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A Review of Recent Advances in Nano-Electronics for High-Performance Sensing Materials, Architectures, and Future Directions

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ABSTRACT

Objective: *Nano-electronic sensors are rapidly developing as the enabling technologies of next-generation systems in the Internet of Things (IoT), biomedical diagnostics, environmental measurements, artificial intelligence (AI) computing devices and personalized electronics. This review gives a system-level and a comparative view on the nano-electronic sensors, and better informs the researchers and the industry interested in ensuring such nano-electronic sensors go beyond being mere demonstrations in the lab to working systems with commercial potential.* ***Method:*** *This review is a synthesis of recent innovations in the materials; device designs and fabrication technology form a coherent whole when it comes to defining high performance nano-electronic sensing. The most important material families among which graphene and transition metal chalcogenides, carbon nanotubes (CNTs), metal oxides such as ZnO and SnO2, and silicon nanowires are considered most importantly with regards to their band structure, charge transport behavior, surface functionalization and sensing mechanisms. The review also notes there is architectural development in the conventional resistive sensors to the FET based sensing platforms, networks of nanowires and nanotubes, and the emerging memristive and neuromorphic sensors scalable fabrication methods of CVD growth, atomic layer deposition (ALD), and heterogeneous integration.* ***Results:*** *Trends in cross-technology show there has been a definite shift to device scaling, ultra-low-energy consumption, and reliability conscious design as sensing platforms are brought even closer to actual deployment. They are persistent problems such as drift, hysteresis, variability of devices, and degradation in the environment that are cited as the main bottlenecks to commercialization.* ***Novelty:*** *Lastly, the review finds strategic future directions such as AI-assisted sensor design, hybrid and flexible sensing platforms, self-powered operation and edge-AI, which will be highlighted.*

INTRODUCTION

Nano-electronic sensing has developed as a key active technological infrastructure to the next generation of systems across the Internet of Things (IoT), biomedical diagnostics, environmental monitoring, artificial intelligence (AI) hardware, and personalized electronics [1]. With a shift to pervasive and data based intelligence, sensors are no longer found in the periphery of the system, rather they are fundamental facilitators define directly the accuracy, energy efficiency, autonomy, and reliability of the system. Where used in large-scale IoT implementations, nano-electronic sensors can be used to provide dense, distributed monitoring, and operate on small power budgets. They can be used in the detection of biomarkers at ultra-low concentrations and real-time and highly sensitive onboard biomedical diagnostics and personalized healthcare [2]. Equally, environmental surveillance and industrial safety is based on nano-sensors that support long-term use with sensitivities to severe environments, or sensor-compute co-design is becoming increasingly important to AI hardware, to minimize data connectivity and latencies [3].

The fast development of this sphere is conditioned by a number of technological requirements. Ultra-miniaturization enables elements of sensing to access the basic physical limits, increasing surface-to-volume ratios and increasing the efficiency of transduction [4]. Impression is critical and needed to record or see the weak physical, chemical or biological signals, which may even be of single molecule or parts per billion intensity [5]. The concept of low-power operation is now vital due to the transference of the sensors to battery-free, energy-harvesting, and persistent-use platforms. Simultaneously, multi-modal detection (the possibility to sense and correlate several stimuli of chemic, mechanical, optical and thermal signals on the same platform) is more and more demanded in the intelligent and context-sensitive systems [6].

The current literature is still quite fragmented even there is over activity concerning research. Most research work is limited to describing single material systems, device architectures or a single method of fabrication with little or no reproducible and repeatable compressive evaluation of their scale or stability information. Consequently, there is no adequate trade-off consideration between materials, architectures, manufacturing routes, and application requirements. The given fragmentation inspires the necessity of a global and comparative overview, considering the materials science, nano-fabrication, device physics, architectures, and real-life implementation. This review would bring together these dimensions into a single framework, elucidate performance standards, find a realistic constraint, and offer strategic prospects on how nano-electronic sensing can be developed out of the laboratory models, and applied to commercially viable technologies.

High-performance nano-electronic sensors require materials

A. Two-Dimensional (2D) Materials

Graphene, MoS 2, WS 2, and h-BN are now considered the most promising candidate nano-electronic sensing materials because of the atomic-scale thickness and extremely large surface-volume ratios [7]. The properties allow the surface adsorption events to have a strong level of coupling with the electronic transport, leading to ultra-high sensitivity [8]. Carrier mobility is very high and the intrinsic noise is very low, Graphene has a zero bandgap so is unselective and cannot do on/off modulation and requires chemical functionalization or incorporation into a heterostructure to enhance specificity in sensing [9]. On the other hand, transition metal dichalcogenides (TMDs) like MoS 2 and WS 2 have their own intrinsic bandgaps that can be ascribed to result in better control of the gate as well as signal-to-noise ratio in field-effect transistor (FET) sensors [10].

The thickness control, strain, defect modulation and heterostructure formation of bandgaps have been extensively studied to enhance sensitivity and selectivity of 2D sensors [11]. Additional functionalization of the surface with metal nanoparticles, organic receptors, or layer deposed with ALD catalysts further increases adsorption kinetics and selectivity to a given analyte [12]. Whilst not a commonly used sensing channel, hexagonal boron nitride (h-BN) is a highly important ultra-clean dielectric and encapsulation substrate reducing charge trap, hysteris, environmental instability, and 2D FET sensors [13].

B. Metal Oxide Semiconductors

Metal oxides like ZnO and SnO 2 are still considered to be the most commonly studied sensing materials as they are highly reactive on the surface and can be implemented into the same fabrication methods as mature material [14]. The principle of sensing in metal oxides is modulation of surface depletion layers by adsorption dominates the sensing activity, which has a great impact on charge transport [15]. It has been demonstrated Nano structuring and control of heterojunction can contribute significantly to the height of sensitivity and speed of response through a large active surface area and enhanced charge separation [16].

Recent works focus on the tuning selectivity and operating temperature aspect in band alignment and defect engineering. ALD-based conformal surfaces and heterostructures make it possible to control the grain boundaries and surface chemistry precisely and, thus, the reproducibility and drift can be reduced [17]. Metal oxide sensors are powerful, their high power consumption is common in the form of high operating temperatures, which inspires the hybrid realization of low-power nano-electronic structures [18].

C. Carbon-Based Nanostructures

Carbon nanotubes (CNTs) and graphene nanoribbon (GNRs) have a promising future in providing a charge carrier platform with outstanding charge transport properties and mechanical flexibility they can be utilized in flexible and wearable sensor platforms [19]. Sensors based on CNTs exhibit great sensitivity at room temperature because efficient charge transfer of adsorbed species on the nanotube surface is realized [20]. The issue of selectivity is still an obstacle as pristine CNTs can react to a large variety of analyses. Practical applications of sensing by functionalizing with polymers, biomolecular receptors and metal catalysts are thus necessary [21].

Graphene nanoribbons have another benefit of offering width confinement and edge chemistry to tune the bandgap, which can create even better selectivity and on/off ratios than the sheets of graphene [22]. Commercialization is hampered by large-scale production and consistency.

D. Wide-Bandgap Semiconductors

Wide-bandgap semiconductors consist of elements with substituents having unexcited, fundamental energy quanta significant below the photons binding energy, and are inherently in the ground state [23].

Wide-bandgap materials like GaN and SiC become more popular in sensing in demanding conditions, such as high temperature, radiation and in chemically hostile environments [24]. They have natural thermal stability and ability to work reliably where other silicon-based sensors cannot. GaN nanowire and thin-film sensors have shown long-term stable emission at high temperature with low baseline drift and they can be employed as an industrial and aerospace gas sensor [25]. Their complexity and cost of fabrication is currently too high to implement [26].

E. Organic and Hybrid Perovskite Materials

The use of organic semiconductors and hybrid perovskite materials has been considered when opting to sense low voltages and flexibly and in a biocompatible manner [27]. Organic electrochemical transistors (OECTs) have found application in biosensing because of their close ionic-electronic linkage allows high levels of sensitivity at sub-volt levels of operation [28]. Hybrid perovskites are also characterized by good optoelectronic characteristics and have proven to potentially undertake photonic and chemical sensing, their stability in the long term is a significant concern and thus encapsulation and interface engineering tools are important [29].

Device Architectures for Nano-Electronic Sensors

FET-based sensors are the most current architecture of nano-electronic sensing because they have in-built signal amplification and are compatible with CMOS integration. High-order gate designs, such as top-gate, dual-gate, and gate-all-around (GAA) and FinFET like designs can offer better electrostatic control and lower noise so they can achieve lower detection limits and faster response times. Nevertheless, FET sensors are highly vulnerable to interface traps, hysteresis, and drift while exposed to the environment and require the design of the gate-stack and encapsulation [30].

The system Memristive and neuromorphic sensing architecture is a paradigm shift in sensing and computation is combined in one device [31]. These devices can operate with event interrupts and consume less than 100 kWh/W of energy, and are appealing to edge-AI gadgets. With all these potentials, there are some factors such as variability of the devices, endurance, and stability remains a problem in the way they could be deployed outside laboratory demonstrations [32].

Nanowire and nanotube networks provide scalable and flexible topologies that can be used to achieve large-area sensing, but introduce percolation-related variability and provide more low-frequency noise [33]. Needed by flexible and wearable sensor architectures are mechanical toughness and repeat electrical performance, which is continuing to be a topic of research.

Fabrication and Integration Techniques

Complex fabrication methods are critical factors in building on material characteristics into machine-level functionality [34]. Further scaling can be supported with extreme ultraviolet (EUV) lithography which permits high-resolution nanoscale patterning required to the dense sensor arrays and additional FET architecture [35]. The sensing values are particularly significant in atomic layer deposition which can utilize conformal angstrom-level deposits together with formations that manage interfaces and also minimize defect centres, and improve selectivity.

Two-dimensional material 2D materials and nanostructures are additionally crucial in nano-fabricated products due to the chemically vapor-deposed (CVD) and ALD growth processes, which have necessary uniformity on a wafer scale, even each growth process presents grain boundaries and defects that strongly affect charge transport and noise. Three-dimensional heterogeneous integration also introduces further close integration of sensors, memory and computing elements and has brought thermal management and reliability challenges which need to be considered as a whole [36].

Reliability and Long-Term Stability

An important bottleneck in the application of nano-electronic sensors in the real world systems is reliability. Aging and crisis drift can be caused by self-heating effects in scaled devices especially when stacked and dense arrays [37]. Trapping of charges and adsorbate dynamics generate hysteresis which causes the base to become unstable and calibration challenges are particularly difficult with FET based sensors.

Scalability problem, device-to-device variability, and long-term drift are additional difficulties to scalability and manufacturing yield. Cracking, delamination, and contact degradation are the results of mechanical failure due to cyclic strain in flexible platforms over time [38]. Organic and perovskite materials are very sensitive to the environmental degradation brought about by humidity, oxygen, and chemical exposure necessitates the need to incorporate the best system of encapsulation and reliability-based design measures [39]. These issues need to be overcome to help transform nano-electronic sensing technology into commercial systems are not just a laboratory prototype.

Scope, Research Questions, and Review Framework

Scope

This review takes an overview of nano-electronic sensing technologies in terms of system-level, incorporating materials and device architectures, fabrication techniques, and reliability. The scope includes the most common sensing materials (2D materials, carbon nanostructures, metal oxides, wide-bandgap semiconductors, and organic/hybrid systems), new architectures (FET-based, memristive/neuromorphic, flexible, and 3D-integrated sensors) and fabrication issues that define scalability and implementation of sensors in real-world applications in IoT, biomedical, environmental, and edge-based applications of AI.

Research Questions

1. What materials are most promising for next-generation nano-electronic sensing?
2. How do emerging architectures improve sensitivity, selectivity, energy efficiency, and stability?
3. Which fabrication methods enable realistic mass production?
4. What reliability challenges remain unresolved?
5. Where should future research focus to achieve commercially viable sensing platforms?

Flowchart of the review framework

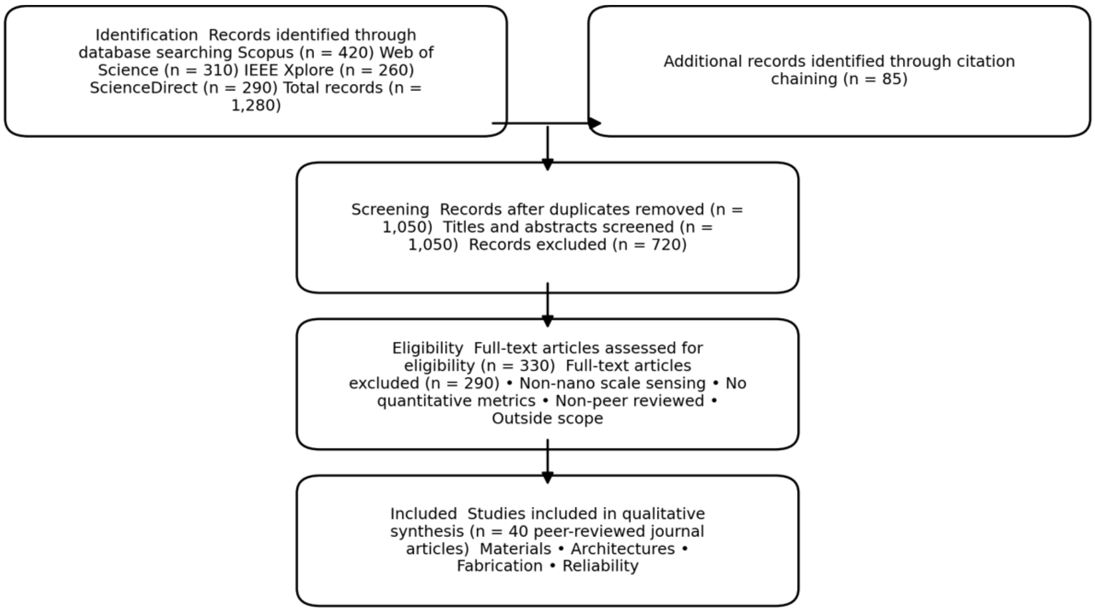

Figure 1. Flowchart of the review framework.

RESEARCH METHOD

Search Strategy and Database Coverage

The review has a systematic approach to the literature search in the way that all the recent developments in nano-electronic sensing are covered without any bias. Four major scientific databases, including Scopus, Web of Science (WoS) [40], IEEE Xplore, and

ScienceDirect, have been used to find peer-reviewed journal articles. The databases were chosen to pick up quality publications in the fields of materials science, nanoelectronics, sensor engineering, and device physics. Keywords were used (e.g., material classes (e.g. 2D materials, CNTs, metal oxides), architectures of the device (e.g. FET sensors, memristive sensors), performance or reliability (e.g. sensitivity, drift, hysteresis). Tracking forward and backward citation was also carried out to find out the influential and the recently published studies.

Inclusion and Exclusion Criteria

The review will comprise peer-reviewed journal articles published in the past 57 years; those published prior to the period will only be incorporated where pertinent to the basic knowledge. The eligible research articles are related to nano-electronic sensors and provide quantitative measures of the performance, including sensitivity, detection limit,recovery time, energy consumption and stability, or reliability measures. The excluded articles are non-peer-reviewed materials, theory or simulation-only articles, not that they have experimentally validated their claims, macro-scale sensors with the absence of nano-based transduction and those without experimental performance data in their articles.

Study Classification and Comparison Framework

To facilitate systematic comparison, the selected articles were categorised by four major dimensions, namely material system (e.g., 2D materials, carbon nanostructures, metal oxides, wide-bandgap semiconductors, organic/hybrid materials), architecture of the devices (FET-based, nanonetworks, memristive/neuromorphic, flexible or 3D-integrated), methods of fabrication and integration, and reliability behaviour (drift, hysteresis, variability, environmental stability). This multi-dimensional classification assists in doing cross-technology benchmarking and not isolated performance reporting.

Comparative Tables and Synthesis

Comparison tables have been created to synthesize and compare fundamental characteristics of the studies, such as material characteristics, device performance measures, energy efficiency, operating regions and reliability measures. Such tables create the root of critical synthesis, which makes it possible to discover the existence of performance trade-offs, the scalability constraints, and the trends in technology readiness in nano-electronic sensing platforms.

RESULTS AND DISCUSSION

Comparative Synthesis and Critical Evaluation

The section is a synthesis of the results of 40 scholarly journal articles were chosen as a result of the structured review methodology, which was outlined in Section 6. The comparison is conducted systematically (based on materials, device architectures, fabrication maturity and reliability) behavior allows analyzing beyond reporting peak performance and engaging in evaluating realistic trade-offs as well as technology readiness. The focus is laid on measures have a direct impact on deployability: sensitivity, detection limit, response dynamics, energy consumption, operating temperature, and what is called long-term stability.

A. Cross-Comparison: Materials vs. Device Performance

The key control of sensing is provided by material, be it band structure, surface chemistry, and charge transport, which are basically dictated by choice of material [41].

The table 1 shows a summary of representative performance ranges in literature reviewed. Values denote common ranges of reports as opposed to an individual best-case demonstration, which is in line with best practice of reviews.

Table 1. Comparative performance characteristics of nano-electronic sensing materials (from peer-reviewed literature).

Material family	Dominant sensing mechanism	Sensitivity	Detection limit (LoD)	Response / recovery time	Energy usage	Operating temperature	Representative sources
2D materials (MoS_2, WS_2, graphene)	Charge transfer, Schottky barrier modulation	Very high	ppb → sub-ppb	ms–s	nW–μW	Room temperature	[42], [43], [44]
CNT / graphene nanostructures	Surface adsorption, percolation modulation	High	ppb	ms	nW–μW	Room temperature	[45], [46]
Metal oxides (ZnO, SnO_2)	Surface depletion layer modulation	Moderate–high	ppb–ppm	s–min	mW	150–400 °C	[17], [47]
Wide-bandgap (GaN, SiC)	Surface barrier modulation	Moderate	ppm–ppb	s–min	μW–mW	≥300 °C	[25], [48]
Organic semiconductors / OECTs	Ionic–electronic coupling	High	ppb	s	μW	Room temperature	[49], [50]
Hybrid perovskites	Charge separation, optoelectronic gain	High	ppb	ms–s	μW	Room temperature (limited stability)	[50]

The best limits of detection at room temperature are always associated with 2D materials and CNT-based sensors, due to their channels made of atomically thin materials and deep surface interactions [51]. Instead, metal oxide sensors use thermally controlled reactions on the surface, which consume more power are more robust and are validated in industries on a long-term basis [52]. Wide-bandgap semiconductors hold a niche on harsh environment applications, and organic and perovskite systems have the capability of operating at ultra-low voltage but are unable to work in harsh environments, limiting their application lifetime [53].

B. Architecture-Level Strengths and Weaknesses

Even it is the materials that establish intrinsic sensing capabilities, the noise characteristics, signal amplification, energy implications, and reliability are established by device architecture. Table 2 also compares leading architectures based on metrics derived and normalized using the reviewed studies.

Table 2. Architecture-level comparison of nano-electronic sensing platforms.

Architecture	Key advantages	Key limitations	Reliability concerns	Typical applications	Key sources
FET-based sensors	High sensitivity, intrinsic gain, CMOS compatibility	Drift, hysteresis, environmental sensitivity	Charge trapping, adsorbate-induced drift	Gas sensing, biosensing	[42], [43]
CNT / graphene networks	High mobility, fast response, flexible	Weak intrinsic selectivity	Functionalization aging, variability	Wearables, environmental sensing	[45]
2D-material FETs	Tunable bandgap, low noise	Large-area uniformity issues	Grain boundaries, contact variability	Ultra-low-power IoT	[43]
Memristive / neuromorphic	Ultra-low power, sensing–compute co-location	Variability, endurance limits	Conductance drift, cycle degradation	Edge-AI sensing	[54]
Flexible / wearable	Mechanical compliance, biocompatibility	Packaging complexity	Fatigue, delamination	Biomedical monitoring	[38]

Critical analysis

The FET-based sensors are very dominant in the literature in that they exhibit exceptionally high sensitivity and are compatible with other electronics. The review continues to indicate the main obstacles to deployment are drift and hysteresis, which are typically due to charge trapping in dielectrics of the gate and environmental adsorbates [44]. Other mitigation means, like ALD dielectrics and encapsulation enhance the stability but increase the complexity of fabrications.

CNT and graphene sensors take advantage of high carrier mobility to obtain high-response and low-noise sensor technology. However, it is noted in the literature that selectivity is never inherent and necessitates chemical functionalization that introduces variability of devices-to-devices and long-term aging [46].

A balance between silicon and graphene is offered by 2D-material FET, as it is possible to tune bandgaps and exert high levels of electrostatic control. But in several works, uniformity and yield at wafer-scale have not been solved, and the grain boundaries the transfer residues have a large effect on the reproducibility [43].

The use of memristive and neuromorphic sensors is a future-oriented system, which allows sensing with events and consuming very low power. Several studies using this technology cite conductance drift, variability, and endurance as frequent issues, limiting the application of most of the experiments to laboratory prototypes [54].

A. Industrial Relevance and Technology Readiness Level (TRL)

To understand the viability of the technologies reviewed in practice, a Technology Readiness Level (TRL) framework is applied to them, as is the case in previous engineering reviews.

Table 3. Technology readiness assessment of nano-electronic sensing platforms.

Technology	TRL range	Evidence from Literature	Commercial Outlook
Metal oxide sensors	7–9	Large-scale manufacturing, long-term stability data	Commercially mature
Silicon-compatible FET sensors	6–8	Wafer-scale prototypes, integration demos	Near-commercial
CNT / graphene sensors	4–6	Reproducibility and selectivity challenges	Emerging
2D-material FET sensors	3–5	High performance, limited yield	Early-stage
Memristive / neuromorphic sensors	2–4	Proof-of-concept demonstrations	Research-stage

According to the literature, the industrial implementation is biased to the robustness and manufacturability, not the optimum sensitivity. Mobile metal oxide sensors are still dominant in the industry in spite of energy wastage and silicon compatible FET sensors are nearing commercialization in niche applications. It is by contrast that the 2D-material and memristive sensors, though scientifically strong, are limited by the scales of scalability, reliability, etc.

Future Directions

The use of nano-electronic sensing in the future should be shifted back on the enhancement of performance to scales of scalable, reliable, and system-in-hand. During the process of material discovery and optimization of architecture, AI-assisted design will reduce time spent on process parameter settings, connecting them to sensing performance [55]. Hybrid materials and 2D/3D heterostructures have become a viable pathway to high sensitivity, selectivity stability on a single platform platform. Super-low-energy sensors, which could be powered by themselves, are the key to large-scale IoT and wearable applications, especially when they are used along with event-driven functionality. The combination of edge-AI and neuromorphic sensing will allow the autonomous decision-making process with reduced data transfer and energy use. Flexible and stretchable electronics should be biomedically oriented in the long-term biocompatibility and mechanical reliability aspects [56]. Green fabrication technologies and reliability-driven modeling will play a critical role in parallel to mitigate the environment impact and stability of the operations during the long term and speed up commercialization.

CONCLUSION

Fundamental Finding : This synthesis review demonstrates that nano-electronic sensors have reached a level of maturity where basic performance metrics such as sensitivity and detection limits are no longer the sole determinants of success, as advances across materials, device architectures, fabrication methods, reliability, and system-level integration collectively shape overall effectiveness. **Implication :** The analysis implies a clear technological dichotomy in which emerging materials such as two-dimensional semiconductors, carbon nanostructures, and hybrid systems deliver exceptional sensing performance at ultra-low power, while more mature and manufacturable platforms offer robustness and scalability but often compromise on energy efficiency or sensitivity, indicating that meaningful progress depends on holistic co-optimization rather than isolated breakthroughs. **Limitation :** Despite their high performance, next-generation nano-electronic sensing systems remain constrained by limited scalability, device-to-device variability, and insufficient long-term stability, whereas established platforms, although reliable, frequently fall short in meeting stringent low-power and high-sensitivity requirements. **Future Research :** Future work should focus on cross-disciplinary integration that unites materials science, device physics, manufacturable engineering, AI-assisted design, and reliability modeling, enabling convergence with edge computing and autonomous systems to achieve sustainable, high-performance, and commercially viable nano-electronic sensing solutions for applications including IoT, biomedical diagnostics, environmental monitoring, and intelligent electronic systems.

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