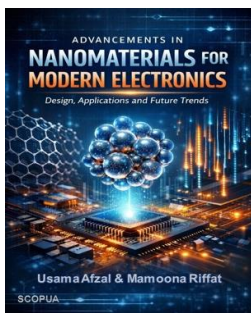


CHAPTER 3

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.

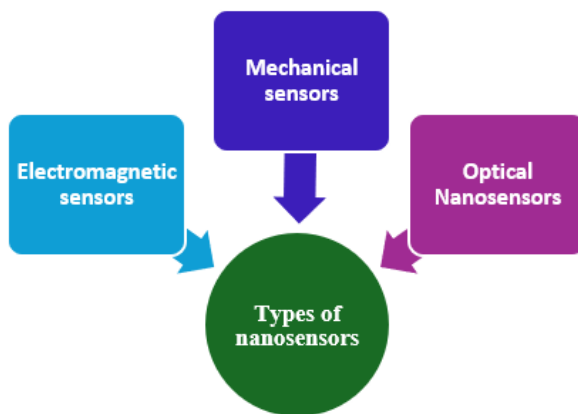


Figure 3.1: *Types of nanosensors based on structure.*

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].



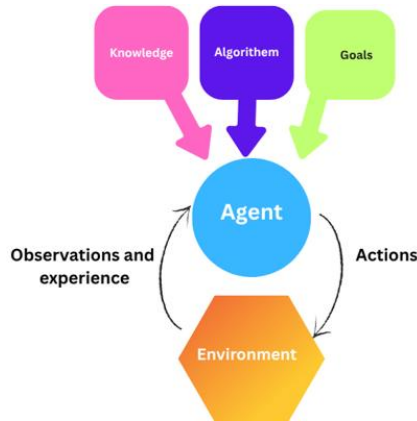


Figure 3.2: Block Diagram of an AI system

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.

