parts could offer on their own.

Nanocomposites are formed by dispersing nanoparticles such as metallic particles, metal oxides, or carbon-based materials like graphene within a bulk matrix, often made of polymers or ceramics. This method permits the material to have electrical, thermal, or mechanical properties. For example, embedding conductive nanoparticles into a flexible polymer can create films that are both electrically conductive and physically adaptable, making them perfect for wearable sensors or bendable electronic devices [24]. Various properties of electronic devices are given in 1.2.

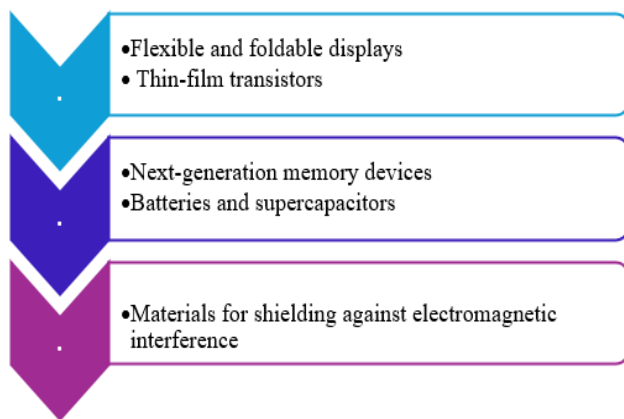


Figure 1.2: Properties of electronic devices.

Hybrid nanomaterials are designed by combining inorganic structures with organic molecules at the molecular or nanometer scale. These hybrids often deliver unique characteristics, such as high conductivity, optical responsiveness, and chemical durability.



The organic-inorganic perovskites family has gained recognition in solar cell technology due to their remarkable efficiency and lightweight nature [25].

These cutting-edge materials are unique in that they may be adjusted. Scientists can carefully regulate their composition and structure to alter their conductivity, optical transparency, band gap, and other essential characteristics. This alteration in the properties of nanomaterials makes them suitable for electronic applications [26].

Furthermore, nanocomposites can improve thermal regulation in electronics, resulting in first-class performance. As electronic devices constantly shrink in size and improve performance, efficiently managing the heat they generate becomes increasingly essential. According to Moore's law, the number of transistors on a chip doubles every 18 months. However, the density of semiconductor integrated circuits which can be most economically manufactured, doubles about every two years [27].

Incorporating nanomaterials with excellent thermal conductivity, such as carbon nanotubes or boron nitride, into polymers makes it possible to create materials that efficiently spread heat while still providing electrical insulation.

From a production standpoint, these materials are well-suited for low-temperature and scalable fabrication methods, including solution-based techniques and printing processes. Besides reducing energy consumption during manufacturing, this also enables the production of lightweight, flexible electronics on plastic substrates, paving the way for wearable and even rollable devices.

1.4. Methods of Green Hydrogen Production

The fabrication of nanomaterials for electronic applications relies on precise control over structure, composition, and morphology at the atomic and molecular levels. Two principal



strategies, **top-down** and **bottom-up**, form the foundation of nanoscale fabrication. The schematic diagram for the top-down and bottom-up approach is shown in Figure 1.3.

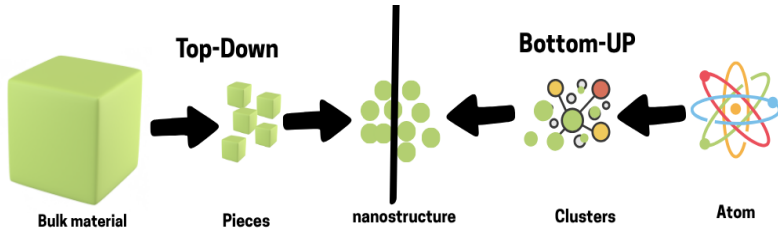


Figure 1.3: Top-down and bottom-up approaches

1.4.1. Top-Down vs. Bottom-Up Approaches

The fabrication of nanomaterials generally follows two fundamental strategies: the top-down and bottom-up approaches. In the top-down approach, bulk materials are physically or chemically reduced to nanoscale dimensions using methods such as lithography, etching, milling, or laser ablation. This technique enables precise control over shape and patterning, making it ideal for semiconductor device manufacturing and microelectronic applications. However, it is often associated with high production costs, material wastage, and the potential introduction of surface defects due to mechanical stress or chemical exposure. In contrast, the bottom-up approach builds nanostructures atom by atom or molecule by molecule through techniques like chemical vapour deposition (CVD), sol-gel synthesis, self-assembly, or molecular beam epitaxy (MBE). This method allows for excellent control over material composition, crystal quality, and surface functionality, resulting in uniform and defect-free nanostructures. While top-down methods excel in scalability and pattern precision, bottom-up strategies offer superior control at the atomic level. In modern nanotechnology, these two approaches are often integrated to combine their strengths using the structural precision of top-down



fabrication with the molecular control of bottom-up synthesis to produce highly functional and complex nanostructures for advanced electronic applications [28],[29].

1.4.2. Innovative Fabrication Strategies (e.g., Directed Assembly, 3D Printing)

Innovative fabrication strategies are advanced and creative methods for producing materials, devices, or structures that go beyond traditional techniques, aiming to enhance performance, precision, efficiency, and functionality. These strategies often involve novel approaches such as nanofabrication, 3D printing, self-assembly, hybrid or composite fabrication, and eco-friendly synthesis, enabling complex, scalable, and multifunctional structures. By leveraging such methods, researchers and engineers can overcome the limitations of conventional fabrication, achieve superior material properties, and develop next-generation technologies in fields like electronics, sensors, and biomedical devices.

Directed Assembly: Directed assembly is an innovative bottom-up nanofabrication strategy that uses external physical fields such as magnetic, electric, optical, and acoustic forces to guide the organisation of nanoparticles, colloids, or macromolecules into well-defined structures with spatial precision. This approach contrasts with traditional top-down methods and direct laser writing (DLW), offering enhanced material selection and structure complexity flexibility. Directed assembly can be performed using either vast fields, which enable large-scale, ordered formations like 1D chains and 2D films, or spatially resolved fields, which provide localised control to construct intricate 3D architectures with high regioselectivity. Researchers can fabricate superstructures such as photonic crystals, chiral clusters, and colloidal micro-robots by tuning particle properties (e.g., symmetry, polarity, surface chemistry) and manipulating field parameters (e.g., orientation,



frequency). Furthermore, incorporating surface functionalization and asymmetric particles enables the assembly of complex geometries while combining different particle types under mixed-field environments (e.g., diamagnetic and paramagnetic in ferrofluids) facilitates the formation of hierarchical 3D architectures. Although directed assembly must balance throughput, resolution, and complexity, its ability to create programmable, multi-functional nanostructures makes it a powerful tool in advanced nanomanufacturing [30],[31].

3D Printing at Nanoscale: Three-dimensional (3D) nanofabrication enables the construction of complex structures across all spatial dimensions, significantly enhancing nano-devices' performance in optics, mechanics, electromagnetics, and thermal applications. Traditional methods like 2D/2.5D lithography and etching are limited in flexibility. In contrast, techniques such as direct laser writing (DLW), including two-photon lithography (TPL), have become prominent for their ability to build nanostructures through localised photo-initiated or thermal reactions. However, DLW faces key challenges, notably restricted material choices (primarily photopolymers and sintered metals/oxides) and resolution limits imposed by optical diffraction. In contrast, directed material assembly offers a promising bottom-up alternative, where nanoparticles, clusters, and macromolecules are positioned using physical forces such as electric, magnetic, optical, or acoustic fields to achieve regioselective and scalable 3D structures. This approach broadens material compatibility and allows finer control at the nanoscale, advancing the capabilities of nanoscale 3D printing [32],[33].



1.5. Summary of Chapter

Nanomaterials, by exploiting quantum confinement, surface dominance and interface engineering at the 1–100 nm scale, deliver electrical, optical and mechanical properties unattainable in bulk phases, enabling faster, smaller and greener electronics; carbon-based allotropes (graphene, CNTs, fullerenes) furnish ballistic transport and mechanical resilience, metal-oxide nanostructures (ZnO, SnO₂, TiO₂) combine wide-band-gap semi-conductivity with earth-abundant processing, and hybrid nanocomposites merge organic flexibility with inorganic functionality for printable, flexible devices, while convergent top-down/bottom-up fabrication including directed assembly and 3D nano-printing provides the atomic-level precision needed to translate these fundamental advantages into commercial transistors, sensors, transparent conductors and energy-harvesting systems that will define the next generation of electronic technology.

References

1. N. B. Singh, "Introduction to Nanomaterials," 2023. doi: 10.21741/9781644902295-1.
2. H. Cerjak, "Nanomaterials: an introduction to synthesis, properties and applications," *Materials Technology*, vol. 24, no. 2, 2009, doi: 10.1179/175355509x454827.
3. Z. H. Khan, A. Kumar, S. Husain, and M. Husain, "Introduction to nanomaterials," in *Advanced Structured Materials*, vol. 79, 2016. doi: 10.1007/978-81-322-2668-0_1.
4. K. Kang, Y. Cho, and K. J. Yu, "Novel nano-materials and nano-fabrication techniques for flexible electronic systems," 2018. doi: 10.3390/mi9060263.
5. M. A. Darwish, W. Abd-Elaziem, A. Elsheikh, and A. A. Zayed, "Advancements in nanomaterials for nanosensors: a comprehensive review," May 24, 2024, *Royal Society of Chemistry*. doi: 10.1039/d4na00214h.
6. N. Baig, I. Kammakakam, W. Falath, and I. Kammakakam, "Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges," 2021. doi: 10.1039/d0ma00807a.
7. Q. Wu, W. S. Miao, Y. Du Zhang, H. J. Gao, and D. Hui, "Mechanical properties of nanomaterials: A review," *Nanotechnol Rev*, vol. 9, no. 1, 2020, doi: 10.1515/ntrev-2020-0021.
8. N. S. Mohammad, "Understanding quantum confinement in nanowires: Basics, applications and possible laws," 2014. doi: 10.1088/0953-8984/26/42/423202.
9. Paras *et al.*, "A Review on Low-Dimensional Nanomaterials: Nanofabrication, Characterization and Applications," 2023. doi: 10.3390/nano13010160.



10. S. Gong and W. Cheng, "One-Dimensional Nanomaterials for Soft Electronics," 2017. doi: 10.1002/aelm.201600314.
11. M. Słoma, "3D printed electronics with nanomaterials," 2023. doi: 10.1039/d2nr06771d.
12. M. M. Rahman, M. Islam, R. Roy, H. Younis, M. AlNahyan, and H. Younes, "Carbon Nanomaterial-Based Lubricants: Review of Recent Developments," 2022. doi: 10.3390/lubricants10110281.
13. S. K. Tiwari, V. Kumar, A. Huczko, R. Oraon, A. De Adhikari, and G. C. Nayak, "Magical Allotropes of Carbon: Prospects and Applications," 2016. doi: 10.1080/10408436.2015.1127206.
14. Y. M. Manawi, Ihsanullah, A. Samara, T. Al-Ansari, and M. A. Atieh, "A review of carbon nanomaterials' synthesis via the chemical vapor deposition (CVD) method," 2018. doi: 10.3390/ma11050822.
15. S. Bakhsh, "Fullerene, Carbon Nanotubes and Graphene: A Comprehensive Review," 2023. doi: 10.33640/2405-609X.3301.
16. V. V. Ram, L. Arivarasu, S. Rajeshkumar, and L. Thangavelu, "Green Synthesis and Characterisation of Mucuna Pruriens Mediated Titanium Dioxide Nanoparticles Using Transmission Electron Microscope," *J Pharm Res Int*, 2021, doi: 10.9734/jpri/2021/v33i62b35624.
17. J. S. Chen and X. W. Lou, "SnO₂ and TiO₂ nanosheets for lithium-ion batteries," 2012. doi: 10.1016/S1369-7021(12)70115-3.
18. V. Parihar, M. Raja, and R. Paulose, "A brief review of structural, electrical and electrochemical properties of zinc oxide nanoparticles," 2018. doi: 10.1515/rams-2018-0009.
19. J. Abad and J. Padilla, *Transparent Conductive Materials: Materials, Synthesis, Characterization, Applications*, 2018.
20. K. Ellmer, R. Mientus, and S. Seeger, "Metallic Oxides (ITO, ZnO, SnO₂, TiO₂)," in *Transparent Conductive Materials*, Wiley, 2018, pp. 31–80. doi: 10.1002/9783527804603.ch2_1.
21. R. A. Gonçalves, R. P. Toledo, N. Joshi, and O. M. Berengue, "Green synthesis and applications of ZnO and TiO₂ nanostructures," 2021. doi: 10.3390/molecules26082236.
22. S. Vyas, "A short review on properties and applications of zinc oxide based thin films and devices: ZnO as a promising material for applications in electronics, optoelectronics, biomedical and sensors," 2020. doi: 10.1595/205651320X15694993568524.
23. D. C. Look, "Recent advances in ZnO materials and devices," *Mater Sci Eng B Solid State Mater Adv Technol*, vol. 80, no. 1–3, 2001, doi: 10.1016/S0921-5107(00)00604-8.
24. C. Zhan, G. Yu, Y. Lu, L. Wang, E. Wujcik, and S. Wei, "Conductive polymer nanocomposites: a critical review of modern advanced devices," 2017. doi: 10.1039/c6tc04269d.
25. V. P. Ananikov, "Organic-inorganic hybrid nanomaterials," 2019. doi: 10.3390/nano9091197.
26. R. Vargas-Bernal, "Introductory Chapter: Hybrid Nanomaterials," in *Hybrid Nanomaterials - Flexible Electronics Materials*, 2020. doi: 10.5772/intechopen.92012.
27. B. El Zein and S. S. Habib, "Small is the next big thing: Thermal phenomenon on the nanoscale electronic devices," *Int J Nanomanuf*, vol. 4, no. 1–4, 2009, doi: 10.1504/IJNM.2009.028128.



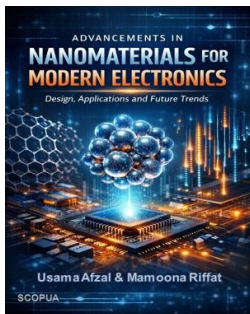
28. Abid, Namra, et al. "Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review." *Advances in Colloid and Interface Science* 300 (2022): 102597.
29. Teo, Boon K., and X. H. Sun. "From top-down to bottom-up to hybrid nanotechnologies: road to nanodevices." *Journal of cluster science* 17.4 (2006): 529-540.
30. Grzelczak, Marek, et al. "Directed self-assembly of nanoparticles." *ACS nano* 4.7 (2010): 3591-3605.
31. Tan, Shu Fen, et al. "Direct observation of interactions between nanoparticles and nanoparticle self-assembly in solution." *Accounts of chemical research* 50.6 (2017): 1303-1312.
32. Yin, Yuxiang, et al. "Nanoscale 3D Printing for Empowering Future Nanodevices." *Advanced Materials Technologies* (2025): 2500083.
33. Cheng, Lijia, et al. "3D printing of micro-and nanoscale bone substitutes: a review on technical and translational perspectives." *International journal of nanomedicine* (2021): 4289-4319.



CHAPTER 2

ADVANCED NANOMATERIALS FOR SEMICONDUCTOR DEVICES

USAMA AFZAL ^{1*}

**Book Title**

Advancements in Nanomaterials for Modern Electronics:
Design, Applications and Future Trends

Series Title

Books of Research Collection

Published On

January 02, 2026 (Edition 1)

Publisher

Scientific Collaborative Online Publishing Universal
Academy, Lahore, Pakistan

DOI: <https://doi.org/10.64060/978-627-7898-01-4-2>

Book ISBN: 978-627-7898-01-4

THIS WORK IS LICENSED UNDER A CREATIVE COMMONS ATTRIBUTION NONCOMMERCIAL
NODERIVATIVES 4.0 INTERNATIONAL LICENSE. SCOPUA (SCIENTIFIC COLLABORATIVE ONLINE
PUBLISHING UNIVERSAL ACADEMY) PUBLISHER REMAINS NEUTRAL REGARDING JURISDICTIONAL
CLAIMS IN PUBLISHED MAPS AND INSTITUTIONAL AFFILIATIONS.

¹School of Microelectronics, Tianjin University, Tianjin 300072, China.

*Corresponding: mohammadusamafzal7@gmail.com (U. Afzal)

Abstract

This chapter presents a comprehensive overview of advanced nanomaterials and their transformative role in next-generation semiconductor and optoelectronic devices. It explores the unique properties and integration strategies of emerging materials such as graphene, transition metal dichalcogenides (TMDs), black phosphorus, MXenes, and quantum dots (QDs), which have collectively redefined the boundaries of nanoscale electronics. The discussion begins with two-dimensional (2D) materials, emphasising their exceptional electrical, mechanical, and optical characteristics, and examines how bandgap engineering and heterostructuring overcome intrinsic limitations for high-performance transistor applications. The chapter further elaborates on the role of QDs in realising quantum confinement effects for advanced transistors, photodetectors, light-emitting diodes, and photovoltaic systems, as well as in hybrid architectures that enhance charge transport and light–matter interaction. Advanced lithography and nanofabrication techniques, including EUV, EBL, NIL and DSA, are reviewed as key enablers of sub-10 nm device scaling. Finally, the chapter highlights the intersection of nanotechnology and optoelectronics, where engineered nanostructures such as QDs, nanowires, and 2D materials underpin the development of compact, flexible, and high-efficiency nano-optoelectronic systems. Together, these insights outline the critical advancements driving the evolution of semiconductor technologies beyond the silicon era.

Keywords: *Advanced nanomaterials; nanoelectronics; nanolithography; nano-optoelectronics; next-generation transistors; semiconductor devices; transition metal dichalcogenides (TMDs)*

The continuous scaling of semiconductor devices, as described by Moore's Law, has driven the relentless pursuit of novel materials with superior electrical, optical, and mechanical properties to overcome the fundamental limitations of traditional silicon-based technologies. In this context, advanced nanomaterials such as graphene, other two-dimensional (2D) materials, transition metal dichalcogenides (TMDs), quantum dots (QDs), and complex nanostructures have emerged as pivotal building blocks for next-generation electronic and optoelectronic devices. These materials exhibit unique quantum phenomena, tunable electronic structures, and enhanced surface-to-volume ratios



that enable unprecedented device functionalities, including ultra-fast switching, high sensitivity, energy efficiency and mechanical flexibility.

This chapter explores the landscape of advanced nanomaterials tailored for semiconductor applications, focusing on their fundamental properties, integration strategies and demonstrated applications in state-of-the-art devices.

2.1. 2D materials for Nanoelectronics

Two-dimensional (2D) materials have emerged as a groundbreaking class of nanomaterials with extraordinary structural, electronic, and mechanical properties, driving significant advancements in next-generation nanoelectronics [1],[2],[3]. Defined by their atomic-scale thickness and large surface-to-volume ratio, these materials, such as graphene, TMDs, hexagonal boron nitride (h-BN), and black phosphorus (BP), exhibit remarkable characteristics including high carrier mobility, adjustable bandgaps, and excellent electrostatic control (Figure 2.1). These unique properties allow 2D materials to overcome the limitations of conventional bulk semiconductors, enabling device miniaturisation without compromising electrical performance or stability. Recent research has focused on scalable synthesis techniques, such as chemical vapour deposition (CVD), mechanical exfoliation, and solution-based processing, to achieve uniform and defect-free layers suitable for practical device fabrication. Owing to their exceptional versatility, 2D materials have been successfully utilised in transistors, photodetectors, flexible and wearable electronics, gas sensors, and optoelectronic components. Their compatibility with flexible substrates also makes them ideal for emerging technologies such as bendable displays and biomedical devices. Overall, 2D materials represent a pivotal step toward the



development of ultra-thin, energy-efficient, and high-performance electronic systems. Their tunable properties and integration potential promise to revolutionise the design of future nanoelectronic architectures beyond the limits of traditional silicon-based technologies.

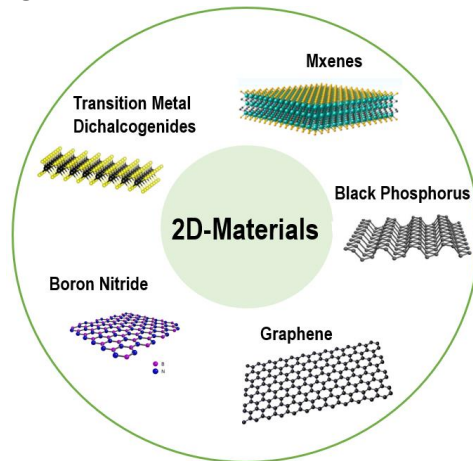


Figure 2.1: Illustration of some representative two-dimensional (2D) materials highlighting their layered atomic structures and potential for advanced nanoelectronic applications.

2.1.1. Graphene in Nanoelectronics

Graphene, an atomically thin layer of sp^2 -hybridized carbon atoms arranged in a two-dimensional honeycomb lattice, has emerged as a paradigm-shifting material in the field of nanoelectronics [4]. Since its isolation in 2004 by Novoselov and Geim, graphene has captivated researchers worldwide due to its unparalleled electrical, thermal and mechanical properties, making it an attractive candidate for a wide range of electronic applications. From an electronic perspective, graphene exhibits extraordinary carrier mobility, with intrinsic values reported exceeding $200,000 \text{ cm}^2/\text{Vs}$ at low temperatures and over $10,000 \text{ cm}^2/\text{Vs}$ at room temperature in suspended samples. This is orders of magnitude higher than that of conventional semiconductors like silicon



($\sim 1,400 \text{ cm}^2/\text{Vs}$) or gallium arsenide ($\sim 8,500 \text{ cm}^2/\text{Vs}$), highlighting graphene's potential for ultra-high-speed transistors and radio-frequency (RF) electronics. In addition, graphene possesses a linear, Dirac-like energy dispersion near the K and K' points of the Brillouin zone, leading to massless charge carriers (Dirac fermions) with a Fermi velocity of approximately 10^6 m/s . This unique band structure underpins graphene's exceptional electronic behaviour, including ballistic transport over sub-micron distances [5],[6].

Graphene also exhibits a remarkably high thermal conductivity, reported to exceed $5,000 \text{ W/mK}$ at room temperature, making it an excellent material for thermal management in densely packed nanoelectronic circuits where heat dissipation is a major bottleneck. Its mechanical strength is equally impressive, with a Young's modulus of $\sim 1 \text{ TPa}$ and intrinsic tensile strength of $\sim 130 \text{ GPa}$, enabling the development of flexible and stretchable electronic devices. Despite these extraordinary properties, the absence of a native bandgap in pristine graphene poses a significant limitation for its application in digital logic circuits. The gapless semimetallic nature of graphene results in an inability to achieve a high on/off current ratio, which is a critical requirement for effective transistor switching in digital electronics. For instance, a graphene field-effect transistor (GFET) typically exhibits an on/off ratio of less than 10, compared to values exceeding 10^6 in silicon MOSFETs.

To address this challenge, researchers have developed several bandgap engineering strategies to modify graphene's electronic properties:

- **Quantum Confinement:** Patterning graphene into narrow graphene nanoribbons (GNRs) induces a bandgap due to quantum confinement effects [7]. Theoretical and experimental studies have shown that GNRs with widths below 10 nm can exhibit bandgaps in the range of $0.1\text{--}0.5 \text{ eV}$, depending on their



edge geometry (armchair or zigzag). For example, Yan, Q. et al. (2007) demonstrated a GNR-based transistor with an on/off ratio of $\sim 10^5$ at room temperature, highlighting the feasibility of GNRs for logic applications [8].

- **Chemical Doping:** Introducing heteroatoms such as nitrogen, boron, or fluorine into the graphene lattice alters its electronic structure by breaking symmetry or introducing localised states. For instance, nitrogen-doped graphene has been shown to exhibit a tunable bandgap and modified carrier concentration, enabling its use in sensors and optoelectronic devices [9].
- **Graphene Heterostructures:** Stacking graphene with other 2D materials, such as h-BN or TMDs, forms van der Waals heterostructures with tailored electronic properties. For example, a graphene/MoS₂ heterostructure can combine the high mobility of graphene with the intrinsic bandgap of MoS₂, enabling tunnelling transistors and photodetectors. Kim, T. et al. (2020) demonstrated a graphene/ MoS₂ tunnelling transistor with a high on/off ratio and subthreshold swing, illustrating the potential of such hybrid architectures for low-power electronics [10].

In addition to logic devices, graphene has found applications in radio-frequency (RF) electronics, where its high carrier mobility and saturation velocity enable devices such as graphene-based transistors and frequency multipliers operating at gigahertz (GHz) and even terahertz (THz) frequencies. For example, a graphene FET demonstrated by Wu Y. et al (2016). achieved a cutoff frequency (f_T) of 427 GHz, surpassing the performance of traditional silicon-based transistors [11]. Graphene's optical transparency ($\sim 97.7\%$ per monolayer) and flexibility have also driven its use in transparent conductive electrodes for displays, touchscreens, and flexible electronics [12]. Furthermore, graphene-based sensors leverage their high surface



area and sensitivity to detect gases, biomolecules, and environmental pollutants at ultralow concentrations, with demonstrated applications in ammonia, NO₂, and humidity sensors.

Graphene's unique combination of exceptional carrier mobility, mechanical strength, thermal conductivity, and optical transparency positions it as a foundational material for next-generation nanoelectronics. However, the lack of an intrinsic bandgap necessitates innovative engineering approaches such as quantum confinement, chemical modification, and heterostructure design to fully harness its potential in digital logic applications. As synthesis methods mature and scalable integration strategies evolve, graphene is expected to play a pivotal role in advancing future electronic technologies, from flexible and wearable devices to ultra-fast communication systems.

2.1.2. Other 2D Materials in Nanoelectronics

Beyond graphene, a diverse family of two-dimensional (2D) materials has garnered significant interest in the field of nanoelectronics, offering a broad spectrum of electronic, optical, and chemical properties that complement or surpass those of graphene in specific applications [13],[14]. These materials, which include TMDs, h-BN, black phosphorus (BP) and MXenes, have opened new avenues for the design and fabrication of next-generation semiconductor devices, optoelectronic components, and sensors. A key advantage of 2D materials beyond graphene is their inherent bandgap, which is often tunable and enables their direct application in FETs for logic circuits and optoelectronic devices. For instance, TMDs such as molybdenum disulfide (MoS₂), tungsten diselenide (WSe₂), and molybdenum diselenide (MoSe₂) are semiconductors with layer-dependent bandgaps typically ranging from 1.0 eV (bulk) to 1.8–2.0 eV (monolayer). This intrinsic bandgap makes TMDs particularly attractive for applications requiring high current on/off ratios, such as digital logic devices, photodetectors, and light-emitting devices.



Furthermore, the tunable bandgap of TMDs enables spectral selectivity in photodetectors and energy harvesting devices, addressing the limitations of zero-bandgap graphene in optoelectronic applications.

- **Hexagonal boron nitride (h-BN)**, often referred to as "white graphene," is another essential 2D material [15]. While it is an electrical insulator with a wide bandgap (~ 5.9 eV), h-BN serves as an excellent dielectric and encapsulation material in van der Waals heterostructures. Its atomically smooth surface, chemical inertness, and lack of dangling bonds provide an ideal substrate for supporting other 2D materials, minimising charge impurities and enhancing carrier mobility. h-BN has been extensively employed as a tunnel barrier in graphene-based devices, enabling tunnelling transistors and high-performance quantum devices.
- **Black phosphorus (BP)**, a layered material with a puckered honeycomb structure, has gained attention for its direct bandgap, which is thickness-dependent and ranges from ~ 0.3 eV (bulk) to ~ 2.0 eV (monolayer, also known as phosphorene) [16]. BP exhibits high carrier mobility (up to $\sim 1,000$ cm²/Vs) and strong in-plane anisotropy in electrical and optical properties, enabling the development of polarisation-sensitive devices and anisotropic transistors. However, BP's stability under ambient conditions remains a challenge, as it is prone to oxidation, necessitating protective encapsulation strategies.
- **MXenes**, a relatively new family of 2D transition metal carbides and nitrides (e.g., Ti₃C₂T_x, Nb₂C), exhibit metallic conductivity and hydrophilic surfaces due to their surface terminations ($-\text{OH}$, $-\text{F}$, $-\text{O}$) [17]. MXenes offer a unique combination of high conductivity, mechanical flexibility, and chemical tunability, making them promising candidates for



energy storage, electromagnetic interference shielding, and potentially interconnects in nanoelectronic devices.

Beyond individual materials, the heterostructuring of 2D materials by stacking atomically thin layers via Van der Waals forces has emerged as a powerful strategy for creating tailored electronic and optoelectronic devices. By combining materials with complementary properties (e.g., semiconducting TMDs, insulating h-BN, and conductive graphene), researchers can engineer band alignments, charge transfer dynamics, and interface phenomena that are inaccessible in bulk systems. This approach has enabled the realisation of vertical tunnelling transistors, atomically sharp p–n junctions, and quantum devices with unprecedented performance metrics [18]. Moreover, the integration of 2D materials with conventional silicon technologies presents opportunities for hybrid systems that leverage the unique properties of atomically thin materials alongside mature CMOS fabrication processes. Challenges such as large-area synthesis, precise layer control, and interface engineering remain at the forefront of research efforts, driving innovations in chemical vapour deposition (CVD), molecular beam epitaxy (MBE), and liquid-phase exfoliation techniques.

This diverse family of 2D materials beyond graphene provides a rich toolbox for advancing nanoelectronics devices. Their tunable band structures, strong light-matter interactions, and compatibility with flexible substrates position them as essential building blocks for the next generation of logic devices, sensors, photodetectors, and energy-efficient electronic components. Continued interdisciplinary research focused on scalable synthesis, device integration, and interface control will be critical to unlocking the full potential of these materials in practical semiconductor applications.



2.2. Transition Metal Dichalcogenides (TMDs) for Next-Generation Transistors

Transition metal dichalcogenides (TMDs) have emerged as a pivotal class of 2D semiconducting materials with significant potential for next-generation transistor technologies (Figure 2.2). TMDs have the general formula MX_2 , where M is a transition metal (e.g., molybdenum (Mo), tungsten (W), rhenium (Re)) and X is a chalcogen (e.g., sulfur (S), selenium (Se), or tellurium (Te)). Structurally, TMDs consist of stacked layers held together by weak van der Waals forces, enabling exfoliation down to single monolayers [19]. Each monolayer consists of a sandwich-like structure: a hexagonally packed metal layer between two chalcogen layers (X-M-X). One of the most attractive properties of TMDs for transistor applications is their layer-dependent electronic bandgap. Unlike graphene, which is a zero-bandgap semimetal, semiconducting TMDs such as MoS_2 (molybdenum disulfide), WS_2 (tungsten disulfide) and WSe_2 (tungsten diselenide) exhibit direct bandgaps in the monolayer form ($\sim 1.8\text{--}2.0$ eV for MoS_2), transitioning to indirect bandgaps in bulk form (~ 1.2 eV). This tunable bandgap is critical for FETs, as it allows for high current on/off ratios essential for logic devices.

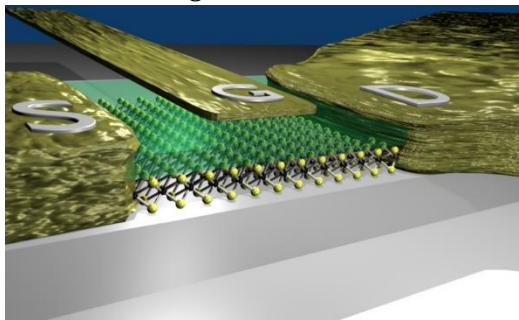


Figure 2.2: Schematic illustration of a two-dimensional (2D) material-based field-effect transistor (FET), showing the source (S), gate (G), and drain (D) configuration. The atomically thin 2D channel enables efficient carrier transport and enhanced electrostatic control for next-generation nanoelectronic devices.



For instance, MoS₂-based transistors have been demonstrated with remarkable performance metrics. In a landmark study by Radisavljevic et al. (2011), a monolayer MoS₂ FET exhibited an on/off current ratio exceeding 10⁸ and a subthreshold swing of ~74 mV/decade [20]. The ultra-thin nature of MoS₂ (thickness ~0.7 nm per layer) ensures excellent gate electrostatic control, suppressing short-channel effects that challenge silicon transistors at sub-10 nm technology nodes. Moreover, WSe₂ transistors have shown promise for ambipolar transport, enabling both electron and hole conduction, a feature advantageous for complementary logic circuits. For example, Fang, H. et al. (2012) demonstrated WSe₂ FETs with high hole mobility (~250 cm²/Vs), which is beneficial for p-type devices in CMOS-like architectures [21]. TMDs also exhibit unique properties such as strong spin-orbit coupling (SOC) and valley polarisation, which enable the development of spintronic and valleytronic devices. For example, MoS₂ and WS₂ exhibit spin-split valence bands at the K and K' points of the Brillouin zone, enabling selective excitation of carriers in different valleys using circularly polarised light [22]. This property opens new possibilities for information storage and processing beyond conventional charge-based electronics. Heterostructures based on TMDs further expand their functionality. By vertically stacking monolayers of different TMDs, such as MoS₂/WSe₂, researchers have created type-II band alignment heterostructures that facilitate charge separation at the interface, useful for photodetectors and solar cells. For example, Jia, S. (2020) et al. demonstrated a MoS₂/WSe₂ p-n heterojunction diode with strong rectifying behaviour and photovoltaic response [23].

Despite these advantages, several challenges hinder the widespread adoption of TMDs in commercial transistors. The scalable synthesis of high-quality, wafer-scale monolayers is still under development. While mechanical exfoliation produces high-quality flakes, it is not scalable for industrial use [24]. Techniques



like CVD have shown promise in growing large-area MoS₂ films, but issues related to grain boundaries, domain size, and defect densities must be addressed to achieve uniform device performance. Another bottleneck is the high contact resistance between metal electrodes and TMDs, which limits carrier injection and degrades device performance. Researchers have explored several strategies to reduce contact resistance, including using low-work-function metals (e.g., scandium, titanium), forming van der Waals contacts (e.g., with graphene), and employing phase engineering, locally transforming semiconducting 2H-phase MoS₂ into metallic 1T-phase for better carrier injection. For example, Kappera et al. (2014) demonstrated that phase-engineered 1T–MoS₂ contacts reduced contact resistance by two orders of magnitude compared to traditional 2H–MoS₂ contacts [25].

In brief, TMDs such as MoS₂, WS₂, and WSe₂ offer a unique combination of atomic-scale thickness, intrinsic and tunable bandgaps, and strong spin-orbit coupling, making them ideal for ultra-scaled, low-power, and multifunctional transistors. Their integration into next-generation semiconductor technologies promises advances in high-performance logic circuits, optoelectronics, and flexible electronics. Continued progress in material synthesis, interface engineering, and device architecture will be key to unlocking the full potential of TMD-based transistors in the post-silicon era.

2.3. Quantum Dots and Their Role in High-Performance Electronics

Quantum dots (QDs) are increasingly recognised for their immense potential in high-performance electronic devices, primarily owing to their discrete energy levels, strong quantum confinement effects, and Coulomb blockade phenomena [26],[27]. These nanoscale characteristics enable QDs to exhibit single-



electron charging and tunnelling behaviours, which are critical for advanced applications such as quantum computing, single-electron transistors (SETs), and memory devices. When QDs are integrated within transistor channels, the gate voltage can modulate the current flow by controlling the Coulomb blockade effect, leading to a quantised, step-like current-voltage characteristic that is distinct from conventional charge transport mechanisms. This precise control of electron flow facilitates the development of SETs, where the Coulomb charging energy ($EC = e^2/2C$, with C denoting the QD capacitance) becomes dominant over thermal energy (kBT), enabling stable operation of QD-based SETs even at room temperature, provided the QDs are sufficiently small. Notably, semiconductor QDs composed of materials such as indium arsenide (InAs), gallium arsenide (GaAs), or silicon (Si) have demonstrated robust single-electron transport behaviour at practical operating conditions, underscoring their promise for the development of low-power logic circuits, ultra-high-density memory arrays, and quantum metrology standards in next-generation semiconductor technologies.

2.3.1. Quantum Confinement and Electronic Properties of Quantum Dots

The unique properties of quantum dots originate from **quantum mechanical confinement**, where the exciton Bohr radius (the spatial extent of the electron-hole pair) becomes comparable to the QD dimensions. This leads to quantisation of energy levels, such that the effective bandgap E_g increases as the QD size decreases, a phenomenon described by the Brus equation (2.1) [28]:

$$E_g(R) = E_g(bulk) + \frac{\hbar^2 \pi^2}{2R^2} \left(\frac{1}{m_c^*} + \frac{1}{m_h^*} \right) - 1.8 \frac{e^2}{4\pi\epsilon R} \quad (2.1)$$

Where R is the QD radius, m_c^* and m_h^* are the effective masses of the electron and hole, respectively, and ϵ is the dielectric



constant. The size-dependent bandgap tuning enables applications across various spectral regimes, including visible (CdSe, Inp QDs), near-infrared (PbS, PbSe QDs) and mid-infrared (HgTe QDs) [29].

For instance, CdSe QDs exhibit photoluminescence emission from ~450 nm to 650 nm depending on size, making them ideal for colour-tunable light-emitting diodes (LEDs) and display technologies. Similarly, PbS and PbSe QDs can be tuned for infrared detection, critical for telecommunications and thermal imaging applications.

2.3.2. Quantum Dots in Optoelectronic Devices

- **Quantum Confinement and Electronic Properties:** The fundamental origin of the exceptional behaviour of quantum dots lies in the phenomenon of quantum confinement [30]. When the size of a semiconductor crystal is reduced below its exciton Bohr radius, the continuous energy bands of the bulk material collapse into discrete energy levels. As a result, the bandgap energy of the quantum dot becomes size-dependent: smaller quantum dots exhibit larger bandgaps, whereas larger quantum dots have narrower bandgaps. This tunability allows for precise control over their optical absorption and emission properties by simply altering the size, shape, and composition of the quantum dots.

For example, CdSe quantum dots can be engineered to emit light ranging from blue to red by adjusting their size from ~2 nm to ~6 nm, making them highly desirable for applications in display technologies and optoelectronic devices [31]. Similarly, PbS and PbSe quantum dots, which possess narrower bandgaps in the infrared region, are extensively utilised for photodetectors operating in the near- to mid-infrared spectral ranges.



- **Quantum Dots in Transistors and Logic Devices:** The integration of quantum dots into FETs has been an area of significant interest, particularly for applications requiring ultra-low power consumption and high charge carrier mobility [32]. Quantum dot-based FETs (QD-FETs) exploit the discrete energy states and Coulomb blockade effects of QDs to modulate current flow. For instance, single-electron transistors (SETs) employing QDs as the active channel material have demonstrated the ability to control the flow of individual electrons, which is a key milestone toward realising quantum logic operations and ultra-dense integrated circuits [33].

A notable example is the demonstration of a silicon-based SET using silicon quantum dots, where Coulomb blockade oscillations were observed at cryogenic temperatures, showcasing the potential for single-electron control [34]. In addition, indium arsenide (InAs) QDs embedded in gate dielectrics have been used to fabricate charge-trap memory devices, where the discrete energy levels of QDs provide superior retention characteristics compared to conventional floating-gate structures [35].

- **Quantum Dots in Photodetectors and Imaging Devices:** Quantum dots offer unique advantages for photodetection, particularly in spectral regions where traditional bulk semiconductors are less efficient. The tunable absorption onset of QDs allows for engineering of photodetectors across a broad wavelength range, including visible, near-infrared (NIR), and mid-infrared (MIR) regions [36]. For instance, lead sulfide (PbS) and lead selenide (PbSe) QDs have been widely explored for NIR photodetectors with high responsivity and detectivity.

A striking example is the use of colloidal quantum dots in solution-processed photodetectors. Researchers have demonstrated PbS QD-based photodetectors with detectivities exceeding 10^{12} Jones and operational wavelengths extending



beyond 1.5 μm , outperforming many traditional materials such as InGaAs [37]. Moreover, the compatibility of colloidal QDs with low-temperature, solution-phase processing enables their integration on flexible and unconventional substrates, facilitating the development of wearable and conformal photodetectors for biomedical imaging and remote sensing.

- **Quantum Dots in Light-Emitting Diodes (QLEDs):** Quantum dots have revolutionised the field of display and lighting technologies due to their narrow emission linewidths, high photoluminescence quantum yields (PLQYs), and tunable emission wavelengths [38]. Quantum dot light-emitting diodes (QLEDs) leverage these properties to achieve vivid, saturated colours, high colour purity, and wide colour gamuts, surpassing the performance of conventional organic LEDs (OLEDs) in several metrics.

Commercially, cadmium-based QDs such as CdSe/ZnS core-shell structures have been successfully integrated into QLED displays, offering enhanced colour accuracy in high-end television panels. More recently, cadmium-free alternatives such as indium phosphide (InP) and perovskite quantum dots (e.g., CsPbBr₃) have garnered significant attention due to regulatory concerns over cadmium toxicity [39]. For instance, InP QDs have demonstrated PLQYs exceeding 80% and emission linewidths below 40 nm, making them suitable for next-generation displays with minimal environmental impact.

Perovskite quantum dots, particularly those based on lead halide perovskites (CsPbX₃, where X = Cl, Br, or I), have shown exceptional performance in QLEDs, achieving external quantum efficiencies (EQEs) exceeding 20% [40]. The combination of high PLQYs, facile solution processability, and tunable emission from ultraviolet to near-infrared regions makes perovskite QDs a promising material system for optoelectronic applications.



- **Quantum Dots in Solar Cells and Photovoltaics:** Quantum dots have also been employed as light-harvesting materials in photovoltaic devices. The tunability of the bandgap allows for tailoring the absorption profile to match the solar spectrum, while the potential for multiple exciton generation (MEG) in QDs offers a pathway to surpass the Shockley-Queisser limit of traditional single-junction solar cells [41].

For instance, PbS and PbSe QD-based solar cells have demonstrated power conversion efficiencies (PCEs) exceeding 13%, while perovskite quantum dot solar cells have reached PCEs over 16% [42]. Moreover, the ability to fabricate QD films via solution processing techniques, such as spin coating or inkjet printing, enables scalable and low-cost manufacturing approaches for solar energy harvesting technologies.

2.3.3. Quantum Dots in Optoelectronic Devices

Hybrid quantum dot (QD) systems, where QDs are integrated with other nanomaterials, offer a powerful approach to overcoming the limitations of individual material systems by leveraging their synergistic interactions [43],[44]. Quantum dots possess unique properties, including size-dependent bandgap tunability, strong light absorption, and high photoluminescence quantum yield, but their performance can be hindered by limited carrier mobility and charge transport issues. By interfacing QDs with high-mobility nanomaterials like graphene, these challenges can be mitigated. For instance, lead sulfide (PbS) QDs combined with graphene have been demonstrated in photodetectors exhibiting ultra-high responsivity exceeding 10^7 A/W and broadband detection across the visible to infrared range [45]. In these systems, graphene acts as an efficient charge transport layer, while QDs serve as tunable light absorbers and exciton generators, resulting in devices that combine high sensitivity with fast response times. Such hybrid



architectures are promising for developing high-performance photodetectors, infrared sensors, and broadband imaging systems.

Beyond graphene, the integration of QDs with other two-dimensional (2D) materials, such as TMDs, has unlocked additional functionalities for optoelectronic devices [46]. QD-2D heterostructures enable efficient energy transfer and charge separation, where the QDs contribute strong light-matter interactions, and the 2D materials, such as MoS₂ or WS₂, facilitate high charge carrier mobility and mechanical flexibility. For example, QD-MoS₂ hybrid photodetectors have demonstrated enhanced photoresponse and stability compared to devices based solely on MoS₂, attributed to the improved light absorption and reduced recombination losses facilitated by the QDs [47]. Furthermore, hybrid systems combining QDs with 2D materials have shown potential for flexible and wearable optoelectronics, where ultrathin device architectures, mechanical robustness, and broadband sensitivity are essential [48]. These synergies open new possibilities for low-cost, high-efficiency devices in applications ranging from wearable health monitors to integrated optoelectronic circuits.

In addition to graphene and 2D materials, QD-perovskite hybrid systems have gained significant attention in the field of solar cells and light-emitting devices. In perovskite photovoltaics, incorporating QDs such as CdSe, PbS, or CsPbBr₃ into the perovskite matrix can improve defect passivation, broaden the absorption spectrum, and facilitate energy transfer processes [49]. This results in improved power conversion efficiencies and enhanced device stability, as QDs can mitigate the formation of non-radiative recombination centres in perovskites. Similarly, perovskite-QD LEDs benefit from the tunable emission properties of QDs and the high radiative efficiency of perovskites, leading to devices with improved external quantum efficiencies and colour purity. For instance, CsPbBr₃ QDs integrated into perovskite LEDs



have demonstrated enhanced brightness and operational lifetimes. These examples highlight how the combination of QDs with diverse nanomaterials enables multifunctional devices that transcend the capabilities of individual components, paving the way for the next generation of high-performance optoelectronics in applications such as photovoltaics, lighting, sensing, and energy harvesting.

2.3.4. Limitations

Despite their promising attributes, several challenges hinder the widespread adoption of quantum dots in high-performance electronics. Stability remains a critical issue, as QDs are often prone to photodegradation, oxidation, and ion migration, which can degrade device performance over time. Surface passivation strategies, such as ligand exchange and core-shell engineering, are crucial to enhancing the stability and electronic coupling of QDs in devices. Toxicity, particularly of heavy-metal-based QDs like CdSe and PbS, raises environmental and health concerns that necessitate the development of safer alternatives. Research into non-toxic QD materials, such as InP, CuInS₂, and carbon-based QDs, is an active area of investigation aimed at creating environmentally benign nanomaterials for electronics.

Furthermore, precise control over quantum dot size distribution, surface chemistry, and assembly remains essential for device reproducibility and scalability. Advanced fabrication techniques, such as atomic layer deposition (ALD), molecular beam epitaxy (MBE), and superlattice engineering, are being explored to address these challenges and enable the integration of QDs into complex device architectures.



2.4. Advanced Lithography and Nanostructuring Techniques for Semiconductor Devices

The relentless miniaturisation of semiconductor devices, in accordance with Moore's Law, has driven the need for increasingly sophisticated lithography and nanostructuring techniques capable of fabricating features at sub-10 nm scales with high fidelity, precision and throughput [50]. As device dimensions approach the fundamental limits of classical scaling, the role of advanced lithography becomes paramount in enabling the fabrication of next-generation semiconductor architectures, including FinFETs, gate-all-around (GAA) FETs, nanosheet transistors, and 3D integrated circuits (3D-ICs). This section provides a comprehensive overview of the state-of-the-art lithography and nanofabrication methodologies that underpin the semiconductor industry, their inherent challenges, and emerging innovations poised to drive future device generations.

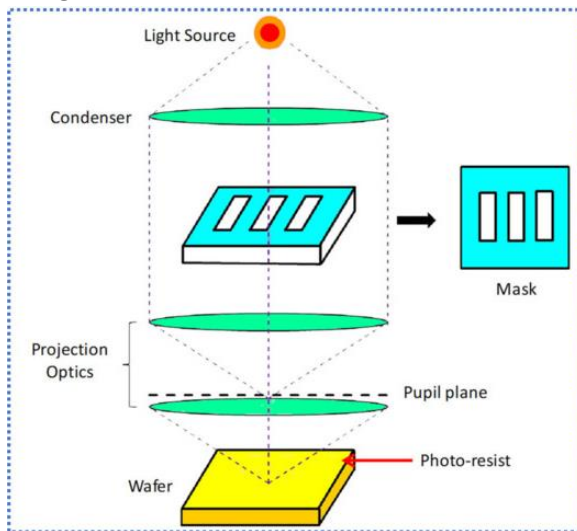


Figure 2.2: Schematic diagram of the photolithography process, illustrating the projection of patterned light through a mask onto a photoresist-coated wafer using condenser and projection optics for micro- and nanoscale pattern transfer [51].



2.4.1. Fundamentals of Lithography in Semiconductor Manufacturing

Lithography is a critical patterning technique that defines the lateral dimensions of semiconductor devices by selectively transferring a pattern from a mask (or template) onto a photosensitive resist layer deposited on a substrate. The resolution of a lithographic process is fundamentally governed by the Rayleigh criterion (2.2) [52]:

$$\text{Resolution } (R) = k_1 \frac{\lambda}{NA} \quad (2.2)$$

Where λ is the wavelength of the exposure source, NA is the numerical aperture of the projection system, and k_1 is a process-dependent factor typically ranging from 0.25 to 0.5. As λ decreases and NA increases, higher resolution can be achieved, albeit with challenges in optics design, resist chemistry, and process control.

Lithography plays a central role in defining the features of modern semiconductor devices. Deep ultraviolet (DUV) lithography [53], which has been the workhorse of the industry for decades, operates at wavelengths of 248 nm (KrF) and 193 nm (ArF). Through innovations like immersion lithography, where a high-refractive-index liquid is introduced between the lens and the wafer, DUV systems have pushed feature sizes down to approximately 38 nm. However, as device geometries continue to shrink, DUV lithography increasingly relies on complex multi-patterning strategies such as self-aligned double patterning (SADP) and self-aligned quadruple patterning (SAQP). These methods, while effective, introduce substantial challenges related to process complexity, variability, and manufacturing costs, limiting their scalability for future technology nodes.

Extreme ultraviolet (EUV) lithography, operating at a wavelength of 13.5 nm, offers a promising path forward by enabling direct patterning of sub-10 nm features in a single exposure [54]. EUV systems have already been deployed in



advanced nodes, such as 5 nm and 3 nm technologies, by leading semiconductor manufacturers like TSMC, Samsung, and Intel. By eliminating the need for multiple patterning, EUV simplifies process flows and enhances throughput. However, several critical challenges remain. These include source power limitations since generating sufficient EUV photon flux via laser-produced plasma remains difficult and issues with resist sensitivity, line-edge roughness, and stochastic defects such as bridging and line breaks. Furthermore, EUV masks, which are complex multilayer structures based on molybdenum and silicon mirrors, are prone to defects that can transfer onto wafers, requiring advanced inspection and repair techniques to ensure defect-free production.

Beyond EUV, nanoimprint lithography (NIL) has emerged as an alternative technique capable of achieving sub-10 nm resolution without the diffraction limitations of light [55]. NIL relies on mechanically imprinting a pre-patterned mould into a resist layer, followed by pattern transfer through etching. This technique has demonstrated potential in applications such as photonic crystals, metasurfaces, and large-area flexible electronics. NIL enables the replication of complex nanostructures with high fidelity, including quantum dot arrays for single-electron devices and high-density memory. Nevertheless, challenges such as overlay accuracy, defect control, and achieving sufficient throughput for mass production continue to limit its widespread adoption in semiconductor manufacturing.

Electron beam lithography (EBL) and focused ion beam (FIB) lithography offer unmatched resolution and design flexibility [56],[57], making them indispensable tools for research, prototyping, and low-volume production of advanced nanoscale devices. EBL can pattern features below 10 nm with high precision, facilitating the fabrication of single-electron transistors, quantum dot arrays, and advanced memory architectures. However, its serial nature inherently limits throughput, rendering it impractical for



high-volume manufacturing. FIB lithography, using ion beams such as Ga^+ or He^+ , enables direct nanopatterning and material modification, supporting applications like circuit editing, defect repair, and rapid prototyping. Yet, like EBL, FIB faces limitations in throughput and may cause substrate damage during the milling process.

Directed self-assembly (DSA) of block copolymers (BCPs) is a promising bottom-up nanofabrication approach that exploits the phase separation properties of BCPs to form ordered nanostructures with feature sizes below 10 nm [58]. By integrating BCP self-assembly with pre-patterned templates through graphoepitaxy or chemoepitaxy, DSA offers a viable path for extending Moore's Law beyond the limits of conventional lithography. Systems such as polystyrene-*b*-polymethylmethacrylate (PS-*b*-PMMA) have demonstrated patterning at a half-pitch of 7 nm, while higher-segregation-strength BCPs like poly(styrene-*b*-dimethylsiloxane) (PS-*b*-PDMS) can achieve sub-5 nm features. DSA has been applied in contact hole shrinking, line/space patterning, and via patterning, serving as a complementary technique to EUV and DUV lithography for advanced node fabrication.

Achieving precise pattern transfer into the underlying substrate is as crucial as the initial lithography step. Advanced dry etching techniques, such as plasma-enhanced reactive ion etching (RIE) and atomic layer etching (ALE) [59],[60], are essential for creating high-aspect-ratio structures with atomic-scale precision. ALE, in particular, enables layer-by-layer material removal with exceptional selectivity and minimal plasma-induced damage, which is critical for manufacturing complex devices like FinFETs, gate-all-around (GAA) transistors, and 3D NAND structures. Additionally, atomic layer deposition (ALD) provides conformal, ultra-thin film coatings over intricate 3D architectures, ensuring precise control of gate dielectrics, barrier layers, and spacers.



Looking ahead, emerging techniques such as three-dimensional nanostructuring are gaining attention. These include sequential layer stacking, wafer bonding, and through-silicon via (TSV) formation, all of which are pivotal for advanced packaging and heterogeneous integration. Two-photon lithography (TPL), based on nonlinear optical absorption, enables true 3D nanoscale patterning, supporting the fabrication of photonic crystals, metamaterials, and micro-optomechanical systems. Tip-based nanolithography methods, such as dip-pen nanolithography (DPN) and scanning probe lithography (SPL), facilitate molecular-scale patterning and functionalization. Helium ion beam lithography (HIBL) has also emerged as a cutting-edge approach, offering sub-nanometer resolution with minimal proximity effects, although system complexity and throughput challenges must be addressed for its broader adoption.

In brief, the landscape of lithography and nanostructuring techniques continues to evolve, driven by the demands of shrinking feature sizes, increasing device complexity, and the integration of novel materials and architectures. Each technique presents unique advantages and challenges, and the future of semiconductor manufacturing will likely involve a combination of these approaches, tailored to specific applications and device requirements.

2.5. Role in Nano-Optoelectronics

Nano-optoelectronics is an interdisciplinary field that merges nanotechnology, photonics, and electronics to manipulate light and electrical signals at the nanoscale, enabling enhanced device functionalities and performance as summarised in Table 2.1. This field has revolutionised technologies such as lasers, photodetectors, and light-emitting diodes (LEDs) by incorporating nanoscale structures like quantum dots, nanowires, and 2D



materials [61],[62]. In lasers, nanoscale engineering allows for low threshold currents, spectral tunability, and compact designs. For photodetectors, nanomaterials enable broadband sensitivity, faster response, and improved efficiency, while LEDs benefit from enhanced light emission, colour purity, and flexible device designs. Overall, nano-optoelectronics paves the way for advanced applications in quantum technologies, wearable electronics, optical communication, and sensing systems.

Nano-optoelectronics is a cutting-edge field that integrates nanotechnology with optoelectronics to design devices capable of controlling and utilising light and electrical signals at the nanometer scale. This miniaturisation enables unique optical and electronic behaviours that are not possible in bulk materials [63]. In the case of lasers, incorporating nanostructures such as quantum dots (QDs) allows for discrete energy states, resulting in low threshold currents, temperature stability, and wavelength tunability, which are essential for applications in photonic circuits and quantum communication. Nanowire lasers, due to their waveguiding capabilities and compact size, support sub-wavelength lasing and directional emission, while plasmonic nanolasers leverage surface plasmon modes to create ultra-compact, high-speed light sources. Photodetectors benefit from nanomaterials like QDs, nanowires, 2D materials (e.g., graphene, MoS₂), and plasmonic structures, which enhance light absorption, spectral tunability, and responsivity, enabling applications in broadband imaging, UV/IR sensing, and wearable optoelectronic systems. LEDs are also transformed through nanoscale design, where quantum dots provide tunable, high-purity emission, nanowires improve charge transport and reduce defects for efficient UV and blue light emission, and plasmonic structures boost light extraction and brightness [64]. Furthermore, the use of flexible and transparent nanomaterials enables the development of next-generation wearable, stretchable, and transparent LEDs for smart surfaces and displays. Overall, nano-optoelectronics drives



the innovation of compact, efficient, and high-performance devices across multiple industries, from communication systems to healthcare and consumer electronics.

Table 2.1:
Impact of advanced nanomaterials on devices

Advantages	Impact on Devices
Quantum confinement effects	Tunable energy levels and emission/absorption spectra
Enhanced light-matter interaction	Increased absorption, emission, and nonlinear optical properties
Reduced device footprint	Integration into nanoscale systems, enabling on-chip photonics
Enhanced surface-to-volume ratios	Higher responsivity and sensitivity in detectors and sensors
Plasmonic field enhancement	Sub-wavelength light confinement for ultra-compact and efficient devices
Compatibility with flexible substrates	Enables wearable and flexible optoelectronic systems

2.6. Conclusion

The Chapter provides a comprehensive exploration of advanced nanomaterials engineered for next-generation semiconductor and optoelectronic devices. It begins with an in-depth analysis of two-dimensional (2D) materials, particularly graphene, highlighting its exceptional electrical conductivity, carrier mobility, and mechanical strength, while addressing challenges related to its zero bandgap and integration into digital logic. The chapter further expands into other 2D materials such as TMDs, black phosphorus, and MXenes, emphasising their tunable bandgaps, quantum confinement effects, and heterostructure compatibility for high-performance transistors, sensors, and logic circuits. It also explores the role of QDs in quantum devices,

photodetectors, LEDs, and photovoltaics, showcasing how their size-dependent energy levels and strong light-matter interactions enable precise control over electronic and optical behaviour. Additionally, the chapter discusses hybrid nanomaterial systems such as QD–graphene and QD–TMD combinations that synergistically enhance charge transport, sensitivity, and device performance. The role of advanced lithography and nanofabrication techniques, including EUV, EBL, NIL, and DSA, is addressed in the context of sub-10 nm device scaling. Finally, the chapter concludes with an overview of nano-optoelectronics, where nanostructures such as quantum dots, nanowires, and 2D materials are used to enhance lasers, photodetectors, and LEDs for high-performance, miniaturised, and flexible optoelectronic systems, paving the way for future innovations in wearable electronics, quantum computing, and integrated photonic circuits.

References

1. Aftab, Sikandar, Sajjad Hussain, and Abdullah A. Al-Kahtani. "Latest innovations in 2D flexible Nanoelectronics." *Advanced Materials* 35.42 (2023): 2301280.
2. Akinwande, Deji, Nicholas Petrone, and James Hone. "Two-dimensional flexible nanoelectronics." *Nature communications* 5.1 (2014): 5678.
3. Ling, Zhi Peng. "Two-Dimensional (2D) Materials for Next-Generation Nanoelectronics and Optoelectronics: Advances and Trends." *Advances in Optoelectronic Materials* (2021): 65-96.
4. Radsar, Tahereh, Hassan Khalesi, and Vahid Ghods. "Graphene properties and applications in nanoelectronic." *Optical and Quantum Electronics* 53.4 (2021): 178.
5. Chen, Jimai. "Graphene-Based Devices: Exploring Advantages, Challenges, and Multidisciplinary Applications." *Highlights in Science, Engineering and Technology* 65 (2023): 121-128.
6. Allen, Matthew J., Vincent C. Tung, and Richard B. Kaner. "Honeycomb carbon: a review of graphene." *Chemical reviews* 110.1 (2010): 132-145.
7. Ma, Liang, Jinlan Wang, and Feng Ding. "Recent progress and challenges in graphene nanoribbon synthesis." *ChemPhysChem* 14.1 (2013): 47-54.
8. Yan, Qimin, et al. "Intrinsic current– voltage characteristics of graphene nanoribbon transistors and effect of edge doping." *Nano letters* 7.6 (2007): 1469-1473.
9. Hu, Zhaoning, et al. "Doping of graphene films: open the way to applications in electronics and optoelectronics." *Advanced Functional Materials* 32.42 (2022): 2203179.



10. Kim, Taesoo, et al. "High-mobility junction field-effect transistor via graphene/MoS₂ heterointerface." *Scientific reports* 10.1 (2020): 13101.
11. Wu, Yun, et al. "200 GHz maximum oscillation frequency in CVD graphene radio frequency transistors." *ACS applied materials & interfaces* 8.39 (2016): 25645-25649.
12. An, Cheng Jin, et al. "A combined graphene and periodic au nanograte structure: Fundamentals and application as a flexible transparent conducting film in a flexible organic photovoltaic cell." *Carbon* 103 (2016): 488-496.
13. Huang, Meina, et al. "MXene and black phosphorus based 2D nanomaterials in bioimaging and biosensing: Progress and perspectives." *Journal of Materials Chemistry B* 9.26 (2021): 5195-5220.
14. Murali, Aswathy S., Sreelekshmi, and Beena Saraswathyamma. "The role of engineered MoS₂ and MoSe₂ transition metal dichalcogenides in electrochemical sensors and batteries: a review." *Tungsten* 7.2 (2025): 215-242.
15. Han, Ziyi, et al. "When graphene meets white graphene—recent advances in the construction of graphene and h-BN heterostructures." *Nanoscale* 13.31 (2021): 13174-13194.
16. Zhang, Guowei, et al. "Layer-Dependent Electronic and Optical Properties of 2D Black Phosphorus: Fundamentals and Engineering." *Laser & Photonics Reviews* 15.6 (2021): 2000399.
17. Hantanasirisakul, Kanit, and Yury Gogotsi. "Electronic and optical properties of 2D transition metal carbides and nitrides (MXenes)." *MXenes* (2023): 135-205.
18. Levendorf, Mark P., et al. "Graphene and boron nitride lateral heterostructures for atomically thin circuitry." *Nature* 488.7413 (2012): 627-632.
19. Chen, E., et al. "2D layered noble metal dichalcogenides (Pt, Pd, Se, S) for electronics and energy applications." *Materials Today Advances* 7 (2020): 100076.
20. Radisavljevic, Branimir, et al. "Single-layer MoS₂ transistors." *Nature nanotechnology* 6.3 (2011): 147-150.
21. Fang, Hui, et al. "High-performance single layered WSe₂ p-FETs with chemically doped contacts." *Nano letters* 12.7 (2012): 3788-3792.
22. Xiao, Di, et al. "Coupled spin and valley physics in monolayers of MoS₂ and other group-VI dichalcogenides." *Physical review letters* 108.19 (2012): 196802.
23. Jia, Shuai, et al. "Lateral monolayer MoSe₂–WSe₂ p–n heterojunctions with giant built-in potentials." *Small* 16.34 (2020): 2002263.
24. Lan, Xiang, et al. "Wafer-scale engineering of two-dimensional transition metal dichalcogenides." *Chip* 2.3 (2023): 100057.
25. Kappera, Rajesh, et al. "Phase-engineered low-resistance contacts for ultrathin MoS₂ transistors." *Nature materials* 13.12 (2014): 1128-1134.
26. Lv, Ziyu, et al. "Semiconductor quantum dots for memories and neuromorphic computing systems." *Chemical reviews* 120.9 (2020): 3941-4006.
27. Lv, Ziyu, et al. "Semiconductor quantum dots for memories and neuromorphic computing systems." *Chemical reviews* 120.9 (2020): 3941-4006.
28. Connerade, Jean-Patrick. "A review of quantum confinement." *AIP Conference Proceedings*. Vol. 1197. No. 1. American Institute of Physics, 2009.



29. Rastogi, Prachi, et al. "Enhancing the performance of CdSe/CdS dot-in-rod light-emitting diodes via surface ligand modification." *ACS applied materials & interfaces* 10.6 (2018): 5665-5672.
30. Li, Qiuyang, et al. "Charge transfer from quantum-confined 0D, 1D, and 2D nanocrystals." *Chemical reviews* 124.9 (2024): 5695-5763.
31. Mimona, Mariam Akter, et al. "Quantum Dot nanomaterials: empowering advances in optoelectronic devices." *Chemical Engineering Journal Advances* (2025): 100704.
32. Taher, Abu, et al. "Quantum dot-based non-volatile memory: a comprehensive outlook." *RSC advances* 15.18 (2025): 14428-14462.
33. Mazumder, Julaiaba Tahsina, Arun B. Aloshious, and Ravindra Kumar Jha. "Single electron transistor based charge sensors: fabrication challenges and opportunities." *Nanoscale* (2025).
34. Tilke, A., R. H. Blick, and H. Lorenz. "Fabrication and integration possibilities of ultrasmall quantum dots in silicon-on-insulator material." *Journal of Applied Physics* 90.2 (2001): 942-946.
35. Islam, Sk Masiul, et al. "InAs quantum dots as charge storing elements for applications in flash memory devices." *Materials Science and Engineering: B* 198 (2015): 102-107.
36. Abbas, Kashif, et al. "Graphene photodetectors integrated with silicon and perovskite quantum dots." *Microsystems & Nanoengineering* 10.1 (2024): 81.
37. Vafaie, Maral, et al. "Colloidal quantum dot photodetectors with 10-ns response time and 80% quantum efficiency at 1,550 nm." *Matter* 4.3 (2021): 1042-1053.
38. Lee, Taesoo, et al. "Recent Advances in Light Outcoupling from Quantum-Dot Light-Emitting Diodes." *ACS Photonics* 11.12 (2024): 5050-5060.
39. Sun, Yi-Lin, et al. "Hybrid graphene/cadmium-free ZnSe/ZnS quantum dots phototransistors for UV detection." *Scientific reports* 8.1 (2018): 5107.
40. Zhao, Qian, et al. "Advantageous properties of halide perovskite quantum dots towards energy-efficient sustainable applications." *Green Energy & Environment* 9.6 (2024): 949-965.
41. Rakshit, Soumyadip, et al. "Combining perovskites and quantum dots: synthesis, characterization, and applications in solar cells, LEDs, and photodetectors." *Advanced Optical Materials* 10.14 (2022): 2102566.
42. Hu, Long, et al. "PbSe quantum dot passivated via mixed halide perovskite nanocrystals for solar cells with over 9% efficiency." *Solar RRL* 2.12 (2018): 1800234.
43. Litvin, Aleksandr P., et al. "Colloidal quantum dots for optoelectronics." *Journal of Materials Chemistry A* 5.26 (2017): 13252-13275.
44. Li, Xiaoming, et al. "Carbon and graphene quantum dots for optoelectronic and energy devices: a review." *Advanced Functional Materials* 25.31 (2015): 4929-4947.
45. Chauhan, Kanika, Ankit Kumar Pandey, and Mitradip Bhattacharjee. "Quantum Dot-Based Flexible Photodetectors: A Review." *ACS Applied Electronic Materials* 7.9 (2025): 3632-3649.
46. Liu, Ming-Jin, et al. "Two-Dimensional Transition Metal Dichalcogenides (2D TMDs) Coupled With Zero-Dimensional Nanomaterials (0D NMs) for Advanced Photodetection." *Small Methods* 9.4 (2025): 2401240.



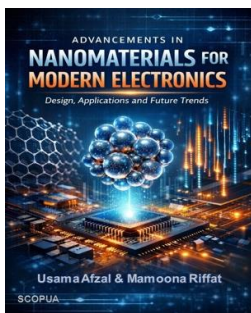
47. Putri, Nur Ajrina, et al. "MoSe₂ quantum dots enhance the performance of ZnO nanostructure-based UV photodetectors." *ACS Applied Nano Materials* 7.4 (2024): 3835-3842.
48. Singh, Nongthombam Joychandra, et al. "Current Trends and Emerging Opportunities for 2D Materials in Flexible and Wearable Sensors." *Chemical Communications* (2025).
49. Peighambardoust, Naeimeh Sadat, Ebrahim Sadeghi, and Umut Aydemir. "Lead halide perovskite quantum dots for photovoltaics and photocatalysis: a review." *ACS Applied Nano Materials* 5.10 (2022): 14092-14132.
50. Basu, Prithvi, et al. "Advancements in Lithography Techniques and Emerging Molecular Strategies for Nanostructure Fabrication." *International Journal of Molecular Sciences* 26.7 (2025): 3027.
51. Sharma, Ekta, et al. "Evolution in lithography techniques: microlithography to nanolithography." *Nanomaterials* 12.16 (2022): 2754.
52. Bowden, Murrae J. "The physics and chemistry of the lithographic process." *Journal of the Electrochemical Society* 128.5 (1981): 195C.
53. Stulen, Richard H., and Donald W. Sweeney. "Extreme ultraviolet lithography." *IEEE journal of quantum electronics* 35.5 (2002): 694-699.
54. Kazazis, Dimitrios, et al. "Extreme ultraviolet lithography." *Nature Reviews Methods Primers* 4.1 (2024): 84.
55. Traub, Matthew C., Whitney Longsine, and Van N. Truskett. "Advances in nanoimprint lithography." *Annual review of chemical and biomolecular engineering* 7.1 (2016): 583-604.
56. Chen, Yifang. "Nanofabrication by electron beam lithography and its applications: A review." *Microelectronic Engineering* 135 (2015): 57-72.
57. Arshak, Khalil, et al. "Focused ion beam lithography-overview and new approaches." 2004 24th International Conference on Microelectronics (IEEE Cat. No. 04TH8716). Vol. 2. IEEE, 2004.
58. Hu, Hanqiong, Manesh Gopinadhan, and Chinedum O. Osuji. "Directed self-assembly of block copolymers: a tutorial review of strategies for enabling nanotechnology with soft matter." *Soft matter* 10.22 (2014): 3867-3889.
59. Yih, P. H., V. Saxena, and A. J. Steckl. "A review of SiC reactive ion etching in fluorinated plasmas." *physica status solidi (b)* 202.1 (1997): 605-642.
60. Kanarik, Keren J., et al. "Overview of atomic layer etching in the semiconductor industry." *Journal of Vacuum Science & Technology A* 33.2 (2015).
61. Ha, Son Tung, et al. "Optoelectronic metadevices." *Science* 386.6725 (2024): eadm7442.
62. Lin, Yu-Sheng, and Zefeng Xu. "Reconfigurable metamaterials for optoelectronic applications." *International Journal of Optomechatronics* 14.1 (2020): 78-93.
63. Chou Chau, Yuan-Fong. "Nanophotonic Materials and Devices: Recent Advances and Emerging Applications." *Micromachines* 16.8 (2025): 933.
64. Wu, Jiang, et al. "Quantum dot optoelectronic devices: lasers, photodetectors and solar cells." *Journal of Physics D: Applied Physics* 48.36 (2015): 363001.



CHAPTER 3

HIGH-PERFORMANCE NANOMATERIAL-BASED SENSORS

MAMOONA RIFFAT ^{1*}



Book Title

Advancements in Nanomaterials for Modern Electronics:
Design, Applications and Future Trends

Series Title

Books of Research Collection

Published On

January 02, 2026 (Edition 1)

Publisher

Scientific Collaborative Online Publishing Universal
Academy, Lahore, Pakistan

DOI: <https://doi.org/10.64060/978-627-7898-01-4-3>

Book ISBN: 978-627-7898-01-4

THIS WORK IS LICENSED UNDER A CREATIVE COMMONS ATTRIBUTION NONCOMMERCIAL
NODERIVATIVES 4.0 INTERNATIONAL LICENSE. SCOPUA (SCIENTIFIC COLLABORATIVE ONLINE
PUBLISHING UNIVERSAL ACADEMY) PUBLISHER REMAINS NEUTRAL REGARDING JURISDICTIONAL
CLAIMS IN PUBLISHED MAPS AND INSTITUTIONAL AFFILIATIONS.

¹Department of Physics, LUT school of Engineering Science, Lappeenranta-Lahti
University of Technology, Finland.

*Corresponding: mamoonariffat@lut.fi (M. Riffat)

Abstract

This chapter provides a comprehensive overview of the recent advances and emerging trends in high-performance nanomaterial-based sensors, emphasising their design, fabrication, and integration into next-generation technological platforms. Nanosensors leveraging materials such as carbon nanotubes, graphene, transition metal dichalcogenides (TMDs), and metal oxides have revolutionised sensing science through their superior sensitivity, selectivity, and rapid response. The chapter discusses the fundamental mechanisms that underpin nanoscale detection and explores how hybrid and composite nanostructures enhance functional performance in gas, chemical, and biosensing applications. It highlights the evolution of flexible, stretchable, and wearable sensor technologies that combine material innovation with mechanical adaptability, enabling real-time and non-invasive monitoring in healthcare, environmental surveillance, and security. Furthermore, the integration of artificial intelligence (AI), deep learning algorithms, and Internet of Things (IoT) frameworks has transformed nanosensors into intelligent, autonomous systems capable of continuous data processing and predictive analytics. Special attention is given to recent innovations in fabrication methods, such as 3D printing and laser direct writing, which have enabled scalable production of high-resolution, multifunctional sensing devices. By critically examining the challenges of long-term stability, biocompatibility, and power efficiency, this chapter underscores the transformative potential of nanomaterials in shaping the next era of smart, connected, and sustainable sensing platforms.

Keywords: *Advanced fabrication techniques, Biosensors, Chemical sensors, Flexible and stretchable sensors, Gas sensors, Smart sensing systems*

3.1. Introduction to Nanosensors

Nanomaterial-based sensors, or nanosensors, are devices that utilise materials at the nanoscale (1-100 nanometers) to detect and respond to changes in their environment. These sensors can detect a wide range of chemical, biological, and physical properties, offering advantages over traditional sensors in terms of sensitivity, speed, and miniaturisation [1]. The materials used in these nanosensors are quantum dots, graphene, gold nanoparticles, etc. Nanosensors, though



synthetically developed only in recent decades, have long existed in nature, embedded in biological systems such as olfactory receptors in animals, sunlight detectors in plants, and vibration sensors in fish [2]. However, graphene has emerged as a leading nanomaterial in (bio)sensor development, driving major initiatives like the EU's €1 billion Graphene Flagship to transition it from lab to market [3]. These naturally occurring nanosensors, often termed bionanosensors, demonstrate the evolutionary integration of nanoscale sensing for environmental interaction and survival. The first synthetic nanosensor was developed at the Georgia Institute of Technology, utilising carbon nanotubes to detect mass changes via vibrational frequency shifts [4]. Since then, various nanomaterials like carbon and titanium nanotubes have been engineered to detect specific chemical and gaseous molecules. Advancements in biotechnology have revealed protein-based nanosensors, such as PHD proteins that respond to oxygen levels, with potential applications in cancer research and tissue regeneration.

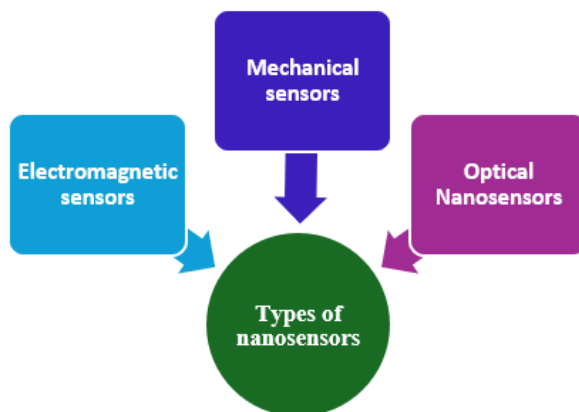


Figure 3.1: *Types of nanosensors based on structure.*

Furthermore, genetically engineered bacterial biosensors and fluorescent nanosensors for pH and iron detection exemplify



the expanding frontier of nanosensors, bridging synthetic systems with biological mechanisms for real-time sensing applications [2].

Electromagnetic, mechanical, and optical nanosensors are classified based on their functional transduction mechanisms, meaning the way they convert a physical or chemical stimulus into a measurable signal, as shown in **Error! Reference source not found.** Electromagnetic nanosensors detect changes in electrical or magnetic properties, such as variations in conductivity, impedance, or magnetic relaxation. They are widely used in chemical detection, biosensing, and magnetic resonance-based applications. Mechanical nanosensors monitor nanoscale mechanical responses such as deflection, stress, strain, or shifts in resonance frequency and are highly sensitive to detecting mass changes, pressure variations, or molecular adsorption on nanocantilevers and NEMS devices. Optical nanosensors rely on light-matter interactions, using changes in absorption, fluorescence, scattering, or plasmonic resonance to detect targeted analytes, making them valuable for highly sensitive, label-free detection in chemical, environmental, and biomedical systems. Together, these three functional categories highlight how nanosensors translate different types of external stimuli into detectable outputs using distinct physical signal pathways.

The development of nanotechnology has fundamentally changed the field of sensor innovation, resulting in remarkable advancements in the design, fabrication, and application of nanosensors. Sensors are recognised as high-performance and efficient if they are effective, selective, and responsive. These sensors are small devices with exceptional qualities. They are more sensitive and accurate than traditional sensors, making them vital for many fields. These sensors are perfect for environmental analysis, industrial monitoring, medical diagnostics, etc [5].

The potential of these nanosensors is beyond the limit, with distinctive properties, like high surface-to-volume ratio, tunable



electronic and optics features, and adaptable surface chemistry opening up promising avenues for the future of sensor technology [1]. Exploring various nanostructures, including quantum dots, CNTs, metal oxide nanoparticles, and nanowires, is evidence of the extraordinary opportunities. These materials have shown the ability to drive highly sensitive detection through mechanisms that involve alterations in conductivity, luminescence, absorption spectra, and mechanical resonance when interacting with specific analytes [6].

Extensive research has focused on improving nanomaterials' inherent characteristics while developing robust surface functionalisations to ensure reliability and specificity in target detection. These developments have given rise to various optical, electrochemical, and mechanical sensing devices demonstrating superior capabilities, including extremely low detection thresholds down to parts per trillion, rapid signal response, and excellent selectivity. Breakthroughs in nanomanufacturing techniques have made it possible to exercise meticulous control over the size and shape of nanomaterials, which in turn enhances sensor precision and efficiency. Emerging low-dimensional materials, especially two-dimensional transition metal dichalcogenides, have unlocked new prospects in luminescence-based and quantum-confinement-driven sensing strategies [7].

Nanomaterials have unique physical properties that significantly depend on their dimensions, especially thickness, enabling precise control over sensor response and performance. Moreover, intentionally combining different nanomaterials into composite or hybrid structures has proven to be practical. This strategy allows the beneficial properties of individual components to merge, often resulting in hybrid systems that outperform single-material alternatives by offering greater sensitivity, wider detection ranges, and enhanced stability in varying environmental conditions. As sensor technology develops, nanomaterials are at the cutting edge of innovation. Their versatility and functionality are driving



the creation of increasingly intelligent, compact, and multifunctional sensing platforms capable of operating reliably in complex real-world environments. The ongoing academic and industrial interest in this field highlights the growing recognition of nanotechnology as a crucial enabler of next-generation sensor systems, emphasising its essential role in shaping the future of high-performance sensing solutions [8],[9].

3.2. Next Generation Gas and Chemical Sensors Using Nanomaterials

Nanomaterials like metal oxides (e.g. ZnO, SnO₂), carbon nanotubes (CNTs), graphene, and noble metals (Au, Pt) are employed in sensing technology due to their high surface area and tunable electrical properties. Furthermore, transition metal dichalcogenide–metal oxide (TMD-MO) hybrid structures emphasising their great potential for high-performance gas sensing in various industrial applications [10]. Transition Metal Dichalcogenides (TMDs) and Metal Oxides (MOs) are promising materials for gas sensing due to:

- High surface area
- Tunable electronic properties
- Strong gas adsorption abilities
- Chemical and thermal stability (especially TMDs)

There are various advantages to these gas sensors over traditional ones. They have Higher sensitivity and selectivity compared to conventional metal oxides alone. They effectively operate in harsh environments, although long-term stability in these conditions still needs further investigation. These sensors have a tunable bandgap and a composite architecture that offer design flexibility for enhancing sensor performance. So, TMD-MO hybrid structures represent a promising next-generation platform for hydrogen gas sensors. These composites leverage the best



properties of both TMDs and metal oxides to offer high sensitivity, selectivity, and environmental stability. While the field is still in its early stages, further development of fabrication techniques and sensing mechanisms could enable these materials to play a central role in safe, scalable, and efficient hydrogen sensing technologies. They are particularly relevant for a sustainable hydrogen economy and diverse industrial applications [10]. Next-generation chemical sensors based on nanomaterials are revolutionising monitoring technologies through their integration into wearable devices, enabling real-time, noninvasive detection of multiple chemical markers in health, environmental, and robotic applications. These sensors feature advanced nanomaterials like graphene derivatives for enhanced sensitivity and selectivity. They are increasingly designed as multifunctional, flexible, and self-powered systems, such as “lab-on-a-glove” or e-tattoos that operate autonomously using energy harvesting technologies. Their compact, innovative design allows seamless data communication within IoT frameworks, supporting continuous, on-site monitoring of toxins, pathogens, or biomarkers, thus paving the way for transformative advances in diagnostics, safety, and human-machine interaction [11].

Nanostructured materials and conductive polymers have been the driving forces behind recent technological advancements in medical gas sensing, greatly increasing sensitivity and selectivity. Because of their high surface area-to-volume ratio, nanomaterials such as nanowires, nanorods, and other carbon-based structures allow for more effective gas adsorption and detection. These materials, when coupled with conductive polymers, produce more stable gas sensors, respond more quickly, and function better in a range of environmental circumstances. These developments have opened the door for small, reasonably priced, high-performing gas-sensing instruments with vital uses in environmental and medical monitoring [12].



3.2.1. Applications of Sensor

Nanomaterial-based chemical sensors have broad and impactful applications across various fields. In environmental monitoring, chemiresistive sensors using carbon nanotubes (CNTs) or graphene are employed for detecting harmful gases like CO₂, NO₂, and NH₃, offering fast response times and high sensitivity. In healthcare, non-invasive wearable sensors and breath analysers track gaseous biomarkers such as H₂S and CO₂, aiding in early diagnosis and monitoring of respiratory conditions. For security and defence, specialised nanosensors such as ZnO nanowire-based devices are designed to detect explosives or toxic gases and can even be integrated into textiles, offering real-time threat detection in military or high-risk environments [13].

3.2.1.1. Environmental Monitoring

Chemical sensors are being developed to be miniaturised, inexpensive, and portable, allowing for static and continuous measurements in remote environments. This is crucial for monitoring air and water quality in areas that are hard to access. Research on nanostructured materials enhances the selectivity and sensitivity of sensors, making them more effective for detecting pollutants and hazardous substances in the environment. The use of sensor arrays in electronic nose (e-nose) systems helps in identifying various chemical compounds in the air, mimicking human olfaction. This technology is particularly useful for environmental monitoring and has commercial applications [13].

3.2.1.2. Healthcare

Chemical sensors, particularly biosensors, are utilised in healthcare for monitoring biochemical markers in bodily fluids. They can provide real-time data on health conditions, enabling timely medical interventions. Advances in sensor technology have led to the development of portable devices that can be used for



health monitoring, such as glucose sensors for diabetes management. These devices are designed to be user-friendly and provide accurate readings [11],[13],[14].

3.2.1.3. Security

- **Detection of Chemical Warfare Agents:** Chemical sensors play a critical role in homeland security by detecting chemical warfare agents and explosives. The article discusses the development of portable, real-time detection systems that can identify these threats quickly [11],[13],[15].
- **Explosives Detection:** The need for effective explosives detection has increased, especially in the wake of terrorist attacks. Chemical sensors are being developed to replicate the detection capabilities of trained dogs, providing a reliable method for identifying explosives in various environments [13],[16].

3.3. Smart Sensors: Integration with IoT and Wearable Devices

Nanomaterial sensors are embedded in IoT platforms and wearable devices for remote monitoring and rapid alerts. The increasing average age of the global population has driven innovation in healthcare monitoring, where smart wearable devices are playing a critical role. These devices offer real-time, continuous monitoring of physiological conditions such as heart rate, blood pressure, motion, and chemical biomarkers (e.g., ions, gases, biomolecules), enhancing early diagnosis, treatment assessment, and patient compliance. Unlike conventional medical equipment, wearable sensors are lightweight, flexible, and wireless, enabling seamless integration with IoT systems that transmit health data to smartphones or medical centres for analysis and telemedicine



support. Modern wearable electronics incorporate smart sensors, stretchable substrates (e.g., PET, Ecoflex), high-performance electrodes (e.g., thin metals, nanowires, liquid metals), and nanomaterials like graphene and carbon nanotubes, which are tunable for different sensing applications. Advanced fabrication methods such as EHD inkjet and 3D printing enable precise, high-resolution sensor production. These sensors often utilise hybrid materials to achieve ultrathin, flexible, and high-sensitivity performance [17].

Wearable sensor systems typically consist of sensing units, power supplies (often using energy-harvesting methods instead of batteries), data processing modules, wireless communication (e.g., Bluetooth, NFC, RF antennas), and user interfaces. Their integration with IoT allows for remote, real-time diagnostics and continuous health tracking, paving the way for non-invasive, user-friendly, and connected healthcare solutions. The field is rapidly progressing towards deformable and fabric-based electronics, enhancing comfort and functionality for users across healthcare, environmental monitoring, and personal wellness domains [16],[17],[18],[19].

Data analytics: When it comes to analysing sensor data for medical gas monitoring, AI and deep learning are revolutionary. Real-time anomaly detection is made possible by these technologies, guaranteeing prompt detection of gas leaks, dangerous concentrations, or departures from typical trends. Large volumes of sensor-generated data can be analysed by AI systems to:

- (I) Flag anomalies that may signal gas leaks or hazardous exposure levels, improving safety for patients and medical personnel.
- (II) Enhance diagnostic precision by identifying subtle patterns in gas concentration changes that may relate to patient health conditions.



- (III) Facilitate predictive maintenance by recognising early signs of equipment failure or inefficiencies in gas delivery systems.
- (IV) Support real-time decision-making, providing alerts and recommendations based on live sensor input to enable swift medical responses.

AI Deep Learning Models work with pattern recognition and adaptive learning, making them ideal for complex, high-stakes environments like hospitals. These tools improve system accuracy and reliability, ensuring gases are used safely and effectively and contributing to regulatory compliance and operational efficiency in healthcare facilities [20].

Artificial Intelligence (AI) can replicate human intellect in activities like language comprehension, image recognition, and decision-making. These systems automate processes, forecast results, and resolve healthcare, financial, and industrial issues using sophisticated algorithms and big datasets.

In healthcare, AI can quickly analyse large volumes of data, identify patterns, and support faster, more accurate decision-making than humans. An AI system operates using three core inputs: knowledge (background information and rules), algorithms (tools for processing data and making decisions), and goals (desired outcomes). The AI agent interacts with its surroundings by observing sensor data and choosing actions accordingly. It learns through feedback, adjusting its behaviour based on the results of its actions. This process is often represented in a block diagram showing input, decision-making, and output, with feedback loops as can be seen in Figure 3.2. AI is now applied widely in healthcare, including in medical gas sensing, to enhance monitoring, diagnosis, and operational efficiency [12].



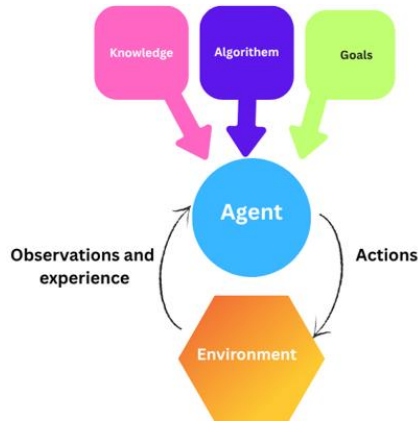


Figure 3.2: Block Diagram of an AI system

Integrating artificial intelligence (AI) into medical fluid system leak detection has an advantage over traditional methods like manual inspection and pressure testing, which are often slow and error-prone. AI-driven systems use machine learning algorithms and real-time data from advanced sensors to monitor pressure, flow rate, and temperature parameters. The ability of AI systems to recognise common operating patterns and identify irregularities that can point to leaks with progressively higher accuracy is one of their greatest features. AI's automated solution improves safety and operational efficiency by reducing the need for human checks, minimising false alarms, speeding up response times, and freeing up healthcare personnel to concentrate more on patient care [21].

3.4. Flexibility and Stretchability in Sensors: Innovations in Materials and Design

Flexibility of sensors has remarkable recognition due to their extraordinary features of wearability, and real-time, non-invasive monitoring ability. These sensors convert physical stimuli into measurable electrical signals. They are built from advanced



materials with excellent stretchability, conductivity, and biocompatibility, making them ideal for interacting safely with the human body. Flexible sensors can adapt to changes in the body along with providing comfort and data-collection accuracy. They are extensively utilised in robotics, wearable technology, healthcare, and environmental monitoring.

The performance of these sensors relies on the choice of sensing materials such as metals, carbon-based compounds, polymers, and hydrogels, highlighting the importance of material selection in sensor design. Despite numerous studies focusing on specific sensor types or materials, comprehensive reviews addressing the full range of sensing materials and detection modes remain limited.

Flexible sensing materials function as transducers, converting external stimuli into measurable signals, and are central to flexible detection systems. Unlike rigid sensors, they require superior mechanical strength, conductivity, stability, and sensing capabilities. That's why material choice is very important and categorised as inorganic, organic, and other materials. Inorganic materials, such as metals, carbon, and inorganic hybrids, offer excellent chemical stability and conductivity. These are excellent properties that make them an appropriate fit for various functional layers in flexible sensors. Metallic materials like silver, copper, and aluminium are commonly used in flexible electronics for their high conductivity and ductility [22]. Although these materials are good quality in terms of sensors but their potential toxicity due to metal ion leaching limits their biomedical applications. To address this, biocompatible alternatives like gold-coated silver nanowires have been developed, enhancing safety and stability in implantable devices [23]. Various fabrication methods, including shadow masking, elastomeric stamping, and printing techniques like inkjet and screen printing, have been explored to create high-resolution electrode patterns [24]. While each method has benefits and



limitations, innovations like using viscous polydimethylsiloxane PDMS substrates have improved inkjet printing by preventing ink diffusion, allowing precise and scalable fabrication of conductive microstructures [25].

Hydrogels and ionogels are emerging materials for flexible sensors due to their exceptional properties. Hydrogels are hydrophilic polymer gels with a 3D network that can swell in water and retain large volumes without dissolving. They offer excellent biocompatibility and design flexibility, making them ideal for wearable devices [26]. Ionogels from ionic liquids and polymers provide high ionic conductivity, tunable mechanical properties, and transparency [27]. Recent advances include using surface microstructures to enhance the compressibility and dielectric properties of ionogel-based capacitive pressure sensors [28].

Graphene is increasingly favoured over traditional metal electrodes in flexible sensors due to its lightweight nature, high surface area, superior conductivity, and chemical stability [29]. However, conventional production methods like chemical stripping or vapour deposition face environmental and efficiency challenges, while typical manufacturing processes (e.g., photolithography, etching, and screen printing) often lead to issues like graphene re-stacking and poor sensor performance. To overcome these limitations, low-cost and efficient methods such as laser direct writing (LDW) have emerged, enabling direct fabrication of 3D porous laser-induced graphene (LIG) from polymers like polyimide. These LIG-based electrodes offer high surface area, thermal stability, and conductivity, avoiding problems like layer stacking and misalignment. Despite these advancements, further research is needed to refine LIG processing and its application in integrated, stretchable, flexible sensors [29].

So, the advancement of flexibility and stretchability in sensors has been significantly driven by innovations in materials science and device design. From traditional inorganic components



to hybrid nanomaterials and smart hydrogels, the integration of mechanically compliant, biocompatible, and conductive materials has enabled the development of highly sensitive and durable wearable devices. Emerging fabrication techniques such as laser direct writing, 3D porous structuring, and microstructure ionogels have further enhanced sensor performance by improving mechanical adaptability and signal responsiveness. As research continues to focus on the synergy between material properties and structural design, flexible and stretchable sensors are poised to revolutionise applications in health monitoring, human–machine interfaces, and soft robotics, offering real-time, unobtrusive, and reliable sensing capabilities in dynamic environments.

3.5. Flexibility and Stretchability in Sensors: Innovations in Materials and Design

Nanomaterial-based sensors offer unique functionalities by incorporating materials such as nanoparticles, nanowires, metal-organic frameworks (MOFs), and nanocomposites. For instance, optical sensors using ultra-fine nanoparticles benefit from properties like fluorescence emission, large surface area, and surface modification potential [30]. These features enable rapid and accurate detection compared to conventional sensors. As healthcare remains a primary application area, recent developments have focused on using nanomaterial-based sensors for detecting biomarkers and pathogens. In addition to biomarker and pathogen detection, nanomaterial-based sensors have been effectively used for detecting environmental pollutants like heavy metal ions, nitrite, and naphthalene [31],[32],[33]. Their excellent sensitivity, selectivity, and rapid response make them ideal for in-field and on-site analyses. Therefore, advancing the development of sensors using novel nanomaterials and expanding their analytical applications is increasingly important.



Nanomaterial-based sensors have shown exceptional improvements in sensitivity, selectivity, and response time due to advanced material design and functionalization strategies. Nanostructuring plays a critical role in hierarchical nanocomposites like SnO₂–CNT provide enlarged active surfaces and tunable depletion layers that improve gas selectivity and signal amplification [34]. These structures also support faster charge transfer, crucial for real-time sensing. Functionalization strategies such as decorating nanomaterials with metal nanoparticles, conductive polymers, aptamers, or molecularly imprinted polymers further refine sensor selectivity, allowing for precise recognition of target analytes like H₂S over NH₃, or specific biomolecules in complex environments [35]. Sensors employing fast kinetics benefit from light-assisted or thermal recovery mechanisms, along with heterogeneous nanostructures, enabling quick response and baseline restoration. Additionally, nanomaterial-enhanced electrochemical sensors achieve ultra-low detection limits, often in the nanomolar (nM) range, making them ideal for detecting trace amounts of neurotransmitters or biomarkers [36]. Collectively, these innovations highlight how nanomaterial integration dramatically advances sensor performance across biomedical, environmental, and industrial applications.

The convergence of nanotechnology and sensor science drives unprecedented advancements in developing high-performance sensing systems. As this chapter has outlined, nanomaterials offer a versatile and robust foundation for designing sensors with exceptional sensitivity, selectivity, and responsiveness across various applications. Their unique physicochemical properties, high surface-to-volume ratios, tunable electronic characteristics, and adaptable surface functionalities have enabled breakthroughs in gas detection, chemical sensing, wearable diagnostics, and intelligent monitoring systems.



Furthermore, innovations in flexible and stretchable materials and seamless integration into IoT and wireless platforms are pushing the boundaries of what sensors can achieve. Hybrid and composite nanostructures are promising, allowing for multifunctional sensor platforms that outperform traditional single-material designs.

As the demand for real-time, reliable, and compact sensing devices grows, nanomaterials will remain central to meeting modern electronics' technical and societal challenges. Continued interdisciplinary research in materials science, nanofabrication, and systems integration will be essential for unlocking the full potential of nanomaterial-based sensors in the future.

3.6. Conclusion

Nanomaterial-based sensors represent a pivotal frontier in modern analytical and diagnostic technologies, embodying the convergence of nanoscience, materials engineering, and intelligent systems design. Their unique physicochemical attributes, such as enhanced surface-to-volume ratios, tunable electrical and optical properties, and adaptable surface chemistries, have established them as indispensable tools for ultra-sensitive and selective detection across diverse domains. The chapter elucidates how innovations in hybrid nanostructures and flexible architectures have expanded the scope of nanosensors from conventional laboratory systems to real-world, multifunctional applications, including wearable electronics, environmental monitoring, and biomedical diagnostics. Moreover, the integration of AI and IoT networks has endowed these sensors with cognitive capabilities, enabling real-time data acquisition, pattern recognition, and autonomous decision-making. Despite substantial progress, challenges persist regarding large-scale fabrication, device stability, and standardisation issues that must be addressed to transition nanosensor technologies from research



prototypes to commercial products. Looking forward, the synergy between materials innovation, data-driven analytics, and sustainable engineering is expected to catalyse the emergence of self-powered, intelligent, and adaptive sensor systems. Such advancements will not only redefine the capabilities of modern sensing platforms but also play a crucial role in realising a more connected, responsive, and health-conscious society.

References

1. M. Javaid, A. Haleem, R. P. Singh, S. Rab, and R. Suman, "Exploring the potential of nanosensors: A brief overview," 2021. doi: 10.1016/j.sintl.2021.100130.
2. A. Atala and J. J. Yoo, Essentials of 3D Biofabrication and Translation. 2015. doi: 10.1016/C2013-0-18665-5.
3. F. Arduini, S. Cinti, V. Scognamiglio, and D. Moscone, "Nanomaterial-based sensors," in Handbook of Nanomaterials in Analytical Chemistry: Modern Trends in Analysis, Elsevier, 2019, pp. 329–359. doi: 10.1016/B978-0-12-816699-4.00013-X.
4. Y. Lin, "Biosensors & Bioelectronics Commentary Mechanism of Operation of a Nanosensor and Its Applications," 2021, doi: 10.37421/jbsbe.2021.12.306.
5. J. Lee, O. Adegoke, and E. Y. Park, "High-Performance Biosensing Systems Based on Various Nanomaterials as Signal Transducers," 2019. doi: 10.1002/biot.201800249.
6. M. A. Darwish, W. Abd-Elaziem, A. Elsheikh, and A. A. Zayed, "Advancements in nanomaterials for nanosensors: a comprehensive review," May 24, 2024, Royal Society of Chemistry. doi: 10.1039/d4na00214h.
7. J. Z. Hassan, A. Raza, Z. U. Din Babar, U. Qumar, N. T. Kaner, and A. Cassinese, "2D material-based sensing devices: an update," 2023. doi: 10.1039/d2ta07653e.
8. R. Ramalingame, J. R. Bautista-Quijano, D. de F. Alves, and O. Kanoun, "Temperature self-compensated strain sensors based on mwcnt-graphene hybrid nanocomposite," Journal of Composites Science, vol. 3, no. 4, 2019, doi: 10.3390/jcs3040096.
9. M. V. Arularasu, M. Harb, R. Vignesh, T. V. Rajendran, and R. Sundaram, "PVDF/ZnO hybrid nanocomposite applied as a resistive humidity sensor," Surfaces and Interfaces, vol. 21, 2020, doi: 10.1016/j.surfin.2020.100780.
10. A. Alaghmandfard, S. Fardindoost, A. L. Frencken, and M. Hoorfar, "The next generation of hydrogen gas sensors based on transition metal dichalcogenide-metal oxide semiconductor hybrid structures," Ceram Int, vol. 50, no. 17, pp. 29026–29043, Sep. 2024, doi: 10.1016/j.ceramint.2024.05.259.
11. F. Wen, T. He, H. Liu, H. Y. Chen, T. Zhang, and C. Lee, "Advances in chemical sensing technology for enabling the next-generation self-sustainable integrated wearable system in the IoT era," 2020. doi: 10.1016/j.nanoen.2020.105155.
12. C. Mahapatra, "Recent advances in medical gas sensing with artificial intelligence-enabled technology," Jun. 01, 2025. doi: 10.4103/mgr.MEDGASRES-D-24-00113.
13. P. K. Sekhar, E. L. Brosha, R. Mukundan, and F. H. Garzon, "Chemical sensors for environmental monitoring and homeland security," Electrochemical Society Interface, vol. 19, no. 4, 2010, doi: 10.1149/2.F04104if.
14. J. Wang and R. Wang, "Development of Gas Sensors and Their Applications in Health Safety, Medical Detection, and Diagnosis," May 01, 2025, Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/chemosensors13050190.



15. R. A. Potyrailo et al., "Wireless sensors and sensor networks for homeland security applications," 2012. doi: 10.1016/j.trac.2012.07.013.
16. S. Singh, "Sensors-An effective approach for the detection of explosives," 2007. doi: 10.1016/j.jhazmat.2007.02.018.
17. B. W. An et al., "Smart sensor systems for wearable electronic devices," 2017. doi: 10.3390/polym9080303.
18. Z. Lou, L. Li, L. Wang, and G. Shen, "Recent Progress of Self-Powered Sensing Systems for Wearable Electronics," 2017. doi: 10.1002/sml.201701791.
19. G. Appelboom et al., "Smart wearable body sensors for patient self-assessment and monitoring," 2014. doi: 10.1186/2049-3258-72-28.
20. J. Zhu et al., "Recent advances in gas and environmental sensing: From micro/nano to the era of self-powered and artificial intelligent (AI)-enabled device," 2022. doi: 10.1016/j.microc.2022.107833.
21. Z. Daraf and H. De Roest, "Advanced AI-Powered Leak Detection Methods for Medical Fluid Systems in Healthcare Devices", doi: 10.13140/RG.2.2.32409.43362
22. Z. Yu et al., "Shaping the Future of the Neurotransmitter Sensor: Tailored CdS Nanostructures for State-of-the-Art Self-Powered Photoelectrochemical Devices," ACS publications, vol. 11, no. 5, May 2024, doi: <https://doi.org/10.1021/acssensors.4c00621>.
23. S. Choi et al., "Highly conductive, stretchable and biocompatible Ag–Au core–sheath nanowire composite for wearable and implantable bioelectronics," Nat Nanotechnol, vol. 13, no. 11, 2018, doi: 10.1038/s41565-018-0226-8.
24. S. Zhang, E. Hubis, G. Tomasello, G. Soliveri, P. Kumar, and F. Cicoira, "Patterning of Stretchable Organic Electrochemical Transistors," Chemistry of Materials, vol. 29, no. 7, 2017, doi: 10.1021/acs.chemmater.7b00181.
25. J. Jiang et al., "Fabrication of Transparent Multilayer Circuits by Inkjet Printing," Advanced Materials, vol. 28, no. 7, 2016, doi: 10.1002/adma.201503682.
26. S. Correa et al., "Translational Applications of Hydrogels," 2021. doi: 10.1021/acs.chemrev.0c01177.
27. J. Chen et al., "Recent Progress in Essential Functions of Soft Electronic Skin," 2021. doi: 10.1002/adfm.202104686.
28. H. Zhang et al., "Ultrastretchable, Self-Healing Conductive Hydrogel-Based Triboelectric Nanogenerators for Human-Computer Interaction," ACS Appl Mater Interfaces, vol. 15, no. 4, 2023, doi: 10.1021/acsami.2c17904.
29. J. Sun, Z. Chen, L. Yuan, J. Xiang, and W. Wang, "Recent advances in flexible/stretchable sensors using laser-induced three-dimensional porous graphene: From precursor to manufacturing," Dec. 01, 2024, Elsevier B.V. doi: 10.1016/j.surf.2024.105359.
30. Y. Zhao et al., "A molecular beacon-like Ag nanocluster fluorescence probe for nucleic acid detection," Analytical Sciences, vol. 38, no. 1, 2022, doi: 10.2116/analsci.21P146.
31. Y. Meng, Z. Ma, Y. Huang, and Y. Song, "Construction of MOF@COF composite-based electrochemical aptasensor for detection of Staphylococcus aureus," Analytical Sciences, vol. 39, no. 6, 2023, doi: 10.1007/s44211-023-00295-8.
32. J. Gao et al., "Detection of Cd²⁺ based on Nano-Fe₃O₄/MoS₂/Nafion/GCE sensor," Analytical Sciences, vol. 39, no. 9, 2023, doi: 10.1007/s44211-023-00359-9.
33. Afzal, Usama, et al. "Chemical engineering for advanced flexible sensors: Novel carbon-metal oxide nanocomposites with superior multi-sensing behavior." Sensors and Actuators B: Chemical 431 (2025): 137449.
34. Afzal, U., Wang, K., Liang, J., Fatima, A., Zhang, L., Wu, T., ... & Ma, K. (2025). High-Performance Flexible Gas Sensors Based on W–VO₂/1D-Carbon Composites for Real-Time Ammonia Detection in Breath and Environmental Monitoring. ACS sensors 10, 11, 9033–9043.



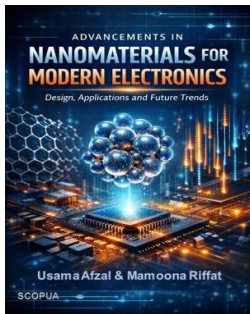
35. Y. Fu et al., “Applications of nanomaterial technology in biosensing,” 2024. doi: 10.1016/j.jsamd.2024.100694.
36. A. R. Jalalvand and M. M. Karami, “Roles of nanotechnology in electrochemical sensors for medical diagnostic purposes: A review,” Feb. 01, 2025, Elsevier B.V. doi: 10.1016/j.sbsr.2024.100733.



CHAPTER 4

ENERGY STORAGE AND HARVESTING TECHNOLOGIES USING NANOMATERIALS

USAMA AFZAL ^{1*}



Book Title

Advancements in Nanomaterials for Modern Electronics:
Design, Applications and Future Trends

Series Title

Books of Research Collection

Published On

January 02, 2026 (Edition 1)

Publisher

Scientific Collaborative Online Publishing Universal
Academy, Lahore, Pakistan

DOI: <https://doi.org/10.64060/978-627-7898-01-4-4>

Book ISBN: 978-627-7898-01-4

THIS WORK IS LICENSED UNDER A CREATIVE COMMONS ATTRIBUTION NONCOMMERCIAL
NODERIVATIVES 4.0 INTERNATIONAL LICENSE. SCOPUA (SCIENTIFIC COLLABORATIVE ONLINE
PUBLISHING UNIVERSAL ACADEMY) PUBLISHER REMAINS NEUTRAL REGARDING JURISDICTIONAL
CLAIMS IN PUBLISHED MAPS AND INSTITUTIONAL AFFILIATIONS.

¹School of Microelectronics, Tianjin University, Tianjin 300072, China.

*Corresponding: mohammadusamafzal7@gmail.com (U. Afzal)

Abstract

The global transition toward sustainable energy systems has intensified interest in nanomaterials for efficient energy storage and harvesting. This chapter reviews recent progress in nanostructured materials that enhance electrochemical, thermal, and photonic energy conversion processes. In batteries and supercapacitors, nanoscale design through graphene, silicon nanowires, and transition metal oxides enables high energy and power densities, rapid charge–discharge kinetics, and long-term stability. Similarly, nanomaterials revolutionise thermoelectric, piezoelectric, and triboelectric systems by improving charge transport, phonon scattering, and mechanical flexibility, while perovskite and quantum dot solar cells exploit quantum confinement and tunable bandgaps for superior photovoltaic performance. Hybrid energy platforms that integrate multiple nanomaterial-based mechanisms, such as battery–supercapacitor or solar–thermoelectric systems, demonstrate multifunctionality, flexibility, and self-powering capabilities vital for wearable and autonomous devices. The chapter also highlights scalable fabrication approaches, eco-friendly synthesis, and the emerging use of biodegradable and self-healing nanocomposites. Together, these advances position nanomaterials as the cornerstone of next-generation energy technologies, offering pathways toward high-performance, sustainable, and adaptive power solutions aligned with the global clean energy agenda.

Keywords: *Energy harvesting; Energy storage; Hybrid energy systems; Lithium–ion batteries; Lithium–sulfur batteries; Nanomaterials; Perovskite solar cells; Piezoelectric nanogenerators; Quantum dot solar cells; Solid–state batteries; Supercapacitors; Sustainable energy; Thermoelectric materials; Triboelectric nanogenerators; Wearable electronics.*

The global transition toward sustainable energy systems has intensified the demand for efficient energy storage and harvesting technologies [1],[2],[3],[4]. As the world moves away from fossil fuels and embraces cleaner energy alternatives, the need to develop advanced materials and systems that can store and convert energy efficiently, reliably, and economically has become increasingly critical. Energy storage systems, such as batteries and supercapacitors, play a vital role in



balancing energy supply and demand, supporting the integration of intermittent renewable sources like solar and wind into power grids, and enabling the advancement of electric vehicles and portable electronics. At the same time, energy harvesting technologies such as thermoelectric, photovoltaic, and hybrid energy systems are essential for capturing and converting ambient energy from various sources, including heat, light, and mechanical vibrations, into usable electrical energy. Nanomaterials have emerged as key enablers in this rapidly evolving landscape [5],[6],[7] as shown in Figure 4.1. Their unique properties, including high surface-area-to-volume ratio, tunable band structures, improved charge transport capabilities, and enhanced mechanical strength, make them ideal candidates for use in energy-related applications. The nanoscale dimension allows for better control over physical and chemical interactions at the material interface, which is crucial for enhancing the performance and efficiency of energy storage and harvesting devices. By tailoring the morphology, composition, and architecture of nanomaterials, researchers have achieved significant progress in overcoming the limitations of conventional bulk materials.

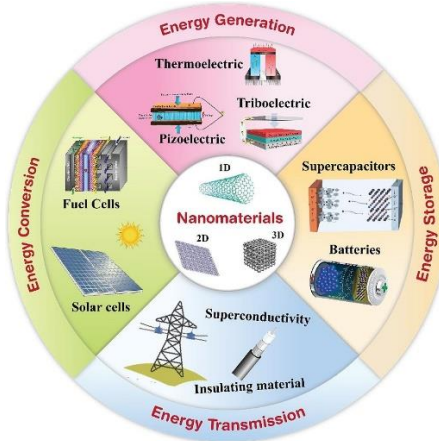


Figure 4.1: Overview of nanomaterials in energy systems, highlighting their roles in energy generation, storage, conversion, and transmission through diverse structures (1D, 2D and 3D) [8].



In the context of energy storage, nanomaterials have been instrumental in improving the energy and power densities of lithium-ion batteries (LIBs), lithium-sulfur batteries (LSBs), and next-generation solid-state batteries [9],[10],[11]. For instance, nanostructured electrodes offer shorter ion diffusion paths, larger surface areas for electrochemical reactions, and greater mechanical resilience against volume expansion during charge-discharge cycles. Similarly, supercapacitors benefit from nanostructured carbon materials, metal oxides, and conductive polymers that provide fast charge-discharge capabilities, long cycle life, and enhanced capacitance. On the energy harvesting front, nanomaterials have revolutionised thermoelectric generators by enhancing their thermoelectric figure of merit (ZT) through phonon scattering and electronic transport optimisation. In solar energy conversion, materials such as perovskites and quantum dots have demonstrated remarkable efficiency improvements due to their tunable optical properties and facile solution processability. The integration of nanomaterials into photovoltaic architectures has also led to improved light absorption, better charge carrier mobility, and increased device stability. Furthermore, hybrid energy systems that combine multiple storage and harvesting technologies have shown great promise in addressing the dynamic energy needs of modern applications. Nanomaterials play a central role in these systems by enabling multifunctional behaviour and compact integration, which are particularly important for self-powered wearable electronics, implantable medical devices, and remote sensing systems.

This chapter provides an in-depth overview of how nanomaterials are reshaping the field of energy storage and harvesting. It explores recent developments, technological advancements, and challenges in deploying nanomaterials in various systems, including batteries, supercapacitors, thermoelectric devices, and solar cells. Through a critical analysis of state-of-the-



art research and emerging trends, this chapter aims to highlight the potential of nanomaterials in driving sustainable energy solutions for the future.

4.1. Nanomaterials for High-Efficiency Batteries

The continuous pursuit of high-efficiency, lightweight, and durable energy storage systems has driven significant advancements in battery technologies. Among these, lithium-based batteries have dominated the market, particularly in consumer electronics, electric vehicles, and grid storage systems. A central challenge in battery technology is balancing high energy density with long cycle life, fast charge/discharge rates, and safety. The application of nanomaterials has emerged as a transformative approach in addressing these multifaceted challenges. Nanostructured materials possess unique characteristics such as high surface area-to-volume ratios, tunable electronic and ionic conductivity, and structural flexibility, making them ideal for use in modern battery systems [12],[13].

Nanomaterials enhance battery performance by reducing ion diffusion lengths, increasing active surface areas for electrochemical reactions, and providing robust structural integrity to accommodate the stresses of repeated cycling. Nanostructured electrodes, nanocomposite electrolytes, and engineered nanointerfaces are increasingly employed across various battery chemistries to achieve superior energy and power densities. This section delves into three key lithium-based battery types where nanomaterials have shown profound impact: lithium-ion batteries (LIBs), solid-state batteries, and lithium-sulfur batteries.

4.1.1. Lithium-Ion Batteries (LIBs)

Lithium-ion batteries have revolutionised portable electronics and are a cornerstone of the emerging electric mobility



industry. Their widespread adoption is attributed to their high energy density, long cycle life, and relatively mature manufacturing infrastructure. However, conventional LIBs still face limitations in terms of rate capability, safety, and capacity retention under extreme operating conditions. Nanomaterials offer promising solutions to these challenges [14].

- **Anode materials**, particularly graphite, have been modified with nanomaterials to enhance lithium intercalation and conductivity. Silicon, with its high theoretical capacity (~ 4200 mAh/g), is a prime candidate for next-generation anodes. However, silicon undergoes drastic volume expansion ($>300\%$) during lithiation, which leads to mechanical degradation. Nanostructured silicon, such as silicon nanowires, hollow nanospheres, and core-shell structures, has shown improved mechanical resilience and capacity retention. These nanostructures effectively accommodate volume changes and minimise the formation of stress-induced cracks.
- **Carbon-based nanomaterials** such as graphene and carbon nanotubes (CNTs) are extensively used to create conductive matrices that buffer volume changes and maintain electrical contact throughout cycling. These nanostructures facilitate efficient electron transport and enhance the structural stability of the electrode. Additionally, nanostructured transition metal oxides (e.g., Fe_3O_4 , MnO_2 , Co_3O_4) and composite nanomaterials have demonstrated improved lithium storage capacities and rate performance. Their ability to undergo reversible redox reactions and sustain high capacity over prolonged cycles makes them promising candidates for future anode designs.
- **Cathode performance** also benefits from nanoscale engineering. Layered transition metal oxides (e.g., LiCoO_2 , LiNiMnCoO_2), spinels (LiMn_2O_4), and olivines (LiFePO_4)



have been synthesised in nanostructured forms to increase surface area and shorten lithium diffusion pathways. Coating these materials with nanolayers of conductive agents or protective shells further enhances their electrochemical stability and suppresses phase transformations during cycling. For example, Al_2O_3 and ZrO_2 coatings on LiNiMnCoO_2 cathodes reduce the formation of detrimental surface films and improve cycling life.

Moreover, nanostructured cathodes provide faster lithium-ion kinetics due to their increased contact area with the electrolyte and reduced particle sizes. This enhances the rate performance and allows for high-power operation, which is essential for applications such as power tools and electric vehicles. In addition, doping strategies using nanoparticles such as Mg, Al, and Ti are employed to stabilise cathode structures and enhance capacity retention.

4.1.2. Solid-State Batteries

Solid-state batteries are considered the next leap in battery technology due to their potential for higher energy density, improved safety, and greater thermal stability. Unlike conventional LIBs that use flammable liquid electrolytes, solid-state batteries utilise solid electrolytes, which eliminate the risk of leakage and thermal runaway [15],[16]. Nanomaterials play a critical role in the development of solid electrolytes with enhanced ionic conductivity and mechanical properties. For instance, oxide-based electrolytes such as garnet-type $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ (LLZO) and sulfide-based electrolytes like $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ (LGPS) have shown significant promise [17]. Nanoscale engineering of these materials leads to improved densification during sintering, reduced grain boundary resistance, and better contact with electrode materials. These factors contribute to lower interfacial impedance and higher ionic mobility across the solid electrolyte.



Moreover, interface engineering using nanoscale coatings or interlayers enhances compatibility between the solid electrolyte and electrodes, mitigating issues such as dendrite formation and interfacial degradation. Composite solid electrolytes that integrate nanofillers like Al_2O_3 , TiO_2 and SiO_2 within polymer matrices have demonstrated improved mechanical strength, flexibility, and ionic conductivity, enabling safer and more durable solid-state battery designs. These nanocomposite materials also offer better processability and allow for thin-film fabrication, which is advantageous for miniaturised applications. The development of nanostructured cathodes and anodes tailored for solid-state systems is also gaining momentum. Nanostructured lithium metal anodes, combined with protective nanolayers, can suppress dendritic growth and enhance cycling performance. For instance, lithium-metal foils coated with lithiophilic nanoparticles (e.g., ZnO , Ag) promote uniform lithium deposition and reduce dendrite propagation [18]. On the cathode side, nanoscale coatings and dopants are employed to improve lithium-ion transport and interface stability. Strategies such as LiNbO_3 and Li_3PO_4 surface modifications have shown enhanced interfacial stability and reduced impedance.

Additionally, nanostructured interlayers and buffer layers are used to mitigate interfacial stress and accommodate volume changes during cycling. These layers help maintain physical integrity and electrical contact between electrodes and solid electrolytes. The integration of 3D nanostructured scaffolds has also been explored to improve mechanical robustness and facilitate ion transport, particularly in high-energy-density designs.

4.1.3. Lithium-Sulfur Batteries

Lithium-sulfur (Li-S) batteries have attracted significant attention due to their high theoretical specific energy (~ 2600 Wh/kg), low cost, and environmental friendliness. However, their practical implementation is hindered by several challenges,



including the low electrical conductivity of sulfur, the dissolution of intermediate lithium polysulfides, and severe volume changes during cycling. Nanotechnology offers multiple strategies to overcome these limitations. One of the most successful approaches is the use of nanostructured carbon hosts to encapsulate sulfur and physically/chemically trap lithium polysulfides. Porous carbon matrices, such as mesoporous carbon, graphene frameworks, and carbon nanotube networks, provide conductive paths for electrons and confine active materials, mitigating polysulfide diffusion (shuttle effect). These carbon hosts also facilitate uniform sulfur distribution and improve rate capability [19],[20].

Furthermore, metal-organic frameworks (MOFs), hollow carbon spheres, and yolk-shell nanostructures have been employed to accommodate sulfur expansion and improve cycle stability. These hosts enable high sulfur loading and uniform sulfur distribution, thereby enhancing electrochemical performance. Polar metal oxide nanoparticles (e.g., TiO_2 , MnO_2) have also been integrated into cathode structures to chemically anchor polysulfides and suppress their migration. These polar interactions inhibit the shuttle effect and extend cycle life. On the electrolyte side, the incorporation of nanoscale additives and coatings improves ionic conductivity and inhibits undesirable side reactions. Solid and gel-based electrolytes with embedded nanofillers are also being explored to address the safety and polysulfide dissolution issues associated with liquid electrolytes. For instance, polyethylene oxide (PEO) or PVDF-based gel electrolytes combined with SiO_2 or Al_2O_3 nanoparticles have demonstrated enhanced conductivity and mechanical stability [21]. For anode improvement, lithium-metal protection strategies using nanolayer coatings and artificial solid-electrolyte interphases (SEIs) are under investigation. These nanoscale barriers prevent dendritic growth and stabilise lithium deposition, extending battery life and enhancing safety. Materials such as graphene oxide, boron nitride, and polymer nanocomposites



have been used to form robust SEI layers that minimise side reactions and improve coulombic efficiency.

Emerging trends in Li-S battery research include the use of dual-functional interlayers, separator coatings, and advanced binders. Nanostructured interlayers placed between the cathode and separator can act as polysulfide reservoirs, capturing dissolved species and facilitating their reutilization. Similarly, functional coatings on separators (e.g., doped graphene, polymer composites) offer a physical and chemical barrier against polysulfide migration. Advanced binders incorporating nanofillers or conductive polymers (e.g., polyaniline, PEDOT: PSS) help maintain electrode integrity and enhance conductivity. These binders improve electrode flexibility and accommodate volume changes during cycling. Together, these strategies are enabling practical Li-S battery designs with high energy density, long cycle life, and enhanced safety.

4.1.4. Emerging Nanomaterials for Next-Generation Batteries

Beyond lithium-based systems, the next frontier in battery technology includes alternative chemistries such as sodium-ion, potassium-ion, magnesium-ion, and multivalent batteries. These systems offer advantages in cost, resource availability, and safety, especially for large-scale energy storage. Nanomaterials are central to the development of these alternative batteries by enhancing electrochemical kinetics, structural stability, and ion transport [22].

- **Sodium-Ion and Potassium-Ion Batteries:** Sodium-ion (Na-ion) and potassium-ion (K-ion) batteries have garnered attention due to the natural abundance and low cost of sodium and potassium [23]. However, their larger ionic radii compared to lithium present challenges in terms of electrode structural stability and diffusion kinetics. Nanostructured materials, such as carbon-based nanocomposites, metal oxides, and layered transition metal



sulfides, are being investigated to accommodate ion expansion and improve rate performance. Graphene, CNTs, and reduced graphene oxide (rGO) frameworks offer high conductivity and structural flexibility, which are essential for maintaining performance during large-volume changes. Additionally, nanostructured NASICON-type materials and Prussian blue analogs have shown promise as cathodes due to their open frameworks and stable cycling behaviour.

- **Magnesium and Multivalent Batteries:** Magnesium (Mg), zinc (Zn), and aluminium (Al) offer higher volumetric capacities and safety advantages due to dendrite-free deposition [24]. However, sluggish diffusion kinetics and limited electrolyte compatibility have hindered progress. Nanomaterials such as Mg-based metal oxides, transition metal chalcogenides, and polymer-gel nanocomposites are being explored to overcome these issues. For instance, nanostructured MgTiO_3 and V_2O_5 have shown enhanced Mg-ion diffusion and improved capacity retention. Similarly, hybrid nanocomposites with high surface area and tailored porosity facilitate ion transport and suppress parasitic reactions. The use of ionic liquids and solid electrolytes with embedded nanofillers is also advancing the development of stable, high-performance multivalent batteries.

4.2. Supercapacitors and Energy Density Enhancement with Nanomaterials

Supercapacitors, also known as electrochemical capacitors or ultracapacitors, are advanced energy storage devices that bridge the gap between traditional capacitors and batteries [25]. They possess unique attributes such as high-power density, long cycle life, and rapid charge-discharge cycles, making them ideal for



applications in electric vehicles, portable electronics, and renewable energy systems. However, despite these advantages, their relatively low energy density remains a critical limitation when compared to batteries. To overcome this barrier, significant research has focused on the integration of nanomaterials to enhance the electrochemical performance of supercapacitors. Nanomaterials offer an unprecedented ability to improve both specific capacitance and energy density due to their high surface area, unique physicochemical properties, and tunable morphology. The energy stored in a supercapacitor is fundamentally governed by the equation (4.1):

$$E = \frac{1}{2} \times C \times V^2 \quad (4.1)$$

Where E is the energy, C is the capacitance, and V is the operating voltage. Nanomaterials contribute to enhancing both the capacitance (C) and, indirectly, the voltage window (V) by enabling stable operation in broader electrochemical environments.

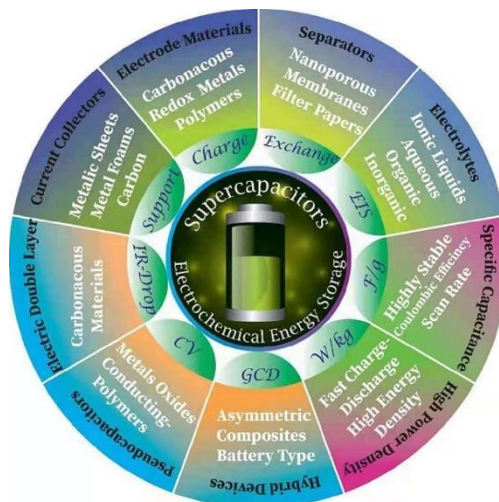


Figure 4.1: Overview of key components, mechanisms and performance parameters governing the operation of supercapacitors. [26].

There are two primary mechanisms of charge storage in supercapacitors: (1) Electrical double-layer capacitance (EDLC)



and (2) Pseudocapacitance. EDLCs depend on the physical separation of charges at the electrode-electrolyte interface, whereas pseudocapacitors involve fast and reversible redox reactions on or near the surface of the electrode material. Nanomaterials enhance both these mechanisms depending on their type and structure.

- **Carbon Nanomaterials:** Carbon-based nanomaterials are widely used for EDLC-type supercapacitors due to their high electrical conductivity, large surface area, and structural stability. Among them, carbon nanotubes (CNTs) and graphene are the most prominent [27]. CNTs offer a high aspect ratio, mesoporous structure, and excellent mechanical flexibility, making them ideal for high-rate performance. Graphene, a two-dimensional sheet of sp^2 -bonded carbon atoms, provides an ultra-large theoretical surface area ($\sim 2630 \text{ m}^2/\text{g}$) and exceptional electronic conductivity. These features enable the formation of a highly efficient electric double-layer, facilitating rapid charge transport and high power output. For instance, a supercapacitor composed of vertically aligned CNTs can provide both short ion diffusion paths and high electron mobility, leading to faster charging and improved power density. Similarly, reduced graphene oxide (rGO) based electrodes have been shown to deliver specific capacitances of up to 200 F/g with excellent cycle stability.
- **Pseudocapacitive Materials:** Beyond carbon materials, nanostructured pseudocapacitive materials play a crucial role in boosting energy density by providing redox-active sites for faradaic reactions [28],[29]. Transition metal oxides such as manganese dioxide (MnO_2), ruthenium dioxide (RuO_2), and nickel cobaltite (NiCo_2O_4) are widely studied due to their high theoretical capacitance values. For example, MnO_2 has a theoretical specific capacitance of approximately 1370 F/g . However, its intrinsic low



electrical conductivity poses a challenge. This limitation is often addressed by integrating MnO_2 with conductive substrates like CNTs or graphene. A composite of MnO_2 nanoparticles anchored on graphene sheets creates a synergistic effect: MnO_2 provides redox activity while graphene ensures electron mobility. Such a hybrid design allows a high specific capacitance ($>300 \text{ F/g}$) with improved cycle life and rate capability. RuO_2 , another high-performance pseudocapacitive material, has gained attention for its high conductivity and fast redox kinetics. Although its cost and toxicity restrict its widespread application, RuO_2 -based nanostructures, especially in hydrated or amorphous form, offer excellent electrochemical characteristics. In one study, mesoporous RuO_2 thin films deposited on carbon paper electrodes demonstrated specific capacitances above 700 F/g and remarkable power density. This highlights the potential of nanostructured metal oxides in pushing the energy density boundaries of supercapacitors. Nickel cobaltite (NiCo_2O_4) is a bimetallic oxide known for its rich redox activity, high theoretical capacity, and stability. Its unique spinel structure enables multiple redox reactions involving $\text{Ni}^{2+}/\text{Ni}^{3+}$ and $\text{Co}^{2+}/\text{Co}^{3+}$ couples. Synthesising NiCo_2O_4 in nanowire or nanosheet morphology provides a high surface area and reduces ion diffusion length. When grown directly on conductive substrates like nickel foam, these nanostructures exhibit enhanced electrochemical accessibility and superior performance. For instance, NiCo_2O_4 nanowire arrays have shown specific capacitances over 1100 F/g and outstanding cycling stability, positioning them as excellent candidates for high-energy supercapacitor applications.



- **MXenes**, a newer class of two-dimensional transition metal carbides and nitrides, have attracted substantial interest in recent years [30],[31]. These materials possess a metallic conductivity and tunable surface functionalities, making them suitable for high-performance supercapacitors. Their layered structure allows intercalation of electrolyte ions, while surface terminations (-OH, -F, -O) contribute to pseudocapacitive behaviour. For example, $\text{Ti}_3\text{C}_2\text{T}_x$ MXene exhibits a high volumetric capacitance ($\sim 1500 \text{ F/cm}^3$) and excellent rate performance. When assembled into flexible or solid-state devices, MXene-based electrodes demonstrate high energy density and mechanical robustness, enabling their use in wearable and flexible electronics.
- **Conducting Polymers**: Conducting polymers such as polyaniline (PANI), polypyrrole (PPy), and polythiophene represent another class of pseudocapacitive materials [32]. These materials exhibit fast electron transfer rates and high capacitance due to their doping/dedoping behaviour during redox reactions. Nevertheless, their mechanical degradation during cycling remains a concern. To address this, nanostructured conducting polymers are synthesised as nanofibers, nanotubes, or composites with carbon materials to enhance their structural stability and conductivity. For example, PANI coated on CNTs or graphene forms a conductive network with improved mechanical integrity, enabling high specific capacitance and prolonged cycle life. A well-designed PANI/rGO composite electrode can deliver capacitances in the range of 600–800 F/g with over 90% capacitance retention after thousands of cycles.
- **Hybrid Supercapacitor**: Hybrid supercapacitor systems combine the advantages of EDLC and pseudocapacitance by integrating carbon-based materials with metal oxides or conducting polymers [33]. These hybrid designs leverage



the high conductivity and stability of carbon nanomaterials and the high redox activity of metal oxides or polymers. One exemplary configuration is a composite of graphene and MnO_2 , where the carbon matrix provides a conductive backbone and structural support while the metal oxide contributes to enhanced capacitance through redox processes [34]. Such hybrid electrodes often exhibit improved overall electrochemical performance compared to their individual components. Another significant advancement is the development of asymmetric supercapacitors, where different electrode materials are used for the positive and negative electrodes to expand the voltage window and thus increase energy density. For example, a typical configuration might use NiCo_2O_4 as the positive electrode and activated carbon as the negative electrode. This arrangement not only enhances the voltage range (up to 1.6–2.0 V) but also improves specific energy, bridging the gap between supercapacitors and batteries [35]. These systems are particularly useful in applications requiring both high energy and high-power delivery, such as regenerative braking systems in electric vehicles. In addition to material composition, nanostructuring techniques such as electrospinning, hydrothermal synthesis, atomic layer deposition, and chemical vapour deposition (CVD) play a pivotal role in fabricating high-performance supercapacitor electrodes. These methods allow precise control over particle size, morphology, porosity, and surface area, all of which significantly influence ion transport and charge storage behaviour. For instance, nanostructured hierarchical architectures such as core-shell structures or porous nanoflowers maximise the active surface area while maintaining efficient pathways for electron and ion transport. These architectures also help



accommodate volume changes during cycling, ensuring stable operation. Electrolytes also play a crucial role in determining the energy density of supercapacitors. Aqueous electrolytes like KOH or H₂SO₄ offer high ionic conductivity but are limited by a narrow electrochemical window (~1.0 V). In contrast, organic or ionic liquid electrolytes enable a broader voltage range (2.5–3.5 V), thereby significantly enhancing energy density. Nanomaterials, due to their tunable surface chemistry, can be engineered to be compatible with these electrolytes, leading to improved electrochemical performance. For instance, surface-functionalized carbon nanomaterials can enhance wettability and compatibility with organic solvents, facilitating high-voltage operation.

Emerging trends also explore the development of solid-state and flexible supercapacitors, particularly for wearable and implantable electronics. In such applications, flexibility, safety, and mechanical robustness become key requirements. Nanomaterials are inherently suitable for such systems due to their mechanical properties and ability to form conformal coatings. For example, flexible electrodes composed of graphene foam decorated with MnO₂ nanosheets exhibit excellent bendability and high capacitance retention under mechanical deformation. Similarly, MXene-based inks can be printed onto flexible substrates, enabling the fabrication of lightweight, stretchable energy storage devices.

4.3. Nanomaterials in Energy Harvesting

The continuous advancement in microelectronics, wearable technologies, and wireless sensor networks has intensified the demand for reliable, sustainable, and miniaturised energy sources. Conventional batteries, while widely used, pose challenges in terms of size, lifespan, environmental impact, and recharging



requirements. This has led to significant interest in energy harvesting technologies, which aim to capture and convert ambient energy from the environment into usable electrical energy. Among the enablers of efficient energy harvesting systems, nanomaterials stand out due to their unique electrical, mechanical, optical, and thermal properties. These materials, owing to their high surface-to-volume ratios and tunable physicochemical characteristics, significantly enhance the performance and efficiency of energy harvesters. This section explores how nanomaterials contribute to various energy harvesting mechanisms, including piezoelectric, triboelectric, thermoelectric, photovoltaic, electromagnetic, and hybrid systems, accompanied by specific examples and scientific insights.

4.3.1. Piezoelectric Energy Harvesting with Nanomaterials

Piezoelectric energy harvesting relies on the ability of certain materials to generate an electrical voltage when subjected to mechanical stress [36]. Traditional piezoelectric materials such as lead zirconate titanate (PZT) offer high piezoelectric coefficients but lack flexibility and are environmentally hazardous. Nanomaterials, especially in one-dimensional forms like nanowires or nanorods, have provided innovative pathways to overcome these limitations.

- **Zinc oxide (ZnO) nanowires** have emerged as a seminal piezoelectric nanomaterial. Due to their high aspect ratio and ability to grow in vertically aligned arrays, ZnO nanowires generate substantial piezopotential under deformation. In a landmark study by Wang et al., ZnO nanowire arrays were grown on a flexible polymer substrate to construct a nanogenerator capable of powering nanoscale devices [37]. This setup demonstrated that even gentle human motion or ambient vibrations could be converted into electricity.



- **Polyvinylidene fluoride (PVDF)** and its copolymers, when embedded with piezoelectric nanoparticles like Barium Titanate (BaTiO_3) or ZnO, form flexible nanocomposites with enhanced piezoelectric responses [38]. These composites are widely used in wearable applications, converting biomechanical energy from body movements into electrical signals.

Such nanogenerators are highly scalable and integrable into fabrics, shoe insoles, and biomedical implants, marking a shift toward self-powered wearable systems.

4.3.2. Triboelectric Nanogenerators (TENGs) and Nanostructures

Triboelectric nanogenerators harvest energy through contact electrification followed by electrostatic induction between two dissimilar materials. Nanomaterials enhance TENGs by increasing effective contact area, dielectric constants, and surface charge retention [39],[40].

Nanostructured polydimethylsiloxane (PDMS) surfaces embedded with carbon nanotubes (CNTs) or graphene oxide (GO) significantly enhance surface roughness, increasing the triboelectric effect. These surfaces create more friction and charge transfer during mechanical contact. Moreover, electrospinning or nanoparticle patterning on polymer surfaces introduces micro/nano textures that amplify the contact area and enhance charge separation. For example, a hybrid TENG developed using GO-coated PDMS and metallic nanodots generated enough power to drive low-energy sensors and LEDs from foot tapping and hand motion. Additionally, combining materials with distinct electron affinity, such as fluorinated ethylene propylene (FEP) and polyamide, further increases the triboelectric output.



These advances enable applications in motion tracking, environmental sensing, and powering wireless nodes, particularly where battery replacement is impractical.

4.3.3. Thermoelectric Energy Harvesting Enhanced by Nanomaterials

Thermoelectric energy harvesters convert temperature differences into electrical energy through the Seebeck effect, where a voltage is generated when a material experiences a heat gradient. The efficiency of thermoelectric materials is measured by the figure of merit (ZT), which depends on the Seebeck coefficient, electrical conductivity, and thermal conductivity. Achieving high ZT requires increasing electrical and Seebeck performance while reducing thermal losses [41],[42],[43]. Among available materials, bismuth telluride (Bi_2Te_3) remains the most effective near room temperature. When synthesised as nanoplates or nanowires, Bi_2Te_3 exhibits reduced thermal conductivity due to enhanced phonon scattering at grain boundaries, without significantly affecting electrical transport. Nanostructured Bi_2Te_3 films have achieved ZT values exceeding 1.2 at 300 K, compared to ~ 0.9 for bulk materials. Flexible thin films of Bi_2Te_3 integrated into thermoelectric generators (TEGs) can maintain stable output during bending and produce open-circuit voltages around 80 mV under a 50°C temperature gradient. Similar improvements are observed in Cu_2S and SnSe nanostructures, where nanoscale control enhances Seebeck coefficients and power factors. Such advances demonstrate how nanoscale engineering enables efficient waste-heat recovery and wearable energy solutions, positioning thermoelectric nanomaterials as key enablers in self-powered and sustainable electronic systems.

Such devices are particularly promising for wearable electronics, where body heat can be harvested to power sensors, smart watches, and health monitors.



4.3.4. Photovoltaic Energy Conversion with Nanomaterials

Photovoltaic (PV) energy harvesting is based on the conversion of light into electricity. While traditional silicon solar cells dominate the market, they are limited by rigidity, cost, and complex fabrication. Nanomaterials provide alternatives by enabling flexible, lightweight, and potentially more efficient PV systems [44],[45].

Perovskite nanocrystals such as methylammonium lead halides (MAPbI_3) offer tunable bandgaps, high absorption coefficients, and long carrier diffusion lengths. These nanomaterials have pushed power conversion efficiencies of perovskite solar cells beyond 25%. Nanostructured TiO_2 and ZnO nanorods act as efficient electron transport layers that reduce recombination and improve charge separation in dye-sensitised and perovskite solar cells.

Quantum dots (QDs) like CdSe and PbS exhibit quantum confinement effects that enable absorption of a broader light spectrum. Graphene and reduced graphene oxide (rGO) are integrated as transparent conducting layers and electron transport materials to improve device stability and conductivity.

These innovations have led to the development of flexible and wearable solar panels, integrated into backpacks or clothing, providing sustainable power sources for mobile electronics and sensors.

4.3.5. Electromagnetic and RF Energy Harvesting

Harvesting ambient electromagnetic radiation, such as radiofrequency (RF) signals from Wi-Fi or cellular networks, is an emerging solution for low-power electronics. The basic components of an RF energy harvester include an antenna, rectifier circuit, and energy storage unit [46],[47].

Nanomaterials such as silver nanowires, graphene and metallic nanoparticles are used to fabricate transparent and flexible



antennas. These antennas maintain high conductivity while reducing material weight and cost. For instance, a graphene-based antenna integrated with a Schottky diode was able to harvest microwatts of power from a 2.4 GHz Wi-Fi signal. Additionally, ferromagnetic nanomaterials like cobalt ferrite (CoFe_2O_4) enhance the inductive components of RF circuits, improving energy capture and conversion. Emerging technologies such as spintronic devices, based on the electron spin in nanostructures, are being investigated for high-frequency energy harvesting.

This technology has applications in wireless sensor networks, passive RFID tags, and remote biomedical devices that require minimal power.

4.3.6. Fabrication, Scalability and Environmental Considerations

Nanomaterials used in energy harvesting applications must be processed through fabrication techniques that support precise structural control, scalability, and economic feasibility. Modern fabrication techniques such as electrospinning, chemical vapour deposition (CVD), inkjet printing, and sol-gel processes have proven to be effective in producing nanostructured films, fibres, and composites with the desired morphology and functional performance. Each of these techniques offers distinct advantages in controlling the alignment, dispersion, and integration of nanomaterials for practical energy harvesting devices [48],[49],[50],[51].

- **Electrospinning** is a versatile and scalable technique for fabricating nanofibers, which can be employed to construct piezoelectric or triboelectric components. A common example involves the use of polyvinylidene fluoride (PVDF), a well-known piezoelectric polymer. When embedded with ZnO nanoparticles, the electrospun PVDF fibres enhance the piezoelectric response significantly due



to the synergistic interaction between the polymer matrix and inorganic filler. These hybrid fibres are lightweight, flexible, and can be integrated into wearable textiles, enabling the conversion of biomechanical energy into electrical signals for health monitoring or human-machine interfaces.

- ***Chemical vapor deposition (CVD)***, another widely used method, enables the growth of high-purity and uniform nanostructures such as CNTs, graphene sheets, and ZnO nanowires on various substrates. CVD-grown ZnO nanowires, for instance, can be aligned perpendicularly on flexible substrates to construct high-performance nanogenerators that are responsive to mechanical deformation. CVD techniques are especially critical in applications requiring precise control over nanomaterial geometry, crystallinity, and alignment, which directly influence the energy harvesting efficiency.
- ***Inkjet printing*** has emerged as a cost-effective and scalable fabrication technique for producing flexible energy devices. Functional inks made from nanocrystalline thermoelectric materials like Bi₂Te₃ or 2D MXenes can be precisely deposited onto substrates to form patterned films. These printed thermoelectric layers can be incorporated into wearable power sources using roll-to-roll manufacturing, which is advantageous for large-scale production of flexible electronics. Inkjet printing also allows multi-material integration, enabling the simultaneous patterning of electrodes, active layers, and encapsulation on a single substrate.
- ***Sol-gel methods*** offer another low-cost and solution-processable route for fabricating metal oxide nanomaterials. By controlling the sol-gel chemistry, nanostructured ZnO, TiO₂, or VO₂ films can be deposited onto flexible or rigid



substrates. These materials are key components in piezoelectric, photovoltaic, or thermochromic energy harvesters. Sol-gel-derived films can also be doped or hybridised with carbon-based materials to improve their functional performance.

In addition to performance and scalability, environmental considerations are becoming increasingly important in the design and fabrication of nanomaterial-based energy harvesting systems. The long-term goal of sustainable nanotechnology mandates the use of non-toxic, renewable, and biodegradable materials wherever possible. Researchers are actively exploring biocompatible alternatives to synthetic polymers and inorganic fillers. For example, cellulose nanocrystals derived from plant biomass exhibit impressive mechanical strength and are being developed as green fillers in piezoelectric or triboelectric nanogenerators. Other promising eco-friendly materials include silk fibroin and chitosan, both derived from natural sources. These biopolymers can form flexible, biodegradable films that serve as functional layers in wearable energy harvesters. Silk fibroin, when combined with carbon-based nanomaterials like graphene or CNTs, can yield conductive and durable films for sensors and energy storage components. Chitosan, with its inherent film-forming capability and ion-conductivity, is being utilised as a matrix in flexible supercapacitors and energy harvesting composites.

Environmental sustainability also involves minimising the carbon footprint and toxic by-products of synthesis routes. Green synthesis methods use plant extracts, bacteria, or water-based chemistry to produce nanomaterials under ambient conditions. These approaches avoid harsh chemicals and high-temperature processes, making them more suitable for large-scale and environmentally friendly production. For example, green synthesis of ZnO nanoparticles using aloe vera or tea extracts can produce bio-compatible nanostructures for piezoelectric devices without the



need for chemical surfactants or stabilisers. Furthermore, the integration of self-healing capabilities in nanocomposites extends the operational life and reliability of energy harvesting systems. Self-healing materials can autonomously repair micro-cracks or delamination caused by mechanical stress or environmental exposure, reducing the need for frequent replacement. Incorporating reversible covalent bonds, hydrogen bonding, or microencapsulated healing agents within the polymer matrix has shown promise in enhancing the durability of flexible nanogenerators.

In brief, the fabrication of nanomaterials for energy harvesting must balance performance, scalability, and environmental responsibility. Techniques like electrospinning, CVD, inkjet printing, and sol-gel processing enable precise and scalable manufacturing of nanostructured components. At the same time, a shift towards biodegradable materials, green synthesis methods, and self-healing nanocomposites is ensuring that these technologies evolve in harmony with ecological and sustainability goals. These efforts are crucial to realising the vision of future energy systems that are not only efficient and versatile but also safe and environmentally friendly.

4.4. Nanomaterial-Based Solar Cells: Perovskite and Quantum Dot Solar Cells

In the global shift toward sustainable and low-carbon energy systems, the innovation and diversification of photovoltaic (PV) technologies remain a high priority. Among the forefront of next-generation solar technologies are nanomaterial-based solar cells, which exploit the unique physicochemical properties of materials at the nanoscale to enhance light absorption, charge carrier mobility, and overall power conversion efficiency (PCE). In particular, perovskite solar cells (PSCs) and quantum dot solar cells (QDSCs) have garnered substantial attention due to their



extraordinary optoelectronic characteristics, scalability, and potential for low-cost fabrication. This section provides an in-depth exploration of the materials, operational mechanisms, current achievements, challenges, and future perspectives related to PSCs and QDSCs [52],[53].

4.4.1. Perovskite Solar Cells (PSCs)

Perovskite materials refer to a class of compounds with a crystal structure analogous to the mineral CaTiO_3 . The general formula of hybrid organic-inorganic perovskites used in photovoltaics is ABX_3 , where ‘A’ typically represents an organic cation such as methylammonium (MA^+), formamidinium (FA^+), or cesium (Cs^+); ‘B’ is a metal cation (commonly Pb^{2+} or Sn^{2+}); and ‘X’ is a halide anion (Cl^- , Br^- , or I^-). This tunable composition allows for precise control over the material’s bandgap, optical absorption properties, and electronic structure, which are essential for efficient solar energy conversion. For example, methylammonium lead iodide ($\text{CH}_3\text{NH}_3\text{PbI}_3$ or MAPbI_3) exhibits a direct bandgap of ~ 1.55 eV, suitable for single-junction solar cells. Additionally, these materials demonstrate high absorption coefficients (exceeding 10^4 cm^{-1}), long charge carrier diffusion lengths ($\sim 1 \text{ }\mu\text{m}$), and low exciton binding energies, enabling efficient charge separation and transport under solar illumination [54].

Perovskite solar cells are highly attractive for flexible, lightweight, and semi-transparent applications. For instance, flexible PSCs can be integrated into wearable devices, vehicle surfaces, and portable power generators. Japan has recently invested \$1.5 billion to develop and commercialise ultra-thin PSCs suitable for infrastructure integration, such as building facades and windows. Moreover, tandem configurations, where PSCs are stacked atop silicon or CIGS bottom cells, have demonstrated



synergetic effects and PCEs exceeding 30%, thus breaking the single-junction Shockley-Queisser limit.

Despite impressive efficiency gains, PSCs face significant challenges regarding operational stability, environmental safety, and scalability. A major concern is the inclusion of lead (Pb^{2+}), which poses toxicity and environmental contamination risks if the devices degrade or are improperly disposed of. While tin (Sn^{2+})-based perovskites (e.g., MASnI_3) have been proposed as alternatives, they suffer from rapid oxidation to Sn^{4+} , reducing stability and performance [55]. Additionally, perovskites are vulnerable to ambient moisture, oxygen, and ultraviolet light, causing degradation. Encapsulation strategies using polymeric barriers, atomic layer deposition (ALD), or hybrid encapsulants are under investigation to prolong device lifetimes under real-world conditions.

4.4.2. Quantum Dot Solar Cells (QDSCs)

Quantum dots (QDs) are semiconductor nanocrystals with dimensions typically between 2–10 nm, exhibiting size-dependent optical and electronic properties due to quantum confinement. Unlike bulk semiconductors, QDs enable tunable bandgaps by simply adjusting particle size, composition, or surface ligands, allowing broad and controlled solar spectrum harvesting. Common QDs for photovoltaics include lead sulfide (PbS), lead selenide (PbSe), cadmium telluride (CdTe), and indium phosphide (InP). For instance, PbS QDs have been engineered to absorb near-infrared (NIR) light, complementing the visible absorption of traditional materials and extending the cell's spectral response beyond 1000 nm [56].

QDSCs operate via excitonic or carrier-transport mechanisms, depending on the quantum dot structure and interfaces. One notable advantage is multiple exciton generation



(MEG), where a single high-energy photon generates two or more electron-hole pairs, increasing theoretical efficiency beyond the Shockley–Queisser limit ($\sim 33\%$). Although MEG has been demonstrated in PbSe QDs under high-photon energy conditions, its practical impact on full devices remains under optimisation. Efforts to enhance charge extraction and reduce recombination have led to the development of core-shell QDs (e.g., CdSe/ZnS) and passivation techniques using halide ligands or perovskite layers. For example, applying a triple-cation perovskite (Cs/MA/FA) passivation layer on PbS QDs improved both open-circuit voltage and stability, achieving PCEs over 12%. Currently, the highest certified efficiency for QDSCs exceeds 18%, showcasing their growing competitiveness with organic and perovskite solar cells.

A critical barrier to widespread adoption of QDSCs is the use of toxic elements such as cadmium (Cd) and lead (Pb). Regulatory constraints and environmental impact have prompted research into cadmium-free quantum dots such as InP/ZnS, CuInS₂, and ZnSe-based systems. These QDs, while environmentally benign, typically offer lower PLQYs (photoluminescence quantum yields) and less efficient charge transport, necessitating ongoing development. Another persistent challenge is the chemical and photostability of QDs. Under illumination and air exposure, QDs can undergo photooxidation, altering their optical properties and reducing device lifetime. Surface ligand engineering, core-shell architectures, and encapsulation technologies (e.g., silica or polymer shells) are crucial to maintaining stability under operational conditions.

4.5. Hybrid Energy Systems Integrating Nanomaterials

Hybrid energy systems that integrate nanomaterials represent a transformative direction in modern energy technology, combining multiple energy harvesting and/or storage mechanisms



into a unified framework. The primary motivation for these systems lies in their ability to overcome the limitations of individual technologies by leveraging the complementary strengths of each component. Nanomaterials play a central role in enhancing the performance of hybrid systems, owing to their unique properties such as high surface area-to-volume ratios, superior electrical conductivity, tunable bandgap characteristics, and remarkable mechanical stability [57].

One of the most widely studied configurations in this domain is the battery-supercapacitor hybrid system, which aims to merge the high energy density typically associated with batteries and the high-power density and fast charge–discharge capability of supercapacitors. In such systems, nanostructured materials with both faradaic (redox-based) and capacitive behaviours are employed to bridge the performance gap. A prime example includes MnO_2 -decorated carbon nanotubes ($\text{MnO}_2@\text{CNTs}$), where the manganese dioxide component contributes pseudocapacitance via redox reactions, while the carbon nanotube matrix provides a conductive network and enhances electrochemical stability. The synergistic effect results in significantly improved energy and power densities, as well as superior cycling life. Similarly, composite materials like graphene polyaniline integrate the conductive and high-surface-area features of graphene with the pseudocapacitive properties of polyaniline, making them ideal for fast-charging, flexible power sources in electronic devices and electric vehicles.

Another significant class of hybrid energy systems involves solar–thermoelectric hybrid configurations, wherein photovoltaic (PV) cells are combined with thermoelectric generators (TEGs) to enhance the overall energy conversion efficiency. Conventional solar cells convert only a portion of incident solar energy into electricity, while a substantial fraction is dissipated as heat. This waste heat can be effectively captured and converted into additional



electrical energy through thermoelectric mechanisms. In this context, nanomaterials such as bismuth telluride (Bi_2Te_3) composites are employed to fabricate highly efficient TEGs. These materials benefit from nanoscale engineering that reduces thermal conductivity while enhancing the Seebeck coefficient, an essential factor in determining thermoelectric efficiency. For instance, a hybrid device consisting of a silicon-based solar cell coupled with a Bi_2Te_3 -based nanostructured TEG can harvest both photonic and thermal energy, significantly improving total power output. These integrated platforms are particularly promising for applications in smart buildings, off-grid power systems, and wearable electronics, where space and efficiency are critical concerns.

A rapidly advancing area within hybrid energy systems is the development of self-powered nanogenerator-based systems, which utilise ambient energy sources such as mechanical movements, vibrations, or thermal fluctuations to autonomously power devices. These systems are vital for the next generation of IoT applications and wearable health monitoring devices. Three major types of nanogenerators are commonly integrated into self-powered systems: piezoelectric, triboelectric, and pyroelectric nanogenerators. PENGs rely on materials such as ZnO nanowires or polyvinylidene fluoride (PVDF) to generate electric charges under mechanical deformation. These are often used in flexible sensors that harvest energy from human motion. TENGs, which generate power through contact electrification and electrostatic induction, often use combinations of nanostructured polydimethylsiloxane (PDMS) with materials like *PTFE* to produce electricity from sliding or tapping motions. Pyroelectric nanogenerators, on the other hand, convert temporal temperature variations into electrical output using materials like BaTiO_3 nanoparticles. These are particularly suitable for thermal sensing and energy harvesting from dynamic thermal environments.



A representative example of such a system is a wearable health-monitoring patch embedded with a ZnO-based piezoelectric nanogenerator. This device can continuously harvest biomechanical energy generated from movements such as walking, breathing, or even pulse rhythms, enabling self-sustained operation of physiological sensors without the need for external batteries. Furthermore, by integrating multiple types of nanogenerators within a single platform, hybrid self-powered systems can harvest energy from multiple ambient sources simultaneously, mechanical, thermal, and even acoustic, thus ensuring a consistent energy supply under varying environmental conditions.

4.6. Summary of Chapter

The chapter presents a detailed exploration of how nanomaterials are revolutionising energy storage and harvesting technologies by enhancing performance, efficiency, and functionality across various systems. It begins with high-efficiency batteries, including lithium-ion, solid-state, and lithium-sulfur types, where nanostructures like graphene and silicon nanowires improve capacity, charge rates, and stability. It then examines the enhancement of supercapacitors using carbon-based materials, transition metal oxides, and conducting polymers to boost energy and power densities. The chapter further discusses nanomaterials in thermoelectric energy harvesting, such as Bi_2Te_3 and Cu_2S composites for converting waste heat into usable electricity, and in photovoltaic systems, particularly perovskite and quantum dot solar cells, which offer high efficiencies, bandgap tunability, and flexible architectures. Finally, it addresses hybrid energy systems that integrate nanomaterials to combine multiple energy sources, such as battery-supercapacitor hybrids, solar, thermoelectric platforms and self-powered systems using piezoelectric and triboelectric nanogenerators. Overall, the chapter highlights the pivotal role of



nanomaterials in enabling next-generation, compact, and sustainable energy technologies for applications in wearable electronics, smart devices, and renewable energy infrastructure.

References

1. Enasel, Eduard, and Gheorghe Dumitrascu. "Storage solutions for renewable energy: A review." *Energy Nexus* (2025): 100391.
2. Su'ait, Mohd Sukor, Norasikin Ahmad Ludin, and Kamaruzaman Sopian. "Introduction to Renewable Energy Technologies and Energy Transition Strategies." *Renewable Energy Technologies and Strategies in the Global Energy Transition*. American Chemical Society, 2025. 1-14.
3. Shafik, Wasswa. "Introduction to renewable energy technologies." *Soft computing in renewable energy technologies*. CRC Press, 2024. 1-31.
4. Bazmi, Aqeel Ahmed, and Gholamreza Zahedi. "Sustainable energy systems: Role of optimization modeling techniques in power generation and supply—A review." *Renewable and sustainable energy reviews* 15.8 (2011): 3480-3500.
5. Bhushan, Brij, and Arunima Nayak. "Application of green nanomaterials for sustainable energy systems: A review of the current status." *Biofuel Technologies for a Sustainable Future: India and Beyond* (2023): 25-50.
6. Chen, Jun, et al. "Functional nanomaterials for sustainable energy technologies." *Journal of Nanomaterials* 2016.2 (2016): 2606459.
7. Serrano, Elena, Guillermo Rus, and Javier Garcia-Martinez. "Nanotechnology for sustainable energy." *Renewable and Sustainable Energy Reviews* 13.9 (2009): 2373-2384.
8. Gohar, O.; Zubair Khan, M.; Bibi, I.; Bashir, N.; Tariq, U.; Bakhtiar, M.; Ramzan Abdul Karim, M.; Ali, F.; Bilal Hanif, M.; Motola, M. *Nanomaterials for Advanced Energy Applications: Recent Advancements and Future Trends*. Mater. Des. 2024, 241, 112930.
9. Kumar, Yedluri Anil, et al. "Revolutionizing energy storage: exploring the nanoscale frontier of all-solid-state batteries." *Dalton Transactions* 53.30 (2024): 12410-12433.
10. Naik, Yashwanth Venkatraman. "Future Perspectives and Emerging Trends in Nanomaterials for Energy Storage." *Advanced Nanomaterials for Energy Storage Devices* (2024): 183-195.
11. Zhang, Qifeng, et al. "Nanomaterials for energy conversion and storage." *Chemical Society Reviews* 42.7 (2013): 3127-3171.
12. Liu, Fangyan, et al. "Advances of nanomaterials for high-efficiency Zn metal anodes in aqueous zinc-ion batteries." *ACS nano* 18.25 (2024): 16063-16090.
13. Hussein, Hala S. "The state of the art of nanomaterials and its applications in energy saving." *Bulletin of the National Research Centre* 47.1 (2023): 7.
14. Nayak, Prasant Kumar, et al. "From lithium-ion to sodium-ion batteries: advantages, challenges, and surprises." *Angewandte Chemie International Edition* 57.1 (2018): 102-120.



15. Chen, Rusong, et al. "Approaching practically accessible solid-state batteries: stability issues related to solid electrolytes and interfaces." *Chemical reviews* 120.14 (2019): 6820-6877.
16. Alsaç, Elif Pınar, et al. "Characterizing electrode materials and interfaces in solid-state batteries." *Chemical Reviews* 125.4 (2025): 2009-2119.
17. Feng, Wuliang, Yufeng Zhao, and Yongyao Xia. "Solid interfaces for the garnet electrolytes." *Advanced Materials* 36.15 (2024): 2306111.
18. Qian, Lanting, et al. "Advanced Material Engineering to Tailor Nucleation and Growth towards Uniform Deposition for Anode-Less Lithium Metal Batteries." *Small* 18.50 (2022): 2205233.
19. Li, Tao, et al. "A comprehensive understanding of lithium–sulfur battery technology." *Advanced Functional Materials* 29.32 (2019): 1901730.
20. Seh, Zhi Wei, et al. "Designing high-energy lithium–sulfur batteries." *Chemical society reviews* 45.20 (2016): 5605-5634.
21. Yang, Jie, et al. "Emerging Roles of Silicon-Based Materials in Advanced Composite Solid-State Electrolytes for Lithium Batteries: From Silicates to Silanes." *Small* (2025): e08761.
22. Saidi, Norshahirah Mohamad, et al. "Advancements in silicon anodes for enhanced lithium-ion batteries performance: innovations toward next-gen superbatteries." *Battery Energy* (2025): e20240048.
23. Sada, Krishnakanth, Joe Darga, and Arumugam Manthiram. "Challenges and prospects of sodium-ion and potassium-ion batteries for mass production." *Advanced Energy Materials* 13.39 (2023): 2302321.
24. Muldoon, John, Claudiu B. Bucur, and Thomas Gregory. "Quest for nonaqueous multivalent secondary batteries: magnesium and beyond." *Chemical reviews* 114.23 (2014): 11683-11720.
25. Kumar, Niraj, et al. "Recent advanced supercapacitor: a review of storage mechanisms, electrode materials, modification, and perspectives." *Nanomaterials* 12.20 (2022): 3708.
26. Yaseen, Muhammad, et al. "A review of supercapacitors: materials design, modification, and applications." *Energies* 14.22 (2021): 7779.
27. Obreja, Vasile VN. "Supercapacitors based on carbon nanomaterials." *Carbon Nanomaterials for Advanced Energy Systems: Advances in Materials Synthesis and Device Applications* (2015): 295-337.
28. Sun, Jinfeng, et al. "One-dimensional nanostructured pseudocapacitive materials: design, synthesis and applications in supercapacitors." *Batteries & Supercaps* 2.10 (2019): 820-841.
29. Sun, Jinfeng, et al. "Recent progresses in high-energy-density all pseudocapacitive-electrode-materials-based asymmetric supercapacitors." *Journal of Materials Chemistry A* 5.20 (2017): 9443-9464.
30. Hu, Minmin, et al. "Emerging 2D MXenes for supercapacitors: status, challenges and prospects." *Chemical Society Reviews* 49.18 (2020): 6666-6693.
31. Forouzandeh, Parnia, and Suresh C. Pillai. "MXenes-based nanocomposites for supercapacitor applications." *Current Opinion in Chemical Engineering* 33 (2021): 100710.



32. Frackowiak, Elzbieta, et al. "Supercapacitors based on conducting polymers/nanotubes composites." *Journal of Power Sources* 153.2 (2006): 413-418.
33. Chatterjee, Dhruva P., and Arun K. Nandi. "A review on the recent advances in hybrid supercapacitors." *Journal of Materials Chemistry A* 9.29 (2021): 15880-15918.
34. Sun, Zhumei, et al. "A novel ϵ -MnO₂/MXene composite as an electrode with excellent conductivity and ultrahigh capacitive deionization." *Separation and Purification Technology* 347 (2024): 127520.
35. Yaqoob, Lubna, Tayyaba Noor, and Naseem Iqbal. "An overview of supercapacitors electrode materials based on metal organic frameworks and future perspectives." *International Journal of Energy Research* 46.4 (2022): 3939-3982.
36. Vijayakanth, Thangavel, et al. "Perspectives on recent advancements in energy harvesting, sensing and bio-medical applications of piezoelectric gels." *Chemical Society Reviews* 52.17 (2023): 6191-6220.
37. Wang, Zhong Lin, and Jinhui Song. "Piezoelectric nanogenerators based on zinc oxide nanowire arrays." *Science* 312.5771 (2006): 242-246.
38. Wang, Yuan, Laipan Zhu, and Cuifeng Du. "Progress in piezoelectric nanogenerators based on PVDF composite films." *Micromachines* 12.11 (2021): 1278.
39. Wu, Changsheng, et al. "Triboelectric nanogenerator: a foundation of the energy for the new era." *Advanced Energy Materials* 9.1 (2019): 1802906.
40. Shi, Qiongfeng, Tianyi He, and Chengkuo Lee. "More than energy harvesting—Combining triboelectric nanogenerator and flexible electronics technology for enabling novel micro-/nano-systems." *Nano Energy* 57 (2019): 851-871.
41. Rahman, Mustafizur, et al. "Nanotechnology and thermodynamics: a comprehensive review." *Nanomaterials and Energy* (2025): 1-26.
42. Al-Fartoos, Mustafa Majid Rashak, et al. "Advancing thermoelectric materials: a comprehensive review exploring the significance of one-dimensional nano structuring." *Nanomaterials* 13.13 (2023): 2011.
43. Jia, Shiyu, et al. "Thermoelectric materials and devices for advanced biomedical applications." *Small* 20.51 (2024): 2405019.
44. Zhou, Hong, et al. "Integrative plasmonics: optical multi-effects and acoustoelectric-thermal fusion for biosensing, energy conversion, and photonic circuits." *Chemical Society Reviews* (2025).
45. Chen, Guanying, et al. "Nanochemistry and nanomaterials for photovoltaics." *Chemical Society Reviews* 42.21 (2013): 8304-8338.
46. Beeby, Stephen P., and Terence O'Donnell. "Electromagnetic energy harvesting." *Energy Harvesting Technologies* (2009): 129-161.
47. Zhang, Xu, et al. "Opportunities and challenges of ambient radio-frequency energy harvesting." *Joule* 4.6 (2020): 1148-1152.
48. Huang, Ya, et al. "Scalable manufacturing and applications of nanofibers." *Materials Today* 28 (2019): 98-113.



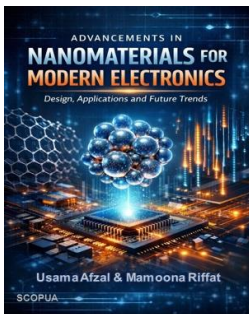
49. Yu, Seung Jung, et al. "Initiated chemical vapor deposition: a versatile tool for various device applications." *Advanced Engineering Materials* 20.3 (2018): 1700622.
50. Huang, Tao-Tse, and Wenzhuo Wu. "Scalable nanomanufacturing of inkjet-printed wearable energy storage devices." *Journal of Materials Chemistry A* 7.41 (2019): 23280-23300.
51. Nassar, Kais Iben, Sílvia Soreto Teixeira, and Manuel PF Graça. "Sol-gel-synthesized metal oxide nanostructures: advancements and prospects for spintronic applications—a comprehensive review." *Gels* 11.8 (2025): 657.
52. Aftab, Sikandar, et al. "Perovskite Quantum Dots: Fabrication, Degradation, and Enhanced Performance Across Solar Cells, Optoelectronics, and Quantum Technologies." *Carbon Energy* (2025): e70018.
53. Tang, Guanqi, et al. "A Review on recent advances in flexible perovskite solar cells." *Solar RRL* 9.5 (2025): 2400844.
54. Baloch, Ahmer AB, et al. "Practical efficiency limit of methylammonium lead iodide perovskite (CH₃NH₃PbI₃) solar cells." *The journal of physical chemistry letters* 9.2 (2018): 426-434.
55. Maietta, Immacolata, et al. "The toxicity of lead and lead-free perovskite precursors and nanocrystals to human cells and aquatic organisms." *Advanced Science* 12.13 (2025): 2415574.
56. Pan, Zhenxiao, et al. "Quantum dot-sensitized solar cells." *Chemical Society Reviews* 47.20 (2018): 7659-7702.
57. Wang, Xudong, et al. "One-dimensional titanium dioxide nanomaterials: nanowires, nanorods, and nanobelts." *Chemical reviews* 114.19 (2014): 9346-9384.



CHAPTER 5

FLEXIBLE, WEARABLE AND STRETCHABLE ELECTRONICS

MAMOONA RIFFAT ^{1*}



Book Title

Advancements in Nanomaterials for Modern Electronics:
Design, Applications and Future Trends

Series Title

Books of Research Collection

Published On

January 02, 2026 (Edition 1)

Publisher

Scientific Collaborative Online Publishing Universal
Academy, Lahore, Pakistan

DOI: <https://doi.org/10.64060/978-627-7898-01-4-5>

Book ISBN: 978-627-7898-01-4

THIS WORK IS LICENSED UNDER A CREATIVE COMMONS ATTRIBUTION NONCOMMERCIAL
NODERIVATIVES 4.0 INTERNATIONAL LICENSE. SCOPUA (SCIENTIFIC COLLABORATIVE ONLINE
PUBLISHING UNIVERSAL ACADEMY) PUBLISHER REMAINS NEUTRAL REGARDING JURISDICTIONAL
CLAIMS IN PUBLISHED MAPS AND INSTITUTIONAL AFFILIATIONS.

¹Department of Physics, LUT school of Engineering Science, Lappeenranta-Lahti
University of Technology, Finland.

*Corresponding: mamoonna.riffat@lut.fi (M. Riffat)

Abstract

The rapid evolution of nanotechnology has propelled the development of flexible, wearable, and stretchable electronics that seamlessly integrate with human life and the environment. These technologies are redefining modern electronics through their lightweight, conformable, and multifunctional characteristics. By leveraging advanced nanomaterials such as graphene, carbon nanotubes, MXenes, silver nanowires, and transition metal dichalcogenides, these systems enable unprecedented performance in displays, sensors, biointerfaces, and smart textiles. The chapter explores recent advancements in material design, device fabrication, and application strategies that enhance durability, sensitivity, and comfort while maintaining electrical integrity under strain. It highlights innovations in flexible healthcare biosensors, stretchable microelectrode arrays, smart garments, and protective nano-coatings. The integration of nanomaterials with advanced fabrication techniques such as direct-ink-writing, electrospinning, and atomic layer deposition has opened pathways for next-generation electronic systems. These developments not only drive progress in healthcare, soft robotics, and environmental sensing but also shape the foundation for sustainable and intelligent human–machine interactions.

Keywords: *Flexible Electronics; Healthcare Monitoring; Nanomaterials; Stretchable Devices; Smart Textiles; Wearable Sensors*

5.1. Introduction

The ongoing miniaturisation of devices and systems demands advanced capabilities to measure, organise, and manipulate matter at the nanoscale (1–100 nm). In nanoelectronics, device dimensions are often a thousand times smaller than in traditional microelectronics. This transition is not just about shrinking size; it introduces fundamentally new physical phenomena, primarily governed by quantum mechanics, which dominate behaviour at the nanoscale. Nanoelectronics represents the convergence of disciplines like physics, chemistry, biology, materials science, and engineering, leading to the rise of nanotechnology. Innovations at this scale allow control of matter atom-by-atom and molecule-by-molecule, offering new functionalities and properties.



One key driver of nanoelectronic development is the insatiable demand for faster, smaller, and more efficient information and communication technologies. This demand has historically followed Moore's Law, which observes that integrated circuit complexity doubles approximately every two years. To meet the performance demands of nanoelectronic devices, it's crucial to understand material-specific limitations such as electron mobility and electric field tolerance. While silicon remains the backbone of electronics, compound semiconductors like III–V materials (e.g., AlGaAs) and alloys like SiGe allow tailored electronic properties.

A significant advancement in nanoelectronics is using heterostructures of multilayered materials with abrupt interfaces between different semiconductors to enable the quantum confinement of electrons. These heterostructures can be engineered to nanometer precision, giving rise to quantum wells (2D), quantum wires (1D), and quantum dots (0D), where electron motion is confined in two, one, or zero dimensions, respectively. These low-dimensional quantum structures can fundamentally manipulate electron behaviour and properties, opening revolutionary possibilities in nanoelectronic devices and systems. When electrons pass through a tiny hole, like in a nanoscale transistor, they do not simply travel in straight lines but instead exhibit diffraction, a wave-like behaviour. This highlights the necessity of accounting for the wave properties of electrons in nanoelectronic devices, especially at such small dimensions.

Flexible, wearable, and stretchable electronics have emerged at the frontier of next-generation technologies that bridge materials science, bioengineering, and electronics. With the increasing demand for devices that are lightweight, unobtrusive, and conformable to dynamic surfaces such as human skin or fabric, the role of nanomaterials has become pivotal. This chapter explores recent advancements in nanomaterial-based systems that enable



flexible displays, healthcare monitoring, stretchable sensors, wearable electronics, and advanced nano-coatings.

5.2. Nanomaterials in Flexible Displays, OLEDs, and Transparent Electronics

Flexible displays and organic light-emitting diodes (OLEDs) have transformed the consumer electronics industry by enabling bendable smartphones, rollable TVs, and wearable screens. Nanomaterials such as graphene, carbon nanotubes (CNTs), silver nanowires (AgNWs), and transition metal dichalcogenides (TMDs) are central to this innovation.

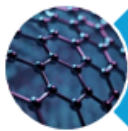
Stretchable and free-form displays are essential for the next generation of electronic devices, with applications ranging from wearable tech and biomedical devices to IoT and soft robotics. Unlike traditional flexible displays, stretchable displays must endure complex deformations, including stretching, bending, and adapting to 3D surfaces (e.g., human skin), without compromising performance [1]. These properties make them ideal for real-time health monitoring, bright clothing, and implantable devices. To achieve true stretchability, displays must maintain image quality and electrical performance under at least 30% strains. Two main strategies have been developed:

1. **Intrinsically Stretchable Displays:** All components (electrodes, emissive layers, etc.) are made from stretchable materials, often polymer-based OLEDs.
2. **Structurally Stretchable Displays:** Rigid materials are integrated into stretchable designs (e.g., buckled, island–bridge structures) to accommodate deformation. While offering material flexibility, these designs still require some strain-tolerant materials.

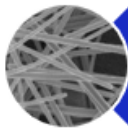
Nanomaterials play a crucial role in both approaches due to their high strain tolerance and reduced mechanical stiffness at



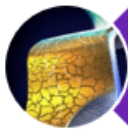
nanoscale dimensions [1],[2]. Organic light-emitting diodes (OLEDs) are promising candidates for flexible and wearable displays due to their ultrathin structure, self-emissive properties, and compatibility with low-temperature fabrication on plastic substrates. However, their commercialisation faces key challenges in transparent electrodes and encapsulation systems that impact device reliability and durability. Conventional OLEDs use Indium Tin Oxide (ITO), which is brittle and prone to cracking under strain when deposited on flexible plastic substrates [3]. Alternatives to ITO include carbon nanotubes, graphene, thin metal films, metal nanowires, and metal nanomeshes (Figure 5.1).



Carbon nanotubes and graphene have high sheet resistance.



Nanowires and nanomeshes may have electrical voids.



Thin metal films offer low resistance and high optical transparency, especially when combined with dielectric layers in dielectric/metal/dielectric (DMD) structures.



Silver (Ag) is commonly used due to its excellent conductivity and low optical loss.

Figure 5.1: *Materials alternative to Indium Tin Oxide.*

- Encapsulation:
 - OLEDs are highly sensitive to moisture, making robust encapsulation essential for flexible applications.



- Glass-lid encapsulation is adequate but not suitable for flexible configurations, requiring the development of thin-film encapsulation methods that are both flexible and impermeable [3].
- Technological Advances:
 - Recent developments in structural designs aim to enhance flexibility and reliability by improving electrode materials and encapsulation layers.
 - Emerging substrates (e.g., fabric or fibre for wearable OLEDs) are being explored to expand application possibilities in next-generation displays [3].

A recent study introduced OLEDs with a neutral-axis mechanical design, achieving 3.3% strain tolerance and stable luminance over prolonged use. This advance allows displays to endure daily wear-and-tear without performance degradation [4]. Researchers developed biodegradable and transparent OLEDs using cellulose nanocrystal membranes and graphene electrodes. This innovation combines sustainability with advanced display performance [5]. Transparent electronics, including flexible touch panels and smart windows, leverage these nanomaterials for enhanced transparency, conductivity, and flexibility. Roll-to-roll processing of nanomaterial inks has also emerged, supporting large-scale, cost-effective manufacturing.

5.3. Advancements in Flexible Electronics for Healthcare Applications

The integration of flexible electronics into medical devices has unlocked new possibilities for real-time physiological monitoring, early disease detection, and personalised healthcare. These systems conform to the body's surface and maintain intimate skin contact, crucial for high-fidelity signal acquisition [6]. Conventional electrical systems cannot be used in applications that



need to adjust complicated surfaces and movements because of their rigidity. Stretchable, foldable, and lightweight gadget components are made possible by flexible electronics, which provide a solution. These developments are beneficial in the healthcare industry, where the move to digital health, which includes telemedicine and remote patient monitoring, requires wearable technology that is discreet, pleasant, and able to monitor patients continuously [7]. Concepts like "fit and forget" or "always-on monitoring" are key to improving patient compliance, and flexible electronics are well-suited for integration into skin patches, bright clothing, and implantable devices [8].

This growing integration of electronics and healthcare is already evident in applications like electronic skin patches for cardiovascular and motion monitoring, e-textiles for biometric tracking, and electrochemical test strips for decentralised diagnostics [9]. While flexible electronics also show potential in innovative packaging for medication adherence, adoption in healthcare remains limited due to regulatory and infrastructure challenges [10]. Flexible Pressure Sensors using CNTs, MXenes, and conductive hydrogels with high sensitivity and stretchability. These are vital for monitoring blood pressure, respiration, and motion [11]. There is recent progress on 2D Materials for Biomedical Electrodes, where thin materials like MoS₂ and h-BN offer tunable conductivity and biocompatibility, enabling conformable bioelectrodes [12]. There are Wearable Biosensors, like Flexible glucose, lactate, and cortisol sensors integrated with wireless modules are entering clinical trials, bringing lab-quality diagnostics to the home [13]. Combined with AI-based analytics, these wearable systems are shaping the future of precision medicine.



5.4. Stretchable Circuits and Sensors: Key Materials and Innovations

Stretchable electronic devices are emerging as crucial technologies for next-generation wearable systems, offering advantages like conformability to complex 3D surfaces (e.g., human skin), enhanced comfort, and adaptability [14]. These systems find applications in health monitoring, soft robotics, bright clothing, and flexible displays [13],[14]. To create stretchable circuits, researchers focus on developing flexible substrates, stretchable electrodes, functional components, and packaging. A key challenge is maintaining electrical conductivity under mechanical strain, which is being addressed through novel materials (like liquid metals, conductive textiles, and printable conductive inks) and structural designs (e.g., 3D spring structures). Additionally, interface engineering and rigid island strategies are being used to integrate traditional rigid components into stretchable systems while minimising mechanical failure.

Despite significant progress, challenges remain in scalability, integration, power supply, and data transmission. Liquid metals offer high conductivity and stretchability, but they face issues such as incompatibility with traditional PCB processes and sensitivity to heat [15]. Structural designs using traditional metals provide better integration but lack high stretchability. Advanced substrate treatments and mechanical isolation of rigid elements enhance stability and durability but may compromise comfort. To fully realise the potential of stretchable electronics, future research must address miniaturisation, manufacturing scalability, self-powered systems, and reliable wireless communication. If these challenges are successfully addressed, then widespread adoption in healthcare, consumer electronics, and beyond will become possible.



5.4.1 Emerging Technologies

- **Direct-Ink-Writing Strain Sensors**

Direct-ink-writing (DIW) 3D-printed sensors hold significant promise due to their customizable structures, simplified fabrication, and potential applications in fields like structural health monitoring, wearable electronics, and harsh environment sensing. However, their long-term stability and durability remain significant obstacles to real-world application. These challenges come from environmental stresses, mechanical fatigue, and inconsistencies in materials and fabrication. Strategies to address them include developing advanced inks with enhanced mechanical and electrical properties, optimising sensor structures to reduce stress concentrations, and improving encapsulation and interlayer bonding. Additionally, refining the printing process, such as controlling rheology, nozzle speed, air pressure, and curing conditions, is essential for minimising defects and enhancing sensor performance. Future directions focus on establishing standardised testing protocols for long-term performance, integrating DIW with other technologies (e.g., AI, machine learning, and intelligent control systems), and extending applications across extreme environments. Standardisation will enable better assessment and comparability of sensor durability, while technological integration can optimise design and manufacturing accuracy. DIW sensors are for widespread use in conventional, industrial, and extreme environments; however, further interdisciplinary research and innovation are required to fully address durability limitations and unlock their full potential in practical and commercial applications [16].

- **Stretchable Microelectrode Arrays (sMEAs)**

The Recent advances in stretchable multiple electrode arrays (MEAs) for neuroscience have focused on their role in studying neuron-motor systems through high-resolution electrical signal detection. While MEAs offer powerful insights, mechanical



mismatches with biological tissues pose challenges for their long-term use, including tissue damage and device failure. Minimising device thickness improves compatibility but limits stretchability, which is essential for dynamic organs. The development of stretchable MEAs strikes a balance between mechanical flexibility and electrical performance, with applications in both on-skin and implantable contexts [17].

These devices are pivotal for human-machine interfaces, soft robotics, and electronic skins. Direct-ink-writing (DIW) strain sensors provide customizable, high-resolution patterning on flexible substrates, enabling the precise detection of mechanical deformations, such as bending, stretching, and pressure. Their tunable mechanical and electrical properties make them ideal for conformal integration with dynamic surfaces, which is crucial in wearable electronics and responsive robotic systems. Meanwhile, stretchable MEAs enable high-fidelity recording and stimulation of bioelectrical signals, allowing for real-time neural interfacing and feedback control in prosthetics and neurorehabilitation devices. Together, these technologies bridge the gap between rigid electronics and the soft, complex architecture of biological systems.

5.5. Smart Clothing and Wearable Devices Powered by Nanomaterials

Smart textiles integrate electronic functions directly into fabrics, allowing real-time sensing, communication, and energy harvesting. Nanomaterials contribute significantly by offering lightweight, flexible, and conductive pathways.

Nanomaterials, such as silver nanoparticles, TiO_2 , ZnO , carbon nanotubes, graphene, and MXenes, have been integrated into fabrics to impart properties including antimicrobial activity, UV protection, electrical conductivity, hydrophobicity, and flame retardancy [18],[19]. More importantly, these materials enable



wearable textiles to sense, store, and harvest energy from the body and its environment using technologies such as piezoelectric, triboelectric, and thermoelectric nanogenerators, supercapacitors, and biofuel cells. Smart garments can monitor physiological signals, power embedded electronics, and even display dynamic visual content using integrated OLEDs, sensors, and photonic fibres. Fabrication techniques such as electrospinning, direct ink writing, and fibre drawing enable the seamless integration of nanodevices without compromising comfort or flexibility. However, challenges like durability, washability, wearer comfort, and nanotoxicity remain [20]. Smart textiles embed sensors and circuits directly into the fabric, eliminating the need for bulky hardware. These systems are applied across various sectors, including healthcare, defence, sports, and fashion, enabling functionalities such as physiological monitoring, energy harvesting, environmental sensing, heating, lighting, and communication. Nanomaterials such as Ag, ZnO, TiO₂, and graphene enhance properties like antimicrobial resistance, UV protection, conductivity, and self-cleaning [21]. Advances in conductive inks, fibre-based electronics, and digital fabrication methods (e.g., 3D printing, embroidery, and inkjet printing) have propelled their development. Despite promising applications, environmental and health concerns related to nanomaterial leaching and e-waste require attention. Future smart e-textiles are expected to support the Internet of Things (IoT), AI, 5G, and sustainable technologies, offering transformative potential in personalised medicine, human-machine interaction, and wearable computing [22].

The advancement of wearable electronics has led to an investigation into piezoelectric nanofibers, particularly for self-powered sensing and energy-harvesting applications. These fibres can conform to human skin or clothing, enabling the detection of physiological signals (e.g., pulse, joint movement) without the need



for external power sources [23]. The useful techniques in these aspects are shown in Figure 5.2.

Advances in fibre alignment, composite design, and textile integration have improved signal detection and multifunctionality (e.g., acoustic, thermal, and luminous sensing). Despite progress, challenges persist in achieving seamless integration of nanofiber sensors into authentic textiles, primarily due to issues such as encapsulation, wearability, and system complexity. These developments position piezoelectric nanofibers as crucial elements for next-generation wearable pressure sensors and Internet of Medical Things (IoMT) systems [23].

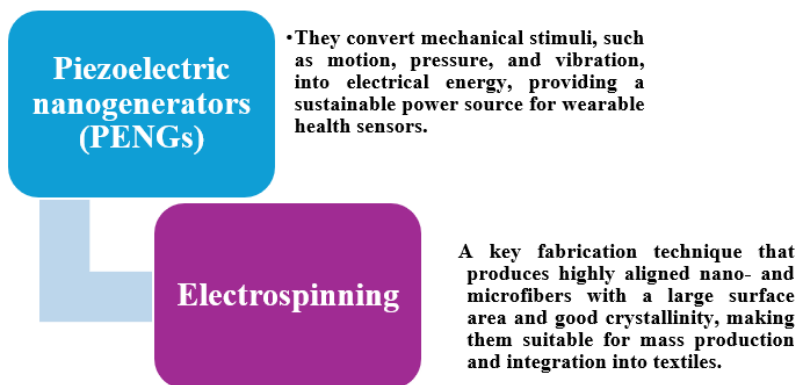


Figure 5.2: Two techniques for self-powered sensing and energy-harvesting applications.

5.6. Development of Nano-Coatings and Thin Films for Flexible Electronics

The reliability and performance of flexible electronics often hinge on surface engineering. Nano-coatings and thin films enhance durability, conductivity, and sensitivity while protecting components from environmental damage. Flexible electronics are transforming modern technology by enabling applications such as wearable devices, e-skins, intelligent textiles, and foldable displays.



A crucial aspect of these systems is the integration of flexible, transparent electrodes, which must balance mechanical flexibility, characterised by thinness and small bending radii, with high electrical performance. Various approaches to flexibility have been explored, including rigid islands with springs, intrinsically stretchable materials, and ultra-thin films on elastomers, with the latter offering a good compromise between flexibility and electronic performance. Thin-film transistors (TFTs), essential components of flexible electronics, have been developed using various semiconductor materials, including low-temperature polycrystalline silicon (LTPS), amorphous oxide semiconductors, carbon nanotubes (CNTs), and organic semiconductors. Each material presents trade-offs in mobility, processing temperature, stability, and mechanical properties. LTPS offers high mobility but requires higher processing temperatures. Oxide semiconductors provide good uniformity but lower ON/OFF ratios. CNTs and organic semiconductors offer transparency and flexibility but face issues with uniformity and long-term stability. The development of flexible, transparent electrodes remains central to the advancement of thin, conformal, and high-performance flexible electronics [24]. There are Hydrophobic and Antimicrobial Nano-Coatings which protect electronics in humid or biomedical environments. The emergence of antibiotic resistance has driven the search for alternative antimicrobial strategies, with nanomaterials offering promising solutions due to their high surface reactivity and multi-mechanism antimicrobial action. In nanoelectronics, hydrophobic antimicrobial Coatings are increasingly vital for reducing microbial contamination on surfaces that are prone to contact, such as touchscreens, sensors, medical devices, and implantable electronics. Nanostructures such as nanoparticles, nanowires, nanotubes, and nanofibers made from silver, copper, zinc oxide, and other materials have been effectively integrated into coatings to inhibit bacteria, viruses, and, to a lesser extent, fungi. These coatings can



be embedded into matrices, deposited via techniques like electrospinning or sonochemistry, or applied as thin films. Importantly, their hydrophobic nature helps repel moisture and biofilms, enhancing surface hygiene and preventing microbial adhesion. Studies show that coatings with slow-release antimicrobial action or stable surface-bound activity maintain efficacy over time and through repeated use, which is essential for wearable or implantable nanoelectronic devices [25].

Moreover, Thin-film sensors, especially those based on materials like SnO_2 with microstructure palladium (Pd) islands, exhibit strong potential due to their high sensitivity (25–250 ppm), fast response times, and selectivity against gases such as CO and NH_3 . These sensors can be fabricated via advanced microelectronic techniques and incorporated into wearable formats. For wearable applications, these hydrogen sensing films must be not only accurate and rapid but also durable, stable under environmental fluctuations, and capable of operating with low power consumption. Advanced fabrication methods, such as electrospinning and thin-film deposition, enable integration onto flexible substrates, making them ideal for leak detection in dynamic and high-risk environments. In addition to this, the integration with wireless networks and AI-driven diagnostics enhances their capability for remote monitoring and predictive maintenance, especially in hydrogen storage, transportation, and fuel cell systems [26]. Techniques like atomic layer deposition (ALD), spray coating, and inkjet printing enable fine control over film thickness and composition [27],[28].

5.6. Conclusion

Flexible, wearable, and stretchable electronics are entering a new era driven by nanomaterials, advanced fabrication techniques, and multi-functional designs. From rollable OLEDs to biosensing



fabrics and recyclable circuits, the synergy between material science and engineering is reshaping how we interact with technology. The progress reviewed in this chapter highlights not just scientific achievement but also a pathway toward sustainable, personalised, and intelligent electronics for everyday use. These electronics based on nanomaterials have revolutionised the way electronic systems interact with our bodies and the world around us. Thanks to their soft, lightweight, and adaptable materials, these devices have opened exciting possibilities in areas such as health monitoring, human-machine interaction, soft robotics, bright clothing, and environmental sensing. The development of sensitive, skin-friendly, long-lasting gadgets that can bend, stretch, and twist while still performing dependably has been made possible by advancements in materials science, nanotechnology, and fabrication techniques. However, there are still significant obstacles to going past. Manufacturing costs, power efficiency, long-term durability, and large-scale production remain significant obstacles. At the same time, researchers are working to improve comfort, functionality, and environmental impact, key goals for the next wave of innovations. Looking ahead, the future of this field will be shaped by the integration of flexible electronics with technologies like artificial intelligence, wireless power, biodegradable materials, and advanced manufacturing.

These developments could lead to innovative devices that respond in real time to a person's health or surroundings. As technology matures, its impact is expected to extend far beyond wearables, reaching into fields such as space exploration, personalised medicine, and national defence. Flexible, wearable, and stretchable electronics have the potential to significantly improve daily living and spur future advancements through sustained interdisciplinary collaboration and a deliberate approach to invention.



References

1. Y. Lee, W. Guan, E. Y. Hsieh, and S. Nam, "Opportunities for Nanomaterials in Stretchable and Free-Form Displays," *Small Science*, vol. 4, no. 3, 2024, doi: 10.1002/smssc.202470008.
2. Y. Lee, W. Guan, E. Y. Hsieh, and S. W. Nam, "Opportunities for Nanomaterials in Stretchable and Free-Form Displays," 2024. doi: 10.1002/smssc.202300143.
3. S. M. Lee, J. H. Kwon, S. Kwon, and K. C. Choi, "A Review of Flexible OLEDs Toward Highly Durable Unusual Displays," 2017. doi: 10.1109/TED.2017.2647964.
4. J. Lee, C. Y. Gu, J. Chang, E. H. Cho, T. S. Kim, and K. C. Choi, "Analytic modeling and validation of strain in textile-based OLEDs for advanced textile display technologies," *npj Flexible Electronics*, vol. 8, no. 1, Dec. 2024, doi: 10.1038/s41528-024-00361-9.
5. B. Kulyk et al., "Flexible OLEDs with graphene electrodes on renewable cellulose platforms," *J Mater Chem C Mater*, Feb. 2025, doi: 10.1039/d4tc05137h.
6. D. H. Kim, R. Ghaffari, N. Lu, and J. A. Rogers, "Flexible and stretchable electronics for biointegrated devices," 2012. doi: 10.1146/annurev-bioeng-071811-150018.
7. H. Jin et al., "Nanosensor-based flexible electronic assisted with light fidelity communicating technology for volatolomics-based telemedicine," *ACS Nano*, vol. 14, no. 11, 2020, doi: 10.1021/acsnano.0c06137.
8. K. Xu, Y. Lu, and K. Takei, "Multifunctional Skin-Inspired Flexible Sensor Systems for Wearable Electronics," 2019. doi: 10.1002/admt.201800628.
9. Y. J. Hong, H. Jeong, K. W. Cho, N. Lu, and D. H. Kim, "Wearable and Implantable Devices for Cardiovascular Healthcare: from Monitoring to Therapy Based on Flexible and Stretchable Electronics," 2019. doi: 10.1002/adfm.201808247.
10. D. Corzo, G. Tostado-Blázquez, and D. Baran, "Flexible Electronics: Status, Challenges and Opportunities," *Frontiers in Electronics*, vol. 1, 2020, doi: 10.3389/felec.2020.594003.
11. Y. Lu et al., "Highly Stretchable, Elastic, and Sensitive MXene-Based Hydrogel for Flexible Strain and Pressure Sensors," *Research*, vol. 2020, 2020, doi: 10.34133/2020/2038560.
12. J. Uddin et al., "Progress in Electronic, Energy, Biomedical and Environmental Applications of Boron Nitride and MoS₂ Nanostructures," 2024. doi: 10.3390/mi15030349.
13. S. Kaur, N. Gupta, and B. D. Malhotra, "Recent developments in wearable & non-wearable point-of-care biosensors for cortisol detection," 2023. doi: 10.1080/14737159.2023.2184260.
14. Y. J. Jo, J. Ok, S. Y. Kim, and T. il Kim, "Stretchable and Soft Organic-Ionic Devices for Body-Integrated Electronic Systems," 2022. doi: 10.1002/admt.202001273.
15. S. Chen et al., "Ultrahigh Strain-Insensitive Integrated Hybrid Electronics Using Highly Stretchable Bilayer Liquid Metal Based Conductor," *Advanced Materials*, vol. 35, no. 5, 2023, doi: 10.1002/adma.202208569.



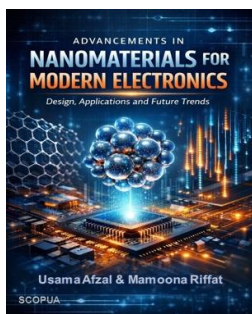
16. Y. Zhao et al., “Long-term stability and durability of direct-ink-writing 3D-printed sensors: challenges, strategies and prospects,” 2025, Taylor and Francis Ltd. doi: 10.1080/17452759.2025.2460211.
17. Z. Jiang, M. Zhu, and X. Chen, “Interfacing Neuron-Motor Pathways with Stretchable and Biocompatible Electrode Arrays,” *Acc Chem Res*, vol. 57, no. 16, pp. 2255–2266, Aug. 2024, doi: 10.1021/acs.accounts.4c00215.
18. H. Kim and J. H. Ahn, “Graphene for flexible and wearable device applications,” *Carbon N Y*, vol. 120, 2017, doi: 10.1016/j.carbon.2017.05.041.
19. Q. Liu, J. Chen, Y. Li, and G. Shi, “High-Performance Strain Sensors with Fish-Scale-Like Graphene-Sensing Layers for Full-Range Detection of Human Motions,” *ACS Nano*, vol. 10, no. 8, 2016, doi: 10.1021/acsnano.6b03813.
20. M. A. Shah, B. M. Pirzada, G. Price, A. L. Shibiru, and A. Qurashi, “Applications of nanotechnology in smart textile industry: A critical review,” 2022. doi: 10.1016/j.jare.2022.01.008.
21. W. Seung et al., “Nanopatterned textile-based wearable triboelectric nanogenerator,” *ACS Nano*, vol. 9, no. 4, 2015, doi: 10.1021/nn507221f.
22. B. Younes, “Smart E-textiles: A review of their aspects and applications,” 2023. doi: 10.1177/15280837231215493.
23. C. Zhi, S. Shi, Y. Si, B. Fei, H. Huang, and J. Hu, “Recent Progress of Wearable Piezoelectric Pressure Sensors Based on Nanofibers, Yarns, and Their Fabrics via Electrospinning,” 2023. doi: 10.1002/admt.202201161.
24. M. J. Mirshojaeian Hosseini and R. A. Nawrocki, “A review of the progress of thin-film transistors and their technologies for flexible electronics,” *Micromachines (Basel)*, vol. 12, no. 6, 2021, doi: 10.3390/mi12060655.
25. A. Ivask, M. Ahonen, and K. Kogermann, “Antimicrobial Nano Coatings,” 2022. doi: 10.3390/nano12234338.
26. S. K. Menon, A. Kumar, and S. Mondal, “Advancements in hydrogen gas leakage detection sensor technologies and safety measures,” *Clean Energy*, vol. 9, no. 1, pp. 263–277, Jan. 2025, doi: 10.1093/ce/zkae122.
27. J. Zhang, Y. Li, K. Cao, and R. Chen, “Advances in Atomic Layer Deposition,” 2022. doi: 10.1007/s41871-022-00136-8.
28. O. Assad, A. M. Leshansky, B. Wang, T. Stelzner, S. Christiansen, and H. Haick, “Spray-coating route for highly aligned and large-scale arrays of nanowires,” *ACS Nano*, vol. 6, no. 6, 2012, doi: 10.1021/nn204513y.



CHAPTER 6

QUANTUM AND NANO-OPTICAL DEVICES

USAMA AFZAL ^{1*}



Book Title

Advancements in Nanomaterials for Modern Electronics:
Design, Applications and Future Trends

Series Title

Books of Research Collection

Published On

January 02, 2026 (Edition 1)

Publisher

Scientific Collaborative Online Publishing Universal
Academy, Lahore, Pakistan

DOI: <https://doi.org/10.64060/978-627-7898-01-4-6>

Book ISBN: 978-627-7898-01-4

THIS WORK IS LICENSED UNDER A CREATIVE COMMONS ATTRIBUTION NONCOMMERCIAL
NODERIVATIVES 4.0 INTERNATIONAL LICENSE. SCOPUA (SCIENTIFIC COLLABORATIVE ONLINE
PUBLISHING UNIVERSAL ACADEMY) PUBLISHER REMAINS NEUTRAL REGARDING JURISDICTIONAL
CLAIMS IN PUBLISHED MAPS AND INSTITUTIONAL AFFILIATIONS.

¹School of Microelectronics, Tianjin University, Tianjin 300072, China.

*Corresponding: mohammadusamafzal7@gmail.com (U. Afzal)

Abstract

The integration of quantum phenomena with nanotechnology has transformed optical device engineering, enabling precise control of light–matter interactions at the nanoscale. This chapter explores the design, materials, and applications of quantum and nano-optical devices, emphasising structures such as quantum dots, nanowires, plasmonic nanoparticles, and metamaterials. These nanostructures enable enhanced emission, subwavelength light confinement, and tailored optical responses for applications in quantum communication, sensing, and photonic integration. Advancements in nanomaterials, including perovskites and two-dimensional semiconductors, have further improved the efficiency, flexibility, and miniaturisation of LEDs, lasers, and other optoelectronic systems. The chapter also discusses challenges related to scalability, stability, and toxicity, alongside ongoing innovations in nanofabrication that continue to expand the frontiers of quantum and nano-optical technologies toward sustainable, high-performance, and multifunctional applications.

Keywords: *Lasers; Metamaterials; Nanowires; Optoelectronics; Perovskites; Photonics; Plasmonics; Quantum Dots; Quantum Communication; Sensors*

The integration of quantum phenomena with nanotechnology has ushered in a new era in optical device engineering, enabling the manipulation of light at dimensions well below the wavelength scale. Quantum and nano-optical devices leverage the unique physical and optical properties of nanostructured materials to achieve functionalities that are unattainable with conventional bulk systems [1],[2],[3]. These advancements are redefining the capabilities of modern photonic and optoelectronic technologies. At the nanoscale, materials exhibit quantum confinement effects, enhanced light–matter interactions, and tailored electromagnetic responses that can be precisely engineered for specific applications. Structures such as quantum dots, nanowires, plasmonic nanoparticles, and metamaterials have become integral components in devices ranging from high-efficiency light-emitting diodes (LEDs) and lasers to ultra-sensitive sensors and quantum communication platforms.



This chapter provides a comprehensive overview of the principles, material systems, and emerging applications of quantum and nano-optical devices. Key areas of focus include the role of nanostructures in photonic devices, plasmonics and metamaterials for optical enhancement, nanomaterials in LEDs and lasers, the fundamentals of nano-photonics, and the growing impact of nanomaterials in quantum computing and cryptography. By examining recent advances and ongoing research in this field, this chapter aims to present a clear understanding of how the convergence of quantum science and nanotechnology is shaping the next generation of optical and quantum devices for applications in communication, computing, sensing, and beyond.

6.1. Quantum Dots and Nanowires in Photonic Devices

Quantum dots (QDs) and semiconductor nanowires have emerged as key nanostructures in the development of advanced photonic devices (Figure 6.1), owing to their unique size-dependent optical and electronic properties [4],[5],[6],[7]. Quantum dots, often referred to as “artificial atoms,” exhibit discrete energy levels and tunable emission spectra that are determined by their size, shape, and composition. This quantum confinement effect results in the ability to finely control the emission wavelength, which is crucial for a wide range of applications, including quantum light sources, solar cells, bio-imaging, and display technologies. For instance, cadmium selenide (CdSe) quantum dots can emit light at different wavelengths (from blue to red) depending on their size, making them ideal for use in multi-colored display systems [8]. Furthermore, their narrow and symmetric emission spectra make them highly suitable for applications requiring high photoluminescence efficiency, such as quantum dot light-emitting diodes (QD-LEDs). In QD-LEDs, quantum dots are employed as emissive layers that convert electrical energy into light with high



colour purity, offering the potential for more vibrant and energy-efficient displays. Similarly, quantum dot-sensitised solar cells (QDSSCs) have gained attention as potential alternatives to traditional photovoltaic technologies due to the enhanced ability of quantum dots to absorb a broad range of wavelengths and potentially surpass the efficiency limits of conventional silicon solar cells.

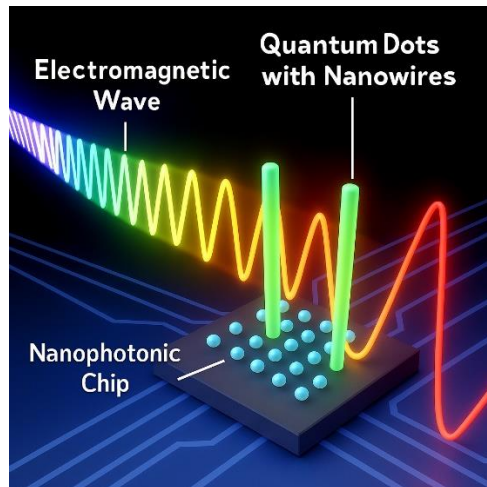


Figure 6.1: schematic illustration of a nanophotonic chip integrating quantum dots and nanowires for manipulating electromagnetic waves in quantum and nano-optical devices.

In addition to their optical properties, QDs are increasingly being explored in quantum communication and cryptography, where they serve as efficient sources of entangled photons or single photons for secure information transfer. The use of InGaAs quantum dots in photonic crystal cavities has made significant strides in enabling high-quality single-photon sources, which are fundamental for quantum key distribution (QKD) systems [9]. However, despite their many advantages, challenges such as the toxicity of materials like cadmium and lead, as well as issues with stability and scalability, remain obstacles to their widespread



commercial deployment. Researchers are actively working on alternative materials, such as InP and carbon-based quantum dots, that offer similar optical performance without the associated environmental concerns.

On the other hand, semiconductor nanowires provide unique advantages due to their one-dimensional geometry, which allows for effective light absorption, carrier transport, and waveguiding [10],[11]. The high aspect ratio of nanowires enables them to exhibit superior optical and electrical properties compared to their bulk counterparts, making them ideal for applications in lasers, photodetectors and solar cells. For example, ZnO nanowires are capable of efficient lasing at room temperature and have been successfully used in nanowire-based lasers with low-threshold operation, which is crucial for applications in miniaturised optoelectronic devices and on-chip optical interconnects [12]. Semiconductor nanowires also serve as excellent candidates for high-performance photodetectors, especially in the infrared region, due to their high surface-to-volume ratio, which leads to enhanced absorption and charge separation. The ability to tailor the wire's diameter and doping levels provides further flexibility in optimising the performance of nanowire-based photodetectors for use in various wavelengths and sensitivities.

Moreover, nanowires are frequently used in nanophotonic devices, such as photonic crystals and waveguides, where their small scale and well-defined structure can help control the propagation of light with greater precision than conventional materials. For instance, silicon nanowire-based photonic crystals have been designed to exhibit strong light confinement and fast light modulation, making them ideal for applications in photonic integrated circuits and optical communications. Semiconductor nanowires also play a significant role in light-harvesting applications such as solar cells, where their high aspect ratio allows for better photon absorption and charge collection. Indium



phosphide (InP) nanowire arrays, for example, have shown promising performance in radial p-n junction solar cells, demonstrating enhanced photocurrent generation and the potential to improve efficiency in next-generation photovoltaic devices [13].

The integration of quantum dots and semiconductor nanowires into hybrid systems holds significant promise for advancing the performance and functionality of photonic devices [14],[15]. For example, combining QDs with nanowires allows for the synergistic enhancement of light emission and charge transport, making these hybrid structures ideal for nanoscale light sources and quantum sensors. In these systems, QDs can act as efficient light emitters while nanowires serve as excellent charge collectors or waveguides. One example is the use of CdSe quantum dots embedded in ZnO nanowires for highly efficient photodetectors and light-emitting devices, where the nanowires provide enhanced light absorption and carrier transport, and the quantum dots contribute to tunable light emission. Similarly, QD-nanowire heterostructures have been proposed for use in next-generation quantum dot-based lasers and photonic circuits, where the unique optical properties of QDs, coupled with the waveguiding capabilities of nanowires, enable enhanced light confinement and directionality.

Despite the promising potential of these nanostructures, several challenges must be addressed to achieve large-scale integration and commercialisation. One of the primary challenges is the toxicity of some of the materials used in quantum dots, such as cadmium and lead, which pose environmental and health risks. As a result, researchers are exploring alternative materials, such as InP and carbon-based quantum dots, that offer similar optoelectronic properties with lower toxicity [16]. Another challenge is the stability of quantum dots and nanowires, particularly under prolonged exposure to light, moisture, and high temperatures. The development of advanced surface passivation techniques, such as coating quantum dots with protective layers or encapsulating



nanowires in durable polymers, has proven effective in improving the longevity and performance of these devices.

The scalability of nanowire and quantum dot fabrication also remains a key concern [17]. While techniques like colloidal synthesis for quantum dots and vapour-liquid-solid (VLS) growth for nanowires have made great strides in producing high-quality nanostructures, achieving uniformity and reproducibility at large scales remains a significant challenge. However, advancements in solution-based processing, roll-to-roll manufacturing and direct printing techniques are opening up new avenues for scalable and cost-effective production. In short, quantum dots and semiconductor nanowires are poised to play a transformative role in the development of next-generation photonic devices. Their ability to control light emission, absorption, and propagation at the nanoscale opens up a wide range of applications in quantum technologies, solar energy harvesting, bio-imaging and flexible electronics. As research progresses in overcoming the challenges of material toxicity, device stability, and scalability, the integration of these nanostructures into commercial devices will likely pave the way for new, more efficient, and multifunctional photonic systems.

6.2. Plasmonics and Metamaterials for Enhanced Optical Properties

Plasmonics and metamaterials represent two revolutionary fields in the manipulation of light at the nanoscale, significantly enhancing optical properties and enabling a broad range of applications in sensing, imaging, and nonlinear optics [18],[19]. Plasmonics is a subfield of nanophotonics that focuses on the interaction between electromagnetic fields and free electrons in conductive materials, typically metals. It leverages surface plasmon resonances (SPRs), collective oscillations of free electrons at the interface between metals and dielectrics, giving rise to



extraordinary optical phenomena such as subwavelength light confinement and field enhancement. Metamaterials, on the other hand, are artificially engineered materials with unique properties not found in naturally occurring substances, such as negative refractive indices or tailored electromagnetic responses. The integration of plasmonic and metamaterial approaches has paved the way for innovative optical components, pushing the boundaries of traditional optics and enabling advancements in a variety of fields, from imaging systems to biosensing.

6.2.1. Plasmonics: Enhancing Light-Matter Interactions

Plasmonic materials, particularly gold (Au) and silver (Ag) nanoparticles, have garnered significant attention due to their ability to manipulate light at scales smaller than the wavelength of light itself [20]. These metallic nanostructures support surface plasmon oscillations of free electrons induced by the electric field of incident light, which can be excited at specific resonant frequencies. These surface plasmons confine light to nanometer-sized volumes and enhance light-matter interactions, providing an effective means to manipulate light at the nanoscale. This phenomenon can be exploited for a wide variety of applications, including surface-enhanced Raman scattering (SERS), plasmonic sensors, bioimaging and nonlinear optics [21]. For example, gold nanoparticles are frequently used in SERS-based sensors for highly sensitive chemical detection. The ability of gold nanoparticles to concentrate electromagnetic fields at their surfaces enables the detection of trace amounts of molecules, even in complex biological environments. This capability has made plasmonics indispensable in fields like diagnostics and environmental monitoring, where the detection of specific chemical species at low concentrations is crucial.

In addition to SERS, plasmonics also plays a key role in plasmonic imaging and lithography. The subwavelength



confinement of light in plasmonic structures enables the resolution of features smaller than the diffraction limit of conventional optics. This has led to the development of super-resolution imaging techniques that offer spatial resolution far beyond the capabilities of traditional optical microscopes. Furthermore, plasmonics can be applied to nonlinear optics, where the enhanced electric fields can induce higher-order nonlinear optical effects such as second-harmonic generation and four-wave mixing. These effects are used in optical switches, amplifiers, and frequency converters for next-generation optical communication systems.

6.2.2. Metamaterials: Tailored Optical Responses

While plasmonics is primarily concerned with enhancing light–matter interactions using metallic nanostructures, metamaterials go a step further by allowing the design of materials with tailored optical properties that are not achievable in naturally occurring materials [22]. Metamaterials consist of subwavelength structures often arranged in periodic arrays that can manipulate electromagnetic waves in ways that standard materials cannot. The most striking feature of many metamaterials is their ability to exhibit a negative refractive index, meaning that light bends in the opposite direction to what is observed in conventional materials. This counterintuitive behaviour opens up the possibility of designing novel optical components such as perfect lenses, invisibility cloaks, and highly efficient optical waveguides. One of the most well-known examples of metamaterials is the negative index material (NIM), which can focus light below the diffraction limit and produce perfect lenses [23],[24]. Conventional lenses focus light using the positive refractive index of materials, where light bends towards the normal of the lens surface. However, a metamaterial with a negative refractive index bends light away from the normal, allowing the lens to focus light beyond the diffraction limit and achieve subwavelength imaging. This has



immense implications for high-resolution imaging systems, enabling microscopic details to be captured with unprecedented precision.

Another exciting application of metamaterials is in the development of invisibility cloaks [25]. Metamaterials can be designed to bend light around an object, rendering it effectively invisible to the human eye or other optical sensors. This is achieved by controlling the flow of electromagnetic waves through carefully engineered structures that guide light in such a way that it appears to pass around an object without interacting with it. The development of optical cloaking devices has significant implications for security, surveillance, and even military applications, where the ability to hide or disguise objects from detection could be crucial.

6.2.3. Plasmonic Metamaterials: Synergistic Enhancements

The combination of plasmonic elements with metamaterials results in plasmonic metamaterials, a hybrid approach that enhances the properties of both fields [26],[27],[28]. By integrating plasmonic nanostructures with metamaterials, researchers have been able to develop novel optical components that exhibit highly tailored electromagnetic responses, such as ultra-sensitive biosensors and highly efficient photodetectors. Plasmonic metamaterials can enhance the field confinement and enhance light-matter interactions in a way that is not possible with conventional materials. An example of this synergy is the plasmonic metamaterial-based biosensor. In such sensors, the combination of plasmonic resonances and metamaterial structures enhances the sensitivity to specific biological or chemical molecules. By designing metamaterial structures that support plasmonic resonances, these sensors can detect even the smallest changes in the local environment, making them highly suitable for early disease diagnosis or environmental monitoring. The ability to



modify the properties of both the metamaterial and the plasmonic element offers a new level of control over sensor performance, providing a powerful tool for real-time detection of pathogens, toxins, or biomarkers.

Similarly, plasmonic metamaterials can be applied in the development of photonic devices such as metamaterial waveguides, which offer enhanced light propagation and reduced signal loss compared to conventional waveguides. These metamaterials can be tailored to operate over a wide range of wavelengths, enabling more efficient on-chip optical communication systems.

6.2.4. Challenges

Despite the tremendous potential of plasmonics and metamaterials, several challenges remain that need to be addressed for their widespread commercial implementation. One of the primary challenges is the fabrication of these structures with high precision at large scales. While individual plasmonic and metamaterial structures can be created with remarkable accuracy at the nanoscale, fabricating them in large quantities with uniform properties remains a challenge. Advances in nanofabrication techniques, such as nanoimprint lithography and self-assembly, are expected to address some of these challenges, enabling the mass production of plasmonic and metamaterial components. Another challenge is the losses associated with plasmonic materials. Metal nanostructures, particularly those made of gold and silver, suffer from resistive losses that can dissipate energy in the form of heat, limiting their efficiency. Researchers are actively investigating alternative materials, such as graphene and topological insulators, that may reduce these losses and improve the overall performance of plasmonic devices. While the theoretical possibilities of plasmonics and metamaterials are vast, the transition from laboratory prototypes to real-world applications is complex. The integration of these advanced materials into existing optical systems



requires careful design and optimisation to ensure compatibility with current technologies.

6.3. Nanomaterials in Light Emitting Diodes (LEDs) and Lasers

The advent of nanomaterials has significantly transformed the field of optoelectronics, particularly in the design and development of Light Emitting Diodes (LEDs) and lasers (Figure 6.2). Nanomaterials such as quantum dots (QDs), perovskites and two-dimensional (2D) semiconductors have introduced remarkable advancements in both the efficiency and functionality of light-emitting devices [29],[2]. These materials, with their size-dependent optical properties and the ability to be engineered at the nanoscale, have enhanced the performance, flexibility, and versatility of light-emitting technologies. From high-colour purity and low energy consumption in LEDs to the creation of low-threshold and ultrafast lasers, nanomaterials have become indispensable components in the development of next-generation optoelectronic systems.

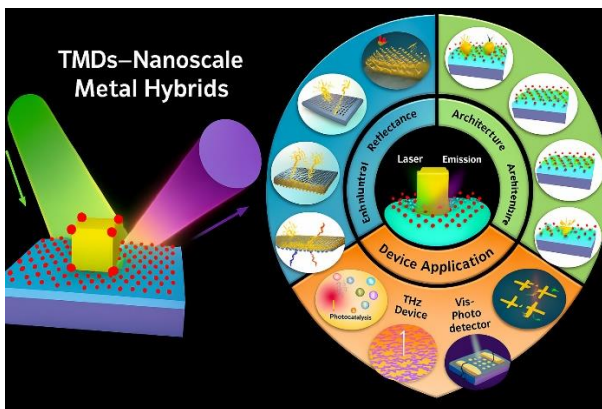


Figure 6.2: schematic representation of tmd–nanoscale metal hybrids illustrating their structural design, optical enhancement mechanisms, and diverse device applications such as THz and visible photodetectors.



6.3.1. Nanomaterials in LEDs: Enhancing Efficiency and Colour Purity

Light Emitting Diodes (LEDs) have become a ubiquitous component of modern lighting and display technologies due to their high efficiency, low energy consumption, and long lifespan [30],[31]. The integration of nanomaterials into LED designs has significantly improved their performance. Quantum dots (QDs), in particular, have proven to be highly effective in LED applications due to their ability to emit light with precise colour control. Quantum dots are nanometer-sized semiconductor particles that exhibit quantum confinement effects, which result in discrete energy levels and tunable emission spectra. The size of the quantum dot determines its emission wavelength, allowing for highly controlled colour purity and colour tunability. In LED applications, quantum dots can be incorporated into the active layer or used as a phosphor material. When excited by an external electric current or light source, quantum dots emit light at specific wavelengths, offering a far broader colour spectrum and more vivid colours compared to conventional LED technologies. This leads to high-quality displays with vibrant colours and better colour rendering for various applications, such as televisions, smartphones, and digital signage.

Moreover, quantum dot-based LEDs (QLEDs) have the advantage of low energy consumption, as they offer higher efficiency in converting electrical energy into light. Quantum dots can also be solution-processed, meaning they can be applied to flexible substrates, opening up possibilities for flexible, lightweight, and wearable LED displays. This makes quantum dot technology an attractive option for next-generation displays, including OLEDs and transparent displays, where flexibility and lightweight properties are essential. Perovskite materials are another class of nanomaterials that have gained significant attention for LED



applications due to their excellent luminescent properties, high photoluminescence efficiency, and ease of fabrication. Perovskite-based LEDs (PeLEDs) have been found to exhibit impressive colour purity and brightness, approaching the performance of quantum dots while offering the advantage of solution processing and low-cost production [32]. The potential for scalable manufacturing of perovskite-based LEDs makes them a promising alternative for large-area, energy-efficient displays.

6.3.2. Nanomaterials in Lasers: Low Thresholds and Ultrafast Performance

In addition to their use in LEDs, nanomaterials also play a crucial role in the development of advanced lasers. Lasers, which generate coherent light through the process of stimulated emission, benefit from the integration of nanomaterials in several key aspects. One of the most significant advantages of using nanomaterials in lasers is the ability to achieve low-threshold lasing and ultrafast performance, making them suitable for a variety of high-performance applications, including telecommunications, biomedical imaging, and material processing [33],[34]. Nanowires, which are one-dimensional (1D) nanostructures, are particularly noteworthy in laser technologies. These materials function as both the gain medium and optical cavity in laser systems, providing excellent confinement of light and charge carriers. The high surface-to-volume ratio of nanowires enables efficient carrier injection, which leads to low lasing thresholds, meaning that less energy is required to achieve lasing. This makes nanowire-based lasers more energy-efficient compared to conventional lasers. In addition, nanowires possess unique optical properties due to their small dimensions and quantum confinement effects, which allow them to support single-mode lasing and narrow linewidth emission. These characteristics result in high-quality, coherent light sources with excellent beam quality, making them ideal for applications



requiring precise, focused light, such as optical communications, sensing, and imaging.

Nanomaterial-based lasers also exhibit ultrafast switching speeds, which is a key feature for applications in high-speed optical communication systems and time-resolved spectroscopy. Nanowires, along with other 2D materials such as graphene and transition metal dichalcogenides (TMDs), are capable of supporting ultrafast dynamics due to their low threshold and high carrier mobility. This enables the development of femtosecond pulsed lasers, which are essential for high-resolution imaging and material modification at the nanoscale.

6.3.3. Integration of Nanomaterials into Photonic Circuits

The integration of nanomaterials into photonic circuits is a significant step towards the miniaturisation and energy efficiency of optical devices, particularly for use in quantum communication and quantum computing [35],[36]. Nanomaterials enable the construction of compact and efficient photonic components that are capable of manipulating and processing light on-chip, eliminating the need for bulky optical components. This is crucial for the development of integrated photonic systems that can interface with microelectronic circuits, thereby enabling faster and more efficient optical interconnects for data transmission. For example, quantum dot lasers can be incorporated into photonic circuits to produce on-demand single photons, which are essential for quantum cryptography and quantum computing applications. Similarly, nanowire-based waveguides can efficiently guide light with low loss, facilitating the integration of laser sources, detectors, and modulators into a single chip. The ability to integrate these nanomaterials into photonic circuits offers the potential to create ultra-compact optical systems with high performance and low power consumption.



Moreover, nanomaterials enable the development of flexible optoelectronic devices. For instance, flexible LEDs and laser diodes made from nanomaterials like quantum dots and perovskites are paving the way for wearable electronics and soft photonic devices. These flexible, lightweight devices could revolutionise sectors such as healthcare, where flexible sensors and wearable light sources could monitor patient conditions in real-time. Nanomaterials are integral to the development of quantum communication systems, where the ability to generate and manipulate single photons with high precision is critical. Quantum dot-based lasers and nanowire lasers are excellent candidates for use in these systems, as they can emit photons at specific wavelengths with minimal noise, enabling secure communication protocols based on quantum key distribution (QKD). In the broader field of optoelectronics, nanomaterials have been employed to enhance the performance of devices like photodetectors, modulators and photovoltaic cells. The high efficiency and tunability of quantum dot and nanowire materials make them highly suitable for next-generation optical communication systems, where fast and efficient data transmission is paramount.

6.3.4. Challenges

While the potential of nanomaterials in LEDs and lasers is clear, there are several challenges to be addressed in order to fully realise their commercial potential. Scalability remains a significant issue, particularly in the large-scale production of quantum dots, perovskites, and other nanomaterials with uniform properties [37]. Furthermore, the stability of some nanomaterials, especially perovskites, can be a limiting factor in their long-term performance. Researchers are actively working on improving the stability, reproducibility, and manufacturability of these materials. Additionally, the integration of nanomaterials into existing device architectures, particularly in flexible and wearable electronics,



requires careful design and optimisation to ensure compatibility with current technologies.

6.4. Summary of Chapter

This chapter explores the transformative role of nanomaterials in advancing quantum and nano-optical devices, focusing on how structures such as quantum dots, nanowires, plasmonic nanoparticles, and metamaterials enable precise control of light at the nanoscale. Quantum dots and nanowires enhance light emission, absorption, and charge transport in applications ranging from LEDs and lasers to solar cells and photonic circuits. Plasmonics and metamaterials introduce novel optical behaviours like subwavelength light confinement, negative refraction, and super-resolution imaging, paving the way for high-performance sensors and optical components. Additionally, nanomaterials such as perovskites and 2D semiconductors contribute to the development of flexible, energy-efficient, and ultrafast optoelectronic systems. While challenges related to material stability, toxicity, and large-scale integration remain, ongoing innovations in nanofabrication and materials engineering continue to expand the potential of quantum and nano-optical technologies for use in computing, secure communication, sensing, and photonic integration.

References

1. Y. Lee, W. Guan, E. Y. Hsieh, and S. Nam, "Opportunities for Nanomaterials in Stretchable and Free-Form Displays," *Small Science*, vol. 4, no. 3, 2024, doi: 10.1002/smssc.202470008.
2. Y. Lee, W. Guan, E. Y. Hsieh, and S. W. Nam, "Opportunities for Nanomaterials in Stretchable and Free-Form Displays," 2024. doi: 10.1002/smssc.202300143.
3. S. M. Lee, J. H. Kwon, S. Kwon, and K. C. Choi, "A Review of Flexible OLEDs Toward Highly Durable Unusual Displays," 2017. doi: 10.1109/TED.2017.2647964.
4. Gurioli, Massimo, et al. "Droplet epitaxy of semiconductor nanostructures for quantum photonic devices." *Nature materials* 18.8 (2019): 799-810.



5. Yan, Ruoxue, Daniel Gargas, and Peidong Yang. "Nanowire photonics." *Nature photonics* 3.10 (2009): 569-576.
6. Quan, Li Na, et al. "Nanowires for photonics." *Chemical reviews* 119.15 (2019): 9153-9169.
7. Uppu, Ravitej, et al. "Quantum-dot-based deterministic photon–emitter interfaces for scalable photonic quantum technology." *Nature nanotechnology* 16.12 (2021): 1308-1317.
8. Xiang, Xianglin, et al. "Cadmium chalcogenide (CdS, CdSe, CdTe) quantum dots for solar-to-fuel conversion." *Advanced Photonics Research* 3.11 (2022): 2200065.
9. Nomura, Masahiro, et al. "Cavity resonant excitation of InGaAs quantum dots in photonic crystal nanocavities." *Japanese journal of applied physics* 45.8R (2006): 6091.
10. Quan, Li Na, et al. "Nanowires for photonics." *Chemical reviews* 119.15 (2019): 9153-9169.
11. Yan, Ruoxue, Daniel Gargas, and Peidong Yang. "Nanowire photonics." *Nature photonics* 3.10 (2009): 569-576.
12. Tawara, T., et al. "Quality factor control and lasing characteristics of InAs/InGaAs quantum dots embedded in photonic-crystal nanocavities." *Optics Express* 16.8 (2008): 5199-5205.
13. Zafar, Fateen, and Azhar Iqbal. "Indium phosphide nanowires and their applications in optoelectronic devices." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 472.2187 (2016): 20150804.
14. Maitra, Sumit Kumar, et al. "A theoretical exploration of quantum dots and nanowires as next-generation photovoltaics." *Solar Energy Advances* 5 (2025): 100085.
15. Elshaari, Ali W., et al. "Hybrid integrated quantum photonic circuits." *Nature photonics* 14.5 (2020): 285-298.
16. Guan, Xinwei, et al. "Emerging trends of carbon-based quantum dots: nanoarchitectonics and applications." *Small* 19.17 (2023): 2207181.
17. García de Arquer, F. Pelayo, et al. "Semiconductor quantum dots: Technological progress and future challenges." *Science* 373.6555 (2021): eaaz8541.
18. Wang, Pan, et al. "Molecular plasmonics with metamaterials." *Chemical Reviews* 122.19 (2022): 15031-15081.
19. Cai, Yi-Yu, Yun Chang Choi, and Cherie R. Kagan. "Chemical and Physical Properties of Photonic Noble-Metal Nanomaterials." *Advanced materials* 35.34 (2023): 2108104.
20. Naik, Gururaj V., Vladimir M. Shalaev, and Alexandra Boltasseva. "Alternative plasmonic materials: beyond gold and silver." *Advanced materials* 25.24 (2013): 3264-3294.
21. Hang, Yingjie, Jennifer Boryczka, and Nianqiang Wu. "Visible-light and near-infrared fluorescence and surface-enhanced Raman scattering point-of-care sensing and bio-imaging: a review." *Chemical Society Reviews* 51.1 (2022): 329-375.



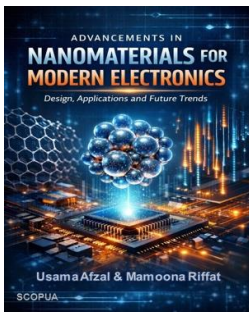
22. Liu, Changxu, et al. "Enhanced light-matter interaction in metallic nanoparticles: a generic strategy of smart void filling." *Nano Letters* 24.15 (2024): 4641-4648.
23. Soukoulis, Costas M., Maria Kafesaki, and Eleftherios N. Economou. "Negative-index materials: new frontiers in optics." *Advanced materials* 18.15 (2006): 1941-1952.
24. Boltasseva, Alexandra, and Vladimir M. Shalaev. "Fabrication of optical negative-index metamaterials: Recent advances and outlook." *Metamaterials* 2.1 (2008): 1-17.
25. Khan, Muhammad Shaheryar, et al. "A focused review on techniques for achieving cloaking effects with metamaterials." *Optik* 297 (2024): 171575.
26. Li, Xuanhua, Jinneng Zhu, and Bingqing Wei. "Hybrid nanostructures of metal/two-dimensional nanomaterials for plasmon-enhanced applications." *Chemical Society Reviews* 45.11 (2016): 3145-3187.
27. Wang, Pan, et al. "Molecular plasmonics with metamaterials." *Chemical Reviews* 122.19 (2022): 15031-15081.
28. Guo, Chang, Jingyue Yu, and Shikai Deng. "Hybrid metasurfaces of plasmonic lattices and 2D materials." *Advanced Functional Materials* 33.42 (2023): 2302265.
29. Wang, Zhiwei, et al. "Two-dimensional light-emitting materials: preparation, properties and applications." *Chemical Society Reviews* 47.16 (2018): 6128-6174.
30. Mokarian Zanjani, Saeedeh, et al. "Tailored ZnO functional nanomaterials for solution-processed quantum-dot light-emitting diodes." *Advanced Photonics Research* 3.12 (2022): 2200159.
31. Zhang, Qiang, et al. "Fluorescent nanomaterial-derived white light-emitting diodes: what's going on." *Journal of Materials Chemistry C* 2.22 (2014): 4358-4373.
32. Wei, Yi, Ziyong Cheng, and Jun Lin. "An overview on enhancing the stability of lead halide perovskite quantum dots and their applications in phosphor-converted LEDs." *Chemical Society Reviews* 48.1 (2019): 310-350.
33. Hasan, Tawfique, et al. "Nanotube-polymer composites for ultrafast photonics." *Advanced materials* 21.38-39 (2009): 3874-3899.
34. Szalkowski, Marcin, et al. "Advances in the photon avalanche luminescence of inorganic lanthanide-doped nanomaterials." *Chemical Society Reviews* (2025).
35. Elshaari, Ali W., et al. "Hybrid integrated quantum photonic circuits." *Nature photonics* 14.5 (2020): 285-298.
36. Sharma, Tarun, et al. "Past, present, and future of hybrid plasmonic waveguides for photonics integrated circuits." *Nanotechnology and Precision Engineering* 7.4 (2024).
37. Bozyigit, Deniz, and Vanessa Wood. "Challenges and solutions for high-efficiency quantum dot-based LEDs." *MRS bulletin* 38.9 (2013): 731-736.



CHAPTER 7

INTEGRATION OF NANOMATERIALS WITH CONVENTIONAL ELECTRONICS

MAMOONA RIFFAT ¹*



Book Title

Advancements in Nanomaterials for Modern Electronics:
Design, Applications and Future Trends

Series Title

Books of Research Collection

Published On

January 02, 2026 (Edition 1)

Publisher

Scientific Collaborative Online Publishing Universal
Academy, Lahore, Pakistan

DOI: <https://doi.org/10.64060/978-627-7898-01-4-7>

Book ISBN: 978-627-7898-01-4

THIS WORK IS LICENSED UNDER A CREATIVE COMMONS ATTRIBUTION NONCOMMERCIAL NODERIVATIVES 4.0 INTERNATIONAL LICENSE. SCOPUA (SCIENTIFIC COLLABORATIVE ONLINE PUBLISHING UNIVERSAL ACADEMY) PUBLISHER REMAINS NEUTRAL REGARDING JURISDICTIONAL CLAIMS IN PUBLISHED MAPS AND INSTITUTIONAL AFFILIATIONS.

¹Department of Physics, LUT school of Engineering Science, Lappeenranta-Lahti University of Technology, Finland.

*Corresponding: mamoona.riffat@lut.fi (M. Riffat)

Abstract

As traditional complementary metal–oxide–semiconductor (CMOS) technology nears its physical and performance limits, integrating nanomaterials with conventional electronics has emerged as a transformative strategy to sustain miniaturisation and performance advancement. This chapter presents an overview of hybrid architectures that merge the scalability and maturity of CMOS with the exceptional electronic, optical, and mechanical properties of nanomaterials such as graphene, transition metal dichalcogenides (TMDs), and semiconductor nanowires. Key developments include graphene–silicon heterostructures, two-dimensional (2D) material–silicon photonic waveguides, and CMOS-compatible nanodevices that enable efficient optoelectronic and neuromorphic computing. The chapter also examines challenges in scaling nanomaterials, including atomic-level instability, fabrication precision, and environmental concerns, while highlighting innovations in nano-device architectures, photonic integration, and next-generation memory systems such as ReRAM and phase-change memory (PCM). Collectively, these advances signify a paradigm shift toward energy-efficient, multifunctional, and miniaturised electronics that bridge the gap between nanoengineering and large-scale manufacturability.

Keywords: *2D materials; CMOS integration; graphene; hybrid electronics; memory devices; nanomaterials; neuromorphic circuits; optoelectronics; photonic integration; ReRAM; scalability; silicon photonics; TMDs*

As the miniaturisation of conventional, complementary metal-oxide-semiconductor (CMOS) devices approaches its physical and performance limits, the need for next-generation materials and novel device architecture has become critical [1]. Despite innovations such as high-k dielectrics, strain engineering, and metal gate technology, which have extended Moore’s Law over the past few decades, further scaling demands a paradigm shift, especially with the growing demand for flexible, wearable, and lightweight electronic systems. This chapter delves into the integration of these materials with traditional semiconductors, examining recent breakthroughs and remaining challenges.



7.1. Hybrid Systems: Integrating Nanomaterials with Traditional Semiconductors

The integration of nanomaterials with traditional semiconductors opens unprecedented opportunities for designing next-generation electronic and optoelectronic devices. Among these, semiconductor nanowires (NWs) and nanorods (NRs) have demonstrated remarkable potential in forming novel nanostructures such as heterojunctions, quantum dots, light-emitting diodes (LEDs), and solar cells. These one-dimensional (1D) structures, when combined with advanced two-dimensional (2D) materials like graphene, create hybrid systems with superior functionality and enhanced performance.

Graphene, a single-atom-thick layer of sp^2 -hybridized carbon, serves as an ideal platform for growing and aligning 1D semiconductor structures. Its exceptional characteristics, including ultra-high carrier mobility, mechanical flexibility, optical transparency (up to 97.7%), and outstanding thermal conductivity, make it a versatile component in integrated nano-architectures [2], [3]. When used as a substrate or interfacial layer, graphene facilitates the controlled nucleation and orientation of nanoribbons (NRBs), resulting in improved structural uniformity and enhanced electronic interaction at the nanoscale [3],[4].

Hybrid systems that combine nanomaterials with silicon-based platforms aim to leverage the best of both worlds: the maturity and scalability of CMOS and the unique electrical, optical, and mechanical properties of nanomaterials.

Graphene-Silicon Hybrid Devices: Graphene–silicon (Gr–Si) hybrid devices represent a transformative class of optoelectronic systems that merge the exceptional properties of two fundamentally different materials: the atomic thinness, ultrahigh carrier mobility, broadband optical absorption, and mechanical flexibility of graphene, with the established CMOS compatibility, maturity, and cost-effective scalability of silicon. Graphene–silicon hybrid



photodetectors support the intrinsic advantages of each material to overcome the limitations of traditional semiconductors, such as SiGe, InGaAs, and GaAs, which suffer from rigidity, limited bandgap tunability, and low optical transparency. By integrating graphene onto silicon substrates, often in a Schottky junction or heterostructure configuration, developed broadband photodetectors that operate from ultraviolet (UV) to mid-infrared (MIR) wavelengths. These devices exhibit enhanced responsivity, fast response times, and excellent quantum efficiency [5].

2D Material-Silicon Waveguide Integration: The integration of two-dimensional materials (2DMs) with silicon waveguide platforms represents a promising direction for advancing compact, high-performance on-chip optoelectronic devices. Due to their atomic thickness, broadband absorption, intense light-matter interaction, and excellent electrical properties, 2DMs (such as graphene, MoS₂, and WSe₂) are ideal candidates for next-generation photodetectors (PDs). When integrated with silicon photonic waveguides structures that confine and guide light at sub-wavelength scales, 2DMs significantly enhance optical absorption despite their ultrathin nature, enabling efficient photodetection within a compact footprint.

This hybrid approach enables CMOS-compatible fabrication, making it suitable for scalable manufacturing and integration into existing optical communication, sensing, and imaging systems. A variety of waveguide structures have been explored to optimise light with 2DM interaction, including rectangular waveguides, slot waveguides, surface plasmon polariton waveguides, photonic crystal waveguides, and micro-ring resonators. Each offers unique benefits in enhancing light confinement and absorption in 2DM layers.

The field is rapidly advancing, and current research focuses on enhancing responsivity, reducing noise, broadening the spectral response, and improving speed. These developments are crucial for



enabling on-chip photonic integrated circuits (PICs) used in data centres, biomedical diagnostics, environmental sensing, and neuromorphic computing [6].

CMOS-Compatible Nanomaterials: The integration of 2D materials (2DMs), especially graphene and transition metal dichalcogenides (TMDs), into CMOS-compatible optoelectronic devices, with a focus on their role in enhancing photodetector (PD) performance and enabling future on-chip applications. 2D materials such as graphene, MoS₂, WS₂, and black phosphorus are promising due to these four factors given in **Error! Reference source not found..**

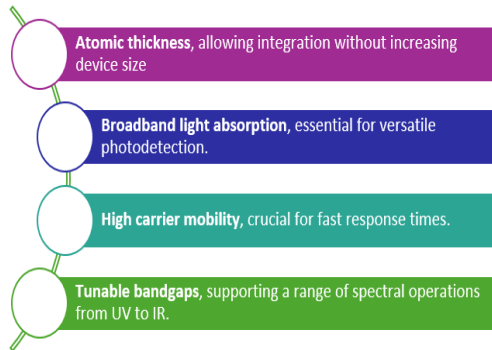


Figure 7.1: Important factors for photodetector and other optoelectronic components in CMOS-compatible systems.

The successful integration of 2DMs with silicon waveguides and photonic circuits enables intense light-matter interaction in compact device footprints and CMOS-friendly processing techniques such as transfer printing, CVD growth, and direct integration [7].



7.2. Challenges in Scaling Nanomaterials for Commercial Electronics

As the demand for faster, smaller, and more intelligent electronics accelerates, nanomaterials have emerged as key enablers of next-generation technologies from artificial intelligence and quantum computing to mobile devices and wearables. However, scaling nanomaterials from laboratory breakthroughs to commercial electronic systems presents a complex set of challenges spanning fabrication precision, material behaviour, manufacturability, and sustainability.

Manufacturing at the Nanoscale (Precision Beyond Limits): Nanomaterials operate at dimensions where the behaviour of materials deviates drastically from traditional expectations. A single dust particle or atomic flaw can compromise an entire nanodevice. The need for atomic-scale precision manufacturing tools and immaculate environments further increases costs and operational complexity. Due to the physical limitations of conventional lithography techniques, companies are investing in cutting-edge technologies such as extreme ultraviolet (EUV) lithography. Nevertheless, these instruments are costly, scarce, and frequently encounter yield problems in large-scale manufacturing [8].

Material Instabilities at the Atomic Level: At the nanoscale, electronic and mechanical properties such as conductivity, heat resistance, and strength become highly sensitive to atomic-level imperfections. Issues such as quantum tunnelling and electrostatic discharge (ESD) are far more pronounced, with minor electrostatic events capable of damaging delicate nanoscale structures. Electrostatic grounding measures and precision control systems must be implemented throughout manufacturing to protect device integrity [9].

Scalability and Yield Constraints: Although nanomaterials may exhibit remarkable performance in research environments, it



isn't easy to translate these findings into scalable commercial applications. Due to the irregularities introduced by mass production, even minor misalignments during etching or deposition can result in significant failure rates. Quality control and process repeatability are crucial. The expense of specialist equipment and cleanroom operations further complicates this, slowing down commercialisation timetables and increasing the barrier to entry for new companies [10].

Thermal and Electrical Challenges: As device dimensions shrink, thermal management and electrical interference become significant issues. High component density leads to increased power density, making heat dissipation more difficult and potentially reducing device lifespan. Similarly, signal crosstalk, where signals in adjacent circuits interfere with each other, becomes more likely, compromising data accuracy and requiring new circuit design approaches to maintain signal integrity.

Health, Safety and Environmental Risks: Scaling nanomaterials also introduces ethical and environmental concerns. Some engineered nanoparticles may pose health risks to workers during fabrication or to consumers during device use. Studies indicate that exposure to specific nanomaterials can cause oxidative stress, DNA damage, and cytotoxicity. Furthermore, the disposal and recycling of nano-enabled electronics remain largely unregulated, posing long-term environmental threats.

Wafer-Scale Uniformity: Achieving large-area, defect-free, and reproducible nanomaterial films remains a primary hurdle. For example, CVD-grown graphene often exhibits grain boundaries and wrinkles that affect device uniformity. Methods such as epitaxial growth and layer-by-layer transfer are being explored to address this issue.



7.3. Nano-Device Architecture and Integration for Next-Generation Circuits

The development of novel device architectures that integrate nanomaterials is reshaping conventional circuit design.

Heterostructure Devices: Some heterostructure devices involve stacking different 2D materials without lattice matching, allowing for novel optoelectronic behaviour. In a recent study, a heterostructure device composed of $\text{Bi}_2\text{O}_2\text{Se}$ and MoTe_2 was designed to function as a multifunctional electronic and optoelectronic component. The electric field-controlled band alignment, the heterostructure can switch between p–n and n–n configurations, allowing it to operate as a forward diode, a backward diode, a photodetector, and a photovoltaic device under various conditions. The distinct band alignments facilitate various charge transport mechanisms, including minority carrier diffusion, thermionic emission, and tunnelling. $\text{Bi}_2\text{O}_2\text{Se}$ offers high carrier mobility, air stability, and a moderate bandgap, while MoTe_2 contributes ambipolar characteristics and suitable band alignment, making their combination ideal for achieving high-performance functionality. The device demonstrates a broad spectral photoresponse, fast switching behaviour, and self-powered photovoltaic operation, highlighting its potential for integration into advanced, compact multifunctional technologies. The $\text{Bi}_2\text{O}_2\text{Se}$ nanosheets used in the heterostructure were synthesised using chemical vapour deposition, ensuring high-quality material interfaces critical for optimal device performance [11].

Neuromorphic and Logic Circuits: Neuromorphic and logic circuits aim to overcome the limitations of traditional CMOS-based digital systems, particularly those rooted in the von Neumann architecture, which separates memory and computation. These conventional systems face significant issues in terms of energy consumption and latency. Neuromorphic systems, by contrast,



merge memory and computation within a single device inspired by the operation of biological neurons.

The core of neuromorphic logic circuits is the neuromorphic transistor, which mimics synaptic behaviour by integrating multiple inputs, electrical, optical or hybrid and executing logic operations based on input combinations. These transistors support dynamic and programmable logic gates, including AND, OR, and XOR, among others. Their capability to reconfigure logic states using various external stimuli (e.g., thermal, triboelectric, or optical signals) adds a layer of adaptive computation not feasible with standard CMOS.

Materials used in these systems range from low-dimensional nanomaterials and oxides to organics and phase-change materials. Device structures often include electrolyte-gated transistors, floating-gate field-effect transistors, and ferroelectric field-effect transistors. These structures enable compact integration, in-situ data storage, and logic computation, allowing for high-density, low-power, and multi-modal computing [12]. TMD-based transistors have been incorporated into logic circuits and neuromorphic architecture. Their steep subthreshold slopes and high on/off ratios make them ideal for brain-inspired computing. Hybrid phototransistors using Gr/PQD structures have achieved ultra-high gain ($>10^8$), enabling photon-triggered logic gates [13].

Integration with Photonic Platforms: Nanomaterial-enhanced photodetectors have been embedded into silicon photonic circuits for compact and low-power communication systems. These devices utilise evanescent coupling between waveguides and 2D layers, improving detection efficiency while maintaining CMOS compatibility. Different material platforms contribute unique properties suited to specific applications, and their combination through heterogeneous integration enables devices that leverage the strengths of each material. Silicon-on-insulator (SOI) provides a mature, CMOS-compatible foundation for compact and scalable



photonic circuits but lacks intrinsic light sources and nonlinear properties, necessitating integration with materials like Indium Phosphide (InP) for lasers and germanium for detectors. InP, conversely, enables the monolithic integration of all core photonic components; however, its complex fabrication and thermal considerations often lead to hybrid configurations with silicon platforms. Silicon Nitride (SiN), with its ultra-low loss and wide spectral transparency, is a strong candidate for passive routing and quantum applications, and it is commonly combined with platforms like SOI or Thin-Film Lithium Niobate (TFLN) to support active functionalities such as modulation [14].

7.4. Advances in Nanomaterial-Based Memory Storage Devices

Memory technologies are witnessing a shift from traditional charge-based storage to novel resistance- and phase-change mechanisms, driven in part by nanomaterials.

Resistive RAM (ReRAM): Resistive Random-Access Memory (ReRAM) is a viable option for next-generation memory devices because, unlike traditional CMOS memory, it stores data using resistive switching rather than capacitive storage. High speed, low power consumption, non-volatility, and scalability to nanoscale dimensions are just a few of the many benefits that ReRAM provides. Despite its widespread use, CMOS-based flash memory has several drawbacks, including high write voltages, slow performance, and limited endurance. ReRAM overcomes these obstacles by permitting both unipolar and bipolar switching through processes such as the creation and breakdown of conductive filaments or valence change processes in oxide layers.

Among various material choices, titanium dioxide (TiO₂) and other transition metal oxides are favoured due to their properties, including a wide bandgap, high thermal stability, and flexible



switching behaviour. Furthermore, ReRAM devices are simple in structure, typically consisting of a metal-insulator-metal stack and can achieve binary data storage through changes in resistance states. Compared to CMOS, ReRAM not only offers better performance metrics but also provides a more brain-like computation approach, aligning well with the future of low-power, high-density memory and neural-network-based processors [15].

Phase Change Memory (PCM) and UltraRAM: Advanced PCM utilises chalcogenide materials to switch between amorphous and crystalline states. Recent research into UltraRAM combining resonant tunnelling with triple-barrier structures shows promise for high-speed, low-power non-volatile memory.

Phase-Change Memory (PCM) utilising GST467 superlattice technology and UltraRAM represents two distinct yet advanced memory architectures designed to address future computing demands. GST467 PCM leverages novel nanocomposite superlattice materials with atomically sharp interfaces to achieve ultra-low power operation, high density through 3D stacking, low-voltage compatibility, and excellent endurance and retention, making it suitable for non-volatile storage. In contrast, UltraRAM is based on standard CMOS SRAM bit cells, offering high-speed access times of ~ 1 ns, low power consumption through configurable standby modes, and exceptional endurance of over 10^{15} cycles. However, it remains a volatile memory supported by embedded NVM for short-term backup [16],[17],[18].

7.5. Energy-Efficient and High-Performance Integrated Circuits

Nanomaterials are enabling the development of ICs that balance performance with energy efficiency, essential for portable and edge-computing applications.



ReRAM in Analog/Mixed-Signal SoCs: Embedded ReRAM in analog and mixed-signal systems allows for on-chip learning, adaptive filtering, and AI inference with minimal power consumption. These devices support in-memory computation, reducing the energy cost of data movement [19].

Silicon Photonics with 2D Materials: Graphene-based photodetectors have achieved >100 GHz bandwidth with extremely small footprints. These are being incorporated into photonic ICs for data centre and telecommunication applications.

7.6. Summary of Chapter

The integration of nanomaterials with conventional electronics is emerging in a new era of hybrid devices that are smaller, faster, and more energy-efficient. Despite fabrication and reliability challenges, continued innovations in materials synthesis, device architecture, and CMOS-compatible processing are driving these technologies toward commercialisation.

Looking forward, the integration of nanomaterials into mainstream semiconductor platforms is becoming increasingly feasible due to advancements in materials synthesis, device architectures, and CMOS-compatible fabrication techniques. These hybrid systems promise to be smaller, faster, and more energy-efficient than ever before, particularly as they are deployed in cutting-edge applications like edge AI, photonic computing, and neuromorphic architectures. Despite ongoing challenges in large-scale fabrication and reliability, the trajectory of innovation indicates that nanomaterials are transitioning from experimental novelties to essential elements in commercial electronics. In conclusion, the fusion of nanomaterials with traditional electronics is not just enhancing current technologies but is laying the groundwork for a transformative new class of hybrid devices that will power the next generation of intelligent and efficient systems.



As new memory and logic technologies mature and are adopted in edge-AI, photonics, and neuromorphic systems, the role of nanomaterials will become increasingly central. The advances detailed in this chapter point to a future where nanomaterials are no longer just laboratory curiosities but foundational components of mainstream electronic systems.

References

1. T. Das and J. H. Ahn, "Development of electronic devices based on two-dimensional materials," 2017. doi: 10.1016/j.flatc.2017.05.001.
2. W. Il Park, C. H. Lee, J. M. Lee, N. J. Kim, and G. C. Yi, "Inorganic nanostructures grown on graphene layers," 2011. doi: 10.1039/c1nr10370a.
3. G. Otnes and M. T. Borgström, "Towards high efficiency nanowire solar cells," 2017. doi: 10.1016/j.nantod.2016.10.007.
4. T. Y, "The Role of Nanotechnology in Semiconductor Industry: Review Article," Journal of Materials Science and Nanotechnology, vol. 5, no. 2, 2017, doi: 10.15744/2348-9812.5.202.
5. M. A. Iqbal et al., "Nanostructures/Graphene/Silicon Junction-Based High-Performance Photodetection Systems: Progress, Challenges, and Future Trends," 2023. doi: 10.1002/admi.202202208.
6. X. He et al., "On-chip two-dimensional material-based waveguide-integrated photodetectors," 2024. doi: 10.1039/d3tc03679k.
7. A. K. Katiyar, J. Choi, and J. H. Ahn, "Recent advances in CMOS-compatible synthesis and integration of 2D materials," Dec. 01, 2025, Korea Nano Technology Research Society. doi: 10.1186/s40580-025-00478-1.
8. S. C. Goldstein, "The Challenges and Opportunities of Nanoelectronics," Most, 2014.
9. P. Politi, G. Grenet, A. Marty, A. Ponchet, and J. Villain, "Instabilities in crystal growth by atomic or molecular beams," 2000. doi: 10.1016/S0370-1573(99)00046-0.
10. S. Tiwari, A. Kumar, C. C. Liu, H. Lin, S. K. Kim, and H. Silva, "Electronics at nanoscale: Fundamental and practical challenges, and emerging directions," in NanoSingapore 2006: IEEE Conference on Emerging Technologies - Nanoelectronics - Proceedings, 2006. doi: 10.1109/NANOEL.2006.1609776.
11. L. Sun et al., "Van der Waals heterostructure of Bi₂O₂Se/MoTe₂ for high-performance multifunctional devices," Nano Energy, vol. 119, 2024, doi: 10.1016/j.nanoen.2023.109047.
12. Y. Wang et al., "Boolean Logic Computing Based on Neuromorphic Transistor," 2023. doi: 10.1002/adfm.202305791.
13. J. Fu, C. Nie, F. Sun, G. Li, and X. Wei, "Photodetectors Based on Graphene-Semiconductor Hybrid Structures: Recent Progress and Future Outlook," 2023. doi: 10.34133/adi.0031.



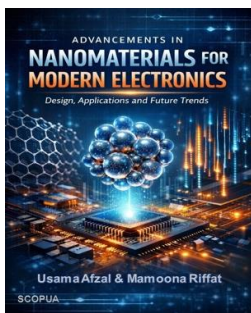
14. M. Takiguchi et al., “Hybrid Nanowire Photodetector Integrated in a Silicon Photonic Crystal,” *ACS Photonics*, vol. 7, no. 12, 2020, doi: 10.1021/acsp Photonics.0c01356.
15. D. Acharyya, A. Hazra, and P. Bhattacharyya, “A journey towards reliability improvement of TiO₂ based Resistive Random Access Memory: A review,” 2014. doi: 10.1016/j.microrel.2013.11.013.
16. A. Ehrmann, T. Blachowicz, G. Ehrmann, and T. Grethe, “Recent developments in phase-change memory,” 2022. doi: 10.1002/appl.202200024.
17. M. Le Gallo and A. Sebastian, “An overview of phase-change memory device physics,” 2020. doi: 10.1088/1361-6463/ab7794.
18. K. Aryana et al., “Interface controlled thermal resistances of ultra-thin chalcogenide-based phase change memory devices,” *Nat Commun*, vol. 12, no. 1, 2021, doi: 10.1038/s41467-020-20661-8.
19. F. Cai et al., “A Fully Integrated System-on-Chip Design with Scalable Resistive Random-Access Memory Tile Design for Analog in-Memory Computing,” *Advanced Intelligent Systems*, vol. 4, no. 8, Aug. 2022, doi: 10.1002/aisy.202200014.



CHAPTER 8

CHALLENGES IN THE FABRICATION AND COMMERCIALIZATION OF NANOMATERIAL ELECTRONICS

USAMA AFZAL ^{1*}



Book Title

Advancements in Nanomaterials for Modern Electronics:
Design, Applications and Future Trends

Series Title

Books of Research Collection

Published On

January 02, 2026 (Edition 1)

Publisher

Scientific Collaborative Online Publishing Universal
Academy, Lahore, Pakistan

DOI: <https://doi.org/10.64060/978-627-7898-01-4-8>

Book ISBN: 978-627-7898-01-4

THIS WORK IS LICENSED UNDER A CREATIVE COMMONS ATTRIBUTION NONCOMMERCIAL
NODERIVATIVES 4.0 INTERNATIONAL LICENSE. SCOPUA (SCIENTIFIC COLLABORATIVE ONLINE
PUBLISHING UNIVERSAL ACADEMY) PUBLISHER REMAINS NEUTRAL REGARDING JURISDICTIONAL
CLAIMS IN PUBLISHED MAPS AND INSTITUTIONAL AFFILIATIONS.

¹School of Microelectronics, Tianjin University, Tianjin 300072, China.

*Corresponding: mohammadusamafzal7@gmail.com (U. Afzal)

Abstract

Nanomaterial-based electronics have emerged as a transformative frontier in modern technology, offering exceptional electrical, optical, and mechanical properties that enable next-generation devices such as flexible sensors, wearable electronics, and quantum systems. However, the path from laboratory-scale innovations to commercial implementation remains fraught with multifaceted challenges. This chapter critically analyses the technical, economic, environmental, and ethical barriers that hinder the fabrication and commercialisation of nanomaterial electronics. Key topics include large-scale manufacturing limitations, cost-reduction strategies, toxicity and sustainability concerns, regulatory and safety frameworks, and integration challenges with existing semiconductor technologies. By addressing these critical issues, the chapter provides insights into future directions for scalable production, responsible commercialisation, and sustainable development of nanomaterial-based electronic systems.

Keywords: *Additive manufacturing; Carbon nanotubes; Commercialization; Environmental impact; Fabrication challenges; Graphene; Integration; Nanomaterials; Quantum dots; Regulations; Safety standards; Scalability; Sustainability; Toxicity; Two-dimensional materials*

The field of nanomaterial-based electronics has experienced rapid advancements in recent years, promising a new generation of high-performance, energy-efficient, and multifunctional devices [1]. Nanomaterials such as carbon nanotubes, graphene, quantum dots, and two-dimensional semiconductors offer unique electrical, optical, and mechanical properties that have the potential to revolutionise traditional electronic systems [2]. From flexible wearable devices to ultra-sensitive sensors and quantum computing elements, the integration of nanomaterials opens unprecedented opportunities in both consumer and industrial applications. Despite these promising developments, the transition of nanomaterial technologies from the research lab to large-scale commercial products remains fraught with significant challenges. Issues related to scalable fabrication, cost-effectiveness, environmental safety, regulatory compliance,



and system-level integration continue to hinder widespread adoption. These challenges not only impact manufacturing feasibility but also raise important considerations regarding sustainability, public trust, and long-term performance.

This chapter aims to critically examine the key challenges associated with the fabrication and commercialisation of nanomaterial electronics. It explores the technical difficulties in scaling up nanomaterial synthesis and device fabrication, assesses the economic and logistical hurdles affecting market viability, and highlights environmental and health concerns related to nanomaterial production and use. Additionally, the chapter discusses the current state of safety standards, regulatory frameworks, and ethical implications, while also investigating integration and compatibility issues with existing electronic platforms. By addressing these multifaceted challenges, the chapter provides a foundation for future research, policy development, and industrial strategies aimed at enabling the successful translation of nanomaterial innovations into practical and commercially viable applications.

8.1. Challenges in Large-Scale Fabrication and Manufacturing

Despite the promising potential of nanomaterial-based electronics, large-scale fabrication remains one of the most significant bottlenecks hindering their transition from laboratory-scale demonstrations to real-world commercial applications [3],[4],[5]. Unlike conventional semiconductor fabrication, which benefits from decades of process standardisation and industrial-scale infrastructure, nanomaterial electronics demand entirely new methods for synthesis, alignment, and integration. High precision is required to control the morphology, distribution, and properties of nanomaterials such as carbon nanotubes (CNTs), graphene,



quantum dots, and transition metal dichalcogenides (TMDs), all of which behave unpredictably under mass-production conditions.

One of the primary fabrication challenges lies in achieving uniformity across large substrates. While techniques like chemical vapour deposition (CVD) have been developed for growing graphene and TMDs on wafer-scale surfaces, issues such as grain boundaries, layer thickness inconsistencies, and defects remain prevalent. For CNTs, the selective synthesis of semiconducting over metallic tubes remains a formidable task. High-throughput alignment techniques, such as Langmuir-Blodgett assembly and dielectrophoresis, are being explored but still face limitations in scalability and repeatability.

Moreover, the integration of nanomaterials into existing complementary metal-oxide-semiconductor (CMOS) technology introduces compatibility issues. Nanomaterials often require lower processing temperatures and different chemical environments than traditional silicon-based processes, necessitating novel hybrid fabrication approaches. Additive manufacturing and printing technologies, while promising for flexible and wearable electronics, still lack the resolution and consistency required for high-performance applications.

8.1. Challenges in Large-Scale Fabrication and Manufacturing

Cost remains a critical barrier to the widespread commercialisation of nanomaterial electronics. The high cost of raw nanomaterials, particularly those requiring elaborate purification and functionalization steps, makes them less competitive compared to traditional materials. For instance, the production of high-quality graphene or single-wall carbon nanotubes involves expensive techniques like high-temperature CVD or laser ablation, which are not yet optimised for cost-effective mass production. Beyond



material synthesis, the equipment and facilities required to handle nanomaterials often demand specialised environments, such as clean rooms and inert gas chambers, further driving up operational costs. Moreover, yield losses due to defects, contamination, or alignment issues during fabrication add to the overall expense.

Efforts are underway to develop low-cost synthesis methods, such as solution-phase processes, electrochemical exfoliation, and roll-to-roll printing techniques. Additionally, research into scalable purification methods like polymer-wrapping and ultracentrifugation for CNTs is crucial for improving material quality without dramatically increasing costs. However, for nanomaterial electronics to become commercially viable, these cost-effective methods must match the performance and reliability of established semiconductor technologies. Another aspect of commercial viability is market readiness. End-user industries such as consumer electronics, automotive, and healthcare require robust supply chains and guaranteed long-term performance before committing to new materials. Therefore, demonstrating not just technological superiority but also economic feasibility and reliability over time is essential for commercial success.

8.2. Cost Reduction and Commercial Viability of Nanomaterial Electronics

Cost remains a critical barrier to the widespread commercialisation of nanomaterial electronics. The high cost of raw nanomaterials, particularly those requiring elaborate purification and functionalization steps, makes them less competitive compared to traditional materials. For instance, the production of high-quality graphene or single-wall carbon nanotubes involves expensive techniques like high-temperature CVD or laser ablation, which are not yet optimised for cost-effective mass production. Beyond material synthesis, the equipment and facilities required to handle



nanomaterials often demand specialised environments, such as clean rooms and inert gas chambers, further driving up operational costs. Moreover, yield losses due to defects, contamination, or alignment issues during fabrication add to the overall expense [6],[7].

Efforts are underway to develop low-cost synthesis methods, such as solution-phase processes, electrochemical exfoliation, and roll-to-roll printing techniques. Additionally, research into scalable purification methods like polymer-wrapping and ultracentrifugation for CNTs is crucial for improving material quality without dramatically increasing costs. However, for nanomaterial electronics to become commercially viable, these cost-effective methods must match the performance and reliability of established semiconductor technologies. Another aspect of commercial viability is market readiness. End-user industries such as consumer electronics, automotive, and healthcare require robust supply chains and guaranteed long-term performance before committing to new materials. Therefore, demonstrating not just technological superiority but also economic feasibility and reliability over time is essential for commercial success.

8.3. Toxicity, Environmental Impact and Sustainability Issues

The potential toxicity and environmental impact of nanomaterials are growing concerns as research shifts from the lab to large-scale production. Nanomaterials possess unique physicochemical properties, including high surface area and reactivity, which may lead to unforeseen interactions with biological systems and ecosystems. Several studies have reported cytotoxic effects associated with exposure to certain nanomaterials. For example, carbon nanotubes and some forms of graphene have shown asbestos-like behaviour when inhaled, posing risks to



respiratory health. Similarly, silver nanoparticles, commonly used for their antimicrobial properties, can accumulate in aquatic systems and disrupt microbial ecosystems. As the use of nanomaterials expands, comprehensive studies on their long-term biocompatibility, bioaccumulation, and degradation are urgently needed. From an environmental perspective, the synthesis and disposal of nanomaterials also raise sustainability concerns. High-energy input methods like plasma-enhanced CVD are resource-intensive, while chemical synthesis routes often involve hazardous solvents and precursors. Furthermore, waste streams containing nanoparticles pose challenges for water treatment and recycling systems [8],[9],[10].

Addressing these issues requires a two-pronged approach: green synthesis and lifecycle assessment (LCA). Green synthesis emphasises the use of environmentally benign solvents, energy-efficient methods, and sustainable feedstocks. LCA evaluates the environmental footprint of nanomaterials from cradle to grave, identifying critical points for intervention. Regulators and industry stakeholders must work together to establish environmental guidelines and best practices to ensure that nanomaterial electronics are not only innovative but also sustainable.

8.4. Safety Standards, Regulations and Ethical Considerations

The rapid advancement of nanomaterial technologies has outpaced the development of comprehensive safety and regulatory frameworks. Current safety standards are largely extrapolated from macro-scale materials and may not adequately capture the risks associated with nanoscale interactions. One major regulatory gap is the lack of standardised testing protocols for evaluating nanomaterial toxicity. While agencies like the U.S. Environmental Protection Agency (EPA) and European Chemicals Agency



(ECHA) have begun to issue guidelines, these are often voluntary or inconsistent across jurisdictions. This creates uncertainty for manufacturers and hinders international trade and collaboration. The development of globally harmonised standards is crucial. Organisations such as the International Organization for Standardization (ISO) and the Organisation for Economic Co-operation and Development (OECD) are actively working to define metrics for nanomaterial characterisation, exposure assessment, and risk management. However, broader adoption and enforcement remain limited [11],[12],[13].

Ethical considerations also play a vital role. The deployment of nanomaterials in consumer products, medical devices, and environmental systems raises questions about informed consent, privacy, and unintended consequences. For example, nanosensors embedded in wearable electronics could collect sensitive biometric data, necessitating strict data governance frameworks. Public engagement and transparent communication are essential to build trust and ensure that ethical principles guide technological innovation. Multidisciplinary collaboration among scientists, ethicists, policymakers, and industry leaders will be vital to developing responsible and inclusive frameworks for nanomaterial applications.

8.5. Overcoming Integration and Compatibility Barriers

Integrating nanomaterials into existing electronic platforms poses significant technical and engineering challenges. These materials often require distinct processing conditions, mechanical properties, and interface behaviours compared to conventional semiconductors. One of the foremost challenges is achieving seamless interfacing between nanomaterials and traditional components. For example, connecting a graphene-based transistor to silicon circuitry involves differences in thermal expansion,



electrical conductivity, and surface chemistry. These disparities can lead to mechanical stress, poor adhesion, and signal loss, thereby compromising device performance.

Moreover, variability in nanomaterial properties across batches, such as size distribution, defect density, and doping levels, introduces inconsistencies that are unacceptable in high-reliability applications like aerospace or medical devices. Strategies to standardise nanomaterial quality through advanced characterisation tools and material certification processes are urgently needed. Another area of concern is system-level integration. Designing circuits that exploit the unique properties of nanomaterials, such as high carrier mobility in graphene or photonic tunability in quantum dots, requires a departure from traditional circuit architectures. New design paradigms, simulation tools, and fabrication workflows must be developed to fully realise the potential of these materials.

Additionally, efforts to integrate nanomaterials into flexible, stretchable, or wearable electronics necessitate innovations in substrate materials, encapsulation techniques, and power management systems. The convergence of flexible substrates with rigid electronic components demands hybrid integration strategies that maintain performance while allowing mechanical flexibility.

8.6. Summary of Chapter

The Chapter examines the significant challenges in the fabrication and commercialisation of nanomaterial-based electronics. Despite the potential of nanomaterials like carbon nanotubes, graphene, and quantum dots, large-scale production remains a bottleneck due to difficulties in achieving uniformity and scalability. High costs associated with raw materials and specialised manufacturing further impede commercial viability. Environmental and health concerns arise from the potential toxicity and resource-intensive synthesis methods of these materials. Regulatory gaps and



ethical considerations, such as data privacy, also pose challenges. Integration into existing electronic platforms is complicated by compatibility issues and the need for new design paradigms. Addressing these multifaceted challenges is crucial for the successful transition of nanomaterial innovations into practical applications.

References

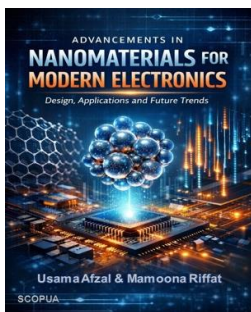
1. Rahman, Mustafijur, et al. "A review on nanomaterial-based additive manufacturing: Dynamics in properties, prospects, and challenges." *Progress in Additive Manufacturing* 9.4 (2024): 1197-1224.
2. Jariwala, Deep, et al. "Carbon nanomaterials for electronics, optoelectronics, photovoltaics, and sensing." *Chemical Society Reviews* 42.7 (2013): 2824-2860.
3. Liu, Song, et al. "Scale-up fabrication of two-dimensional material membranes: challenges and opportunities." *Current Opinion in Chemical Engineering* 39 (2023): 100892.
4. Goh, Guo Dong, et al. "Large-format additive manufacturing of polymers: a review of fabrication processes, materials, and design." *Virtual and Physical Prototyping* 19.1 (2024): e2336160.
5. Wang, Kang L. "Issues of nanoelectronics: A possible roadmap." *Journal of Nanoscience and Nanotechnology* 2.3-4 (2002): 235-266.
6. Wu, Wei. "Inorganic nanomaterials for printed electronics: a review." *nanoscale* 9.22 (2017): 7342-7372.
7. Cenci, Marcelo Pilotto, et al. "Eco-friendly electronics—a comprehensive review." *Advanced Materials Technologies* 7.2 (2022): 2001263.
8. Buchman, Joseph T., et al. "Understanding nanoparticle toxicity mechanisms to inform redesign strategies to reduce environmental impact." *Accounts of chemical research* 52.6 (2019): 1632-1642.
9. Tanzil, Dickson, and Beth R. Beloff. "Assessing impacts: Overview on sustainability indicators and metrics." *Environmental Quality Management* 15.4 (2006).
10. Garud, Aishwarya, et al. "A scientific review of pesticides: Classification, toxicity, health effects, sustainability, and environmental impact." *Cureus* 16.8 (2024).
11. Atkins, Steve. "Ethical and health and safety issues." *Performance Assessment in Strength and Conditioning* (2018): 5-12.
12. Schulte, Paul A., and Fabio Salamanca-Buentello. "Ethical and scientific issues of nanotechnology in the workplace." *Ciência & saúde coletiva* 12 (2007): 1319-1332.
13. Wasti, Sophia, et al. "Ethical and legal challenges in nanomedical innovations: a scoping review." *Frontiers in Genetics* 14 (2023): 1163392.



CHAPTER 9

EMERGING TRENDS AND THE FUTURE OF NANOMATERIALS IN ELECTRONICS

USAMA AFZAL ^{1*}



Book Title

Advancements in Nanomaterials for Modern Electronics:
Design, Applications and Future Trends

Series Title

Books of Research Collection

Published On

January 02, 2026 (Edition 1)

Publisher

Scientific Collaborative Online Publishing Universal
Academy, Lahore, Pakistan

DOI: <https://doi.org/10.64060/978-627-7898-01-4-9>

Book ISBN: 978-627-7898-01-4

THIS WORK IS LICENSED UNDER A CREATIVE COMMONS ATTRIBUTION NONCOMMERCIAL
NODERIVATIVES 4.0 INTERNATIONAL LICENSE. SCOPUA (SCIENTIFIC COLLABORATIVE ONLINE
PUBLISHING UNIVERSAL ACADEMY) PUBLISHER REMAINS NEUTRAL REGARDING JURISDICTIONAL
CLAIMS IN PUBLISHED MAPS AND INSTITUTIONAL AFFILIATIONS.

¹School of Microelectronics, Tianjin University, Tianjin 300072, China.

*Corresponding: mohammadusamafzal7@gmail.com (U. Afzal)

Abstract

This chapter explores the emerging frontiers of nanomaterials in the evolution of modern electronics. It discusses how artificial intelligence (AI) and machine learning (ML) accelerate nanomaterial design by enabling predictive modelling and autonomous experimentation. Advances in quantum nanotechnology are presented as pivotal for realising quantum computing, sensing, and communication systems that surpass classical limitations. The chapter further highlights innovations in self-powered and autonomous electronics driven by nanomaterials for energy harvesting and sustainability. The influence of 5G, the Internet of Things (IoT), and wearable technologies on flexible, multifunctional materials is analysed, emphasising their role in miniaturisation and performance enhancement. Finally, the concept of fully integrated nanoelectronics is examined as a foundation for intelligent, adaptive, and interconnected systems. Together, these developments illustrate how nanomaterials are transforming electronic technologies toward a smarter and more sustainable future.

Keywords: *Artificial Intelligence; Energy Harvesting; Internet of Things; Machine Learning; Nanoelectronics; Quantum Nanotechnology; Smart Systems; Wearable Electronics*

The continuous evolution of electronics toward greater efficiency, miniaturisation, and multifunctionality is increasingly driven by advancements in nanomaterials. These materials, defined by their size-dependent physical, chemical, and electronic properties, are playing a transformative role in redefining the capabilities of modern and future electronic systems. As we transition into an era dominated by smart technologies encompassing artificial intelligence (AI), quantum computing, the Internet of Things (IoT), and 5G connectivity, the demand for high-performance, scalable, and energy-efficient nanomaterials is reaching unprecedented levels. Nanomaterials enable enhanced electron mobility, high surface area-to-volume ratios, and tunable band structures, making them ideal candidates for next-generation electronic components. Their versatility spans across applications such as flexible displays, self-powered sensors, neuromorphic computing devices, and quantum transistors. At the same time, the



fusion of materials science with computational tools like machine learning and data-driven modelling is revolutionising the way new nanomaterials are discovered and optimised.

This chapter explores the emerging trends that are shaping the future landscape of nano-enabled electronics. It begins with the integration of AI and machine learning in nanomaterial design, followed by a discussion on quantum nanotechnology and its implications for quantum electronics. The chapter further delves into self-powered systems empowered by nanomaterial innovations, and assesses the role of nanomaterials in the rapidly expanding domains of 5G, IoT, and wearable technologies. Finally, it offers insights into the prospects of fully integrated nanoelectronics systems that promise to redefine the concept of a smart, connected world. As electronics continue to push the boundaries of speed, efficiency, and intelligence, nanomaterials remain at the forefront of this revolution, enabling breakthroughs that were once thought to be beyond reach. This chapter aims to provide a forward-looking perspective on these developments, grounded in recent advances and visionary concepts.

9.1. The Role of Artificial Intelligence and Machine Learning in Nanomaterial Design

The integration of artificial intelligence (AI) and machine learning (ML) with nanoscience represents one of the most transformative developments in contemporary materials research. Traditional nanomaterial design relied heavily on empirical experimentation and iterative optimisation, which are both time-consuming and resource-intensive. The explosion of computational power and large-scale materials databases has now enabled AI to accelerate discovery, prediction, and design processes across various fields of nanotechnology [1],[2].



Machine learning models are capable of analysing intricate correlations between structural parameters, synthesis conditions, and the resulting physical and electronic properties of nanomaterials. Both supervised and unsupervised algorithms, including random forests, neural networks, and Gaussian process regressors, have been successfully applied to predict bandgap energies, defect behaviour, and surface reactivity [3]. This data-centric approach allows researchers to minimise experimental redundancy while uncovering hidden relationships that conventional methods might overlook.

A particularly powerful application is inverse materials design, where the target property is specified first, and the algorithm then identifies the most suitable material compositions or nanostructures to achieve it [4]. Deep generative models have already been used to propose new 2D materials, catalysts, and hybrid frameworks with desired optoelectronic or mechanical characteristics. Reinforcement learning systems can even guide experimental synthesis in real time, optimising variables such as temperature, precursor ratios, or reaction time to maximise yield or performance [5]. The advent of autonomous research laboratories further extends AI's impact on nanotechnology. In these self-driving labs, robotic synthesis, automated characterisation, and real-time machine learning feedback loops combine to enable continuous cycles of hypothesis generation, testing, and optimisation [6]. This paradigm can drastically shorten the design-to-discovery timeline from years to weeks or even days. In nanoelectronics, AI has also emerged as a critical tool for optimising device-level architectures. Data-driven prediction of carrier mobility, interface states, and contact resistance allows engineers to identify optimal nanomaterial combinations for high-speed transistors and energy-efficient logic devices [7]. Similarly, ML-based models are increasingly used to predict mechanical reliability and fatigue behaviour in flexible or wearable electronics.



However, challenges persist. The accuracy of AI models depends strongly on the availability of representative and high-quality data. Many materials datasets are sparse, incomplete, or biased toward specific compositions, which limits model generalizability [8]. Moreover, the interpretability of complex neural architectures remains a key issue, motivating the rise of explainable AI (XAI) approaches that offer physically meaningful explanations for predictions. The combination of AI with quantum computing could further revolutionise materials simulations, allowing accurate modelling of electron correlation and nanoscale interactions that are currently beyond classical computational limits [9].

9.2. Future Directions in Quantum Nanotechnology and Quantum Electronics

Quantum nanotechnology merges quantum mechanics with nanoscale fabrication to manipulate matter and energy at their most fundamental levels. When materials are confined to dimensions comparable to the de Broglie wavelength of electrons, quantum effects dominate, giving rise to entirely new physical behaviours [10]. Quantum dots (QDs) exemplify this regime: their discrete electronic states and size-dependent optical properties enable applications in quantum communication, computation, and bioimaging [11]. Similarly, colour centres in diamond and defects in silicon carbide can act as spin qubits with long coherence times, suitable for quantum information storage and processing [12].

Another groundbreaking class comprises topological materials, whose conducting surface states are protected by topological invariants and remain robust against disorder. These properties hold promise for fault-tolerant quantum computation and low-power spintronic devices [13]. Future efforts in hybrid quantum architectures aim to couple disparate quantum systems



such as superconducting circuits, spin ensembles, and photonic cavities into coherent networks capable of scalable information transfer [14]. Nanomaterials play a pivotal role in engineering these coupling interfaces, where atomic-scale precision is essential to preserve coherence. Quantum nanotechnology also underpins the rise of quantum sensors, which exploit quantum superposition and entanglement to measure magnetic fields, electric potentials, and temperature variations with sensitivities beyond classical limits [15]. For instance, NV-centre-based nanodiamond sensors have been used for nanoscale magnetometry and biological imaging.

Yet, achieving large-scale quantum electronic systems requires overcoming decoherence and fabrication variability. Improvements in qubit uniformity, isolation from noise, and advanced quantum error-correction schemes are gradually enhancing device scalability [16]. Looking ahead, the convergence of AI, ML, and quantum nanotechnology may yield hybrid systems capable of learning and adapting through quantum parallelism—potentially transforming computation, encryption, and secure communications.

9.3. Self-Powered and Autonomous Electronics: Nanomaterial Innovations

As electronics become increasingly ubiquitous, the need for sustainable, maintenance-free power sources grows urgent. Self-powered and autonomous electronic systems capable of harvesting and storing energy from their surroundings represent a fundamental shift in device design philosophy [17].

Piezoelectric and triboelectric nanogenerators (TENGs) are leading candidates for mechanical-to-electrical energy conversion. Nanostructured materials such as ZnO nanowires, BaTiO₃ nanotubes, and polymer composites can generate electrical output from motion, vibration, or acoustic waves [18]. Thermoelectric



nanomaterials, notably Bi_2Te_3 , SnSe , and hybrid nanocomposites, harvest waste heat by exploiting quantum confinement to enhance the Seebeck coefficient while suppressing thermal conductivity [19]. Nanostructured electrodes based on graphene, MXenes, and transition-metal oxides have revolutionised energy storage by providing high surface area, rapid ion transport, and superior mechanical flexibility [20]. The integration of these materials into micro-supercapacitors and thin-film batteries enables a continuous power supply for miniature electronic components.

In wearable and implantable biomedical devices, energy harvesting from body movement, respiration, or physiological fluids is a rapidly growing field. Biocompatible piezoelectric polymers and nanofibers can generate sufficient voltage to power low-energy biosensors or drug-delivery actuators [21]. Intelligent power-management circuits built from nanomaterial-based components allow adaptive energy allocation, prolonging device lifetime and stability [22]. Moreover, the recent emphasis on eco-friendly and biodegradable nanomaterials such as cellulose nanofibers and bio-derived polymers addresses sustainability and end-of-life concerns, particularly in transient electronics [23]. Together, these innovations point toward a future of autonomous nanosystem devices that not only sense and compute but also generate and manage their own energy, enabling continuous operation in remote or harsh environments.

9.4. The Impact of 5G, IoT and Wearable Tech on Nanomaterial Research

The expansion of 5G communication networks, the Internet of Things (IoT), and wearable technology has had a profound influence on the direction of nanomaterials research [24]. These technologies require electronic components that are flexible, low-power, and capable of operating at high frequencies. For 5G



systems, materials must exhibit ultra-low dielectric loss, high electron mobility, and excellent thermal stability. Graphene, hexagonal boron nitride (h-BN), and high- κ dielectrics have emerged as key enablers for antennas, modulators, and high-frequency transistors [25].

The IoT ecosystem, comprising billions of interconnected sensors, drives demand for scalable, printable, and low-cost electronic materials. Nanomaterials such as carbon nanotubes (CNTs), MoS₂, and conductive polymers allow flexible circuit fabrication via roll-to-roll printing, making large-scale deployment economically viable [26]. Wearable electronics push material performance even further, requiring stretchability, biocompatibility, and resistance to mechanical fatigue. Silver nanowires, conductive textiles, and graphene composites are enabling new generations of smart garments, physiological monitors, and electronic skin systems [27]. The integration of energy-harvesting modules, like piezoelectric or triboelectric generators, into wearables has resulted in self-powered health-monitoring platforms that operate without external batteries [28]. Concurrently, efficient thermal management has become critical as 5G and IoT devices operate at higher power densities. Nanomaterials such as boron nitride nanotubes, graphene, and diamond-like carbon films are being engineered for superior heat dissipation [29].

As sustainability and recyclability gain importance, researchers are developing green nanomanufacturing processes that minimise hazardous chemicals and enable material reuse. Combined with AI-assisted device optimisation and edge computing, nanomaterials will form the backbone of next-generation smart infrastructure, healthcare systems, and environmental networks [30].



9.5. Prospects for Fully Integrated Nanoelectronics: Toward a Smart World

The ultimate vision of nanotechnology is a world of fully integrated nanoelectronics, where sensing, computing, communication, and energy management occur seamlessly at the nanoscale. Advances in nanoscale transistors, including gate-all-around FETs, tunnel FETs, and 2D-material-based transistors, are extending Moore's Law by enhancing electrostatic control and minimising leakage currents [31]. Concurrently, memristive and neuromorphic architectures are reshaping computing paradigms, enabling devices that mimic the adaptive and parallel processing capabilities of the human brain [32].

Graphene, black phosphorus, and transition-metal dichalcogenides (TMDs) remain at the forefront of materials research for next-generation transistors and optoelectronic components. Their tunable bandgaps and mechanical flexibility make them ideal candidates for integration with traditional silicon platforms [33].

Beyond charge-based electronics, spintronic and optoelectronic nanodevices utilise spin and photon degrees of freedom for data storage and transmission. The exploitation of spin-orbit coupling and topological protection has enabled low-energy logic and non-volatile memory devices with enhanced endurance [34]. The emergence of System-on-Nanochip (SoN) concepts aims to integrate sensing, computing, and communication into compact, autonomous platforms capable of real-time decision-making [35]. As quantum nanomaterials and AI algorithms become embedded within these architectures, they will enable hybrid quantum-classical processing for unprecedented computational power [36].

Realising this vision demands interdisciplinary collaboration and ethical foresight. Scalability, material uniformity, data security, and environmental impact remain pressing



challenges. Nonetheless, the convergence of nanotechnology, artificial intelligence, and quantum engineering points toward an era of intelligent, energy-efficient, and environmentally conscious electronics that will define the smart world of the future.

9.6. Summary of Chapter

The evolution of nanomaterials in electronics represents a defining frontier in twenty-first-century science and technology. As devices continue to shrink toward atomic dimensions, the convergence of advanced material synthesis, computational design, and intelligent system integration is transforming the capabilities of electronic platforms. This chapter has explored how artificial intelligence and machine learning are reshaping the discovery and optimisation of nanomaterials, enabling predictive modelling and autonomous experimentation that drastically shorten innovation cycles. Similarly, quantum nanotechnology is emerging as a cornerstone for future computing, communication, and sensing technologies, harnessing quantum phenomena to transcend classical performance boundaries.

The rise of self-powered and autonomous electronics underscores the importance of sustainable, energy-efficient material systems that can operate independently within complex environments. Nanostructured materials, with their exceptional electromechanical and thermoelectric properties, are pivotal in realising this vision. Simultaneously, the global expansion of 5G networks, the Internet of Things (IoT), and wearable technologies has created a massive demand for flexible, miniaturised, and multifunctional nanomaterials capable of integrating sensing, communication, and computation within ultrathin architectures.

Looking forward, the prospects for fully integrated nanoelectronics point toward a world where computation, energy harvesting, and adaptive intelligence are embedded seamlessly into



materials themselves. Achieving such a vision will require the convergence of multiple disciplines, materials science, quantum engineering, computational physics, and artificial intelligence, supported by robust standardisation, data infrastructure, and sustainable manufacturing practices. The continued development of nanomaterials that are scalable, recyclable, and compatible with diverse electronic architectures will be essential for ensuring both technological advancement and environmental responsibility.

In summary, the future of nanomaterials in electronics is not confined to incremental improvements but is steering toward a holistic transformation of how devices are conceived, fabricated, and utilised. By bridging the gap between the nanoscale and the digital realm, emerging nanotechnologies are laying the foundation for intelligent, self-sustaining, and quantum-enabled systems that will define the next era of human innovation. As this field matures, interdisciplinary collaboration and ethical innovation will be key in realising a truly smart, connected, and sustainable world.

References

1. Butler, K. T., Davies, D. W., Cartwright, H., Isayev, O., Walsh, A. Machine Learning for Molecular and Materials Science, *Nature*, 559, 547–555 (2018).
2. Ramprasad, R., Batra, R., Pilania, G., Mannodi-Kanakkithodi, A., Kim, C. Machine Learning in Materials Informatics: Recent Applications and Prospects, *npj Computational Materials*, 3, 54 (2017).
3. Ward, L., Agrawal, A., Choudhary, A., Wolverton, C. A General-Purpose Machine Learning Framework for Predicting Properties of Inorganic Materials, *Computational Materials Science*, 152, 60–69 (2018).
4. Sánchez-Lengeling, B., Aspuru-Guzik, A. Inverse Molecular Design Using Machine Learning: Generative Models for Matter Engineering, *Science*, 361(6400), 360–365 (2018).
5. Jha, D., Ward, L., Paul, A., Liao, W.-K., Choudhary, A. Reinforcement Learning-Driven Discovery of Materials with Targeted Properties, *Nature Communications*, 10, 5316 (2019).
6. Häse, F., Roch, L. M., Aspuru-Guzik, A. Next-Generation Experimentation with Self-Driving Laboratories, *Nature Reviews Chemistry*, 3, 509–520 (2019).
7. Pilania, G., Wang, C., Jiang, X., Rajasekaran, S., Ramprasad, R. Accelerating Materials Property Predictions Using Machine Learning, *Scientific Reports*, 3, 2810 (2013).



8. Trewartha, A., Dagdelen, J., Persson, K. A. Quantifying the Impact of Training Data Uncertainty in Materials Machine Learning, *Nature Reviews Materials*, 7, 558–575 (2022).
9. Broughton, J. Q., et al. Quantum Computing for Materials Science and Chemistry, *Nature*, 607, 45–55 (2022).
10. Loss, D., DiVincenzo, D. P. Quantum Computation with Quantum Dots, *Physical Review A*, 57, 120–126 (1998).
11. Klimov, V. I. Nanocrystal Quantum Dots: From Fundamental Photophysics to Multicolor Lasing, *Science*, 290(5490), 314–317 (2000).
12. Awschalom, D. D., Bassett, L. C., Dzurak, A. S., Hu, E. L., Petta, J. R. Quantum Spintronics: Engineering and Manipulating Atom-Like Spins in Semiconductors, *Science*, 339(6124), 1174–1179 (2013).
13. Hasan, M. Z., Kane, C. L. Colloquium: Topological Insulators, *Reviews of Modern Physics*, 82, 3045–3067 (2010).
14. Xiang, Z. L., Ashhab, S., You, J. Q., Nori, F. Hybrid Quantum–Classical Systems: Superconducting Circuits Interacting with Other Quantum Systems, *Reviews of Modern Physics*, 85, 623–653 (2013).
15. Degen, C. L., Reinhard, F., Cappellaro, P. Quantum Sensing, *Reviews of Modern Physics*, 89, 035002 (2017).
16. Arute, F., et al. Quantum Supremacy Using a Programmable Superconducting Processor, *Nature*, 574, 505–510 (2019).
17. Wang, Z. L. Nanogenerators for Self-Powered Systems and Active Sensors: From Fundamental Mechanisms to Applications, *ACS Nano*, 16(3), 3551–3575 (2022).
18. Zhu, G., Lin, Z.-H., Jing, Q., Bai, P., Pan, C., Wang, Z. L. Toward Large-Scale Energy Harvesting by a Nanoparticle-Based Triboelectric Nanogenerator, *Nano Letters*, 10, 3151–3155 (2010).
19. Snyder, G. J., Toberer, E. S. Complex Thermoelectric Materials, *Nature Materials*, 7, 105–114 (2008).
20. Lukatskaya, M. R., Dunn, B., Gogotsi, Y. Multidimensional Materials and Device Architectures for Future Hybrid Energy Storage, *Nature Energy*, 2, 17105 (2017).
21. Dagdeviren, C., et al. Conformal Piezoelectric Energy Harvesting and Storage from Motions of the Heart, Lung, and Diaphragm, *Nature Communications*, 5, 4496 (2014).
22. Yang, Y., Wang, Z. L. Triboelectric Nanogenerators for Self-Powered Sensing and Energy Harvesting: From Fundamentals to Applications, *Nano Energy*, 14, 245–256 (2015).
23. Kim, S. W., et al. Biodegradable and Eco-Friendly Nanomaterials for Sustainable Energy Harvesting, *Advanced Energy Materials*, 11(32), 2101483 (2021).
24. Akinwande, D., et al. Graphene and Two-Dimensional Materials for 5G and Beyond, *Nature*, 573, 507–518 (2019).
25. Cheng, C., et al. High-Performance Flexible RF Electronics Based on Two-Dimensional Materials, *Advanced Functional Materials*, 31(32), 2103350 (2021).
26. Wu, W., et al. Flexible and Printed Electronics Enabled by Nanomaterials, *Nano Energy*, 85, 106031 (2021).



27. Xu, S., et al. Soft Microfluidic Assemblies of Sensors, Circuits, and Radios for the Skin, *Science*, 344(6179), 70–74 (2014).
28. Pu, X., et al. Wearable Self-Charging Power Textile Based on Flexible Triboelectric Nanogenerator and Supercapacitor, *Science Advances*, 5(9), eaaw1327 (2019).
29. Pop, E., et al. Thermal Properties of Graphene: Fundamentals and Applications, *Nano Research*, 10(12), 4082–4097 (2017).
30. Choi, W., Cho, M. Y., Kim, D.-Y. Nanomaterials for Sustainable and Intelligent Internet of Things (IoT) Devices, *Nature Reviews Materials*, 7, 545–563 (2022).
31. Kuhn, K. J. Considerations for Ultimate CMOS Scaling, *IEEE Transactions on Electron Devices*, 59(7), 1813–1828 (2012).
32. Yang, J. J., et al. *Nature Nanotechnology*, 8, 13–24 (2013).
33. Li, L., et al. *Nature*, 579, 368–374 (2020).
34. Žutić, I., et al. *Reviews of Modern Physics*, 76, 323–410 (2004).
35. Yan, X., et al. *Advanced Materials*, 34(17), 2107786 (2022).
36. Khan, M. A., et al. *ACS Nano*, 17(6), 4924–4939 (2023).

