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An Introductory Review of Carbon Nanotube-Based Sensors: Mechanisms, Fabrication, and Applications

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ABSTRACT

Carbon nanotubes (CNTs) have attracted significant attention in sensor technologies due to their exceptional electrical conductivity, mechanical flexibility, and high surface reactivity. This review provides an in-depth overview of CNT-based sensors, covering their working principles, fabrication techniques, and major application areas. We begin by exploring the fundamental mechanisms underlying CNT sensing behavior—such as piezoresistivity, tunneling effects, and percolation conduction—followed by a discussion of common fabrication methods, including solution processing, printing, and composite integration. Key applications are highlighted, including wearable strain sensors for human motion detection, gas sensors for environmental monitoring, and self-sensing materials for structural health diagnostics. While CNT-based sensors offer clear advantages in sensitivity and form factor versatility, challenges such as material uniformity, signal stability, and long-term durability remain. We conclude by discussing future directions and strategies to overcome these limitations, aiming to guide the development of robust, scalable CNT-enabled sensing systems. This review serves as a timely resource for researchers and engineers seeking to understand and advance CNT-based sensor technologies.

1. Introduction

Carbon nanotubes (CNTs) have emerged as one of the most promising nanomaterials for advanced sensor applications. CNTs, which can be either single-walled (SWCNT) or multi-walled (MWCNT) depending on the number of concentric graphene layers, possess extraordinary properties that are highly advantageous for sensing [1-3]. They exhibit ultrahigh aspect ratios, low density, excellent mechanical strength, and high electrical conductivity, as well as chemical and thermal stability [4, 5]. These characteristics enable CNT networks to form lightweight, conductive and mechanically robust sensing elements that can respond sensitively to various external stimuli. In particular, the large specific surface area (with virtually every atom exposed in a SWCNT) makes them extremely sensitive to surface perturbations such as molecule adsorption or mechanical deformation

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[6, 7]. This combination of properties – high surface-to-volume ratio, flexibility, and conductivity – underpins the significance of CNT-based sensors across a wide range of fields.

CNT-based sensors have seen increasing adoption in diverse applications, including wearable and flexible electronics, environmental monitoring, and structural health diagnostics. In wearable technology, flexible sensors made with CNTs can conform to the human body and monitor physiological signals or motions without restricting movement [1, 8-10]. For example, CNT–polymer composite strain sensors have been developed to track human motion (such as joint bending or muscle activity) due to their lightweight and skin-compatible design [1, 8]. These sensors leverage the piezoresistive effect of CNT networks – i.e. their electrical resistance changes under strain – to transduce deformations into measurable electrical signals. The high tensile strength and elasticity of CNTs, when embedded in a soft polymer matrix, allow such sensors to withstand large deformations (often hundreds of percent strain) while maintaining functionality [8]. Moreover, CNT networks tend to form percolating conductive paths that can self-reconnect after strain, providing a degree of self-healing and repeatability under cyclic loading [1]. This has positioned CNT-based wearable sensors as key components in emerging soft robotics, electronic skins, and personalized health monitoring devices.

CNT nanocomposites offer a material-integrated sensing approach: by dispersing a small fraction of CNTs into an insulating matrix (like epoxy, concrete, or polymer coatings) [11], one can create a material that is electrically conductive and whose conductivity changes under mechanical strain or cracking [12, 13]. The addition of CNTs effectively forms a network of conductive paths (a percolation network) inside the material, enabling it to "feel" and report deformation. When the structure is strained or if micro-cracks form, the CNT network's connectivity is disturbed, leading to a measurable rise in electrical resistance. This piezoresistive self-sensing has been demonstrated in CNT-reinforced composites for monitoring of stress in composites and detection of cracks or damage in real time [11]. For instance, epoxy matrices with <0.1 wt% CNT can reach an electrical percolation threshold and exhibit large resistance changes with strain, suitable for sensing structural deformation [11]. Such CNT-based sensors are attractive because they can be lightweight, passive (requiring only a simple resistance measurement), and scalable over large surfaces. They can complement or replace traditional sensors by providing continuous, distributed monitoring throughout the material's lifecycle.

Environmental and gas sensing is another domain where CNT sensors have demonstrated significant impact [14-17]. Owing to their nanoscale dimensions and conductive surfaces, CNTs are intrinsically sensitive to the adsorption of gas molecules [6]. Even extremely small quantities of gases such as ammonia (NH_3), nitrogen oxides (NO_2), or volatile organic compounds can induce measurable changes in CNT electrical properties [6]. The mechanism typically involves charge transfer or dipole interactions: electron-donating gases (like NH_3) or electron-withdrawing gases (like NO_2) alter the charge carrier concentration in semiconducting CNTs, thereby modulating their resistance. CNT sensors can achieve detection of hazardous gases at ppm or sub-ppm concentrations [18]. Functionalization of CNTs provides a route to enhance selectivity and sensitivity: attaching chemical groups like –COOH or –OH on CNT surfaces increases responses to polar gases by improving adsorption, yielding much higher signal changes compared to pristine CNTs [6]. Additionally, decorating CNTs with metal nanoparticles or polymer coatings can introduce specific binding sites for target analytes, further tuning sensor selectivity. These advances underscore the importance of CNT-based gas sensors in environmental monitoring, industrial safety, and even medical diagnostics (e.g. breath analysis).

Fundamental Sensing Mechanisms: Central to all these applications are the fundamental mechanisms by which CNT-based sensors transduce stimuli into electrical signals. Three primary effects govern the electromechanical or chemoelectrical response of CNT networks: (1) the intrinsic piezoresistivity of the nanotubes, (2) the contact resistance changes at CNT–CNT junctions, and (3) the quantum tunneling between neighboring CNTs [11, 19-21]. The concept of a percolation network is especially important for CNT sensor behavior. When CNTs are dispersed in a non-conductive medium, there exists a critical filler concentration – the percolation threshold at which an infinite conductive network first forms across the material [22]. Below this threshold, the composite is essentially insulating; above it, the conductivity rises rapidly as more conductive pathways percolate through the material. Near the threshold, the network is tenuous, and the conductivity can be extremely sensitive to perturbations – a slight deformation can break or reconnect critical links, causing large resistance shifts. This is advantageous for sensor design: by tuning the CNT content close to the threshold, one can maximize the gauge factor (sensitivity). However, operating too close to the threshold also means the base conductivity is low and the network may become unstable or noisy. Thus, an optimal CNT concentration often exists that balances conductivity and sensitivity [8]. For example, a study on stretchable silicone–CNT sensors (Figure 1) found an optimal loading around 2 wt% CNT (just above percolation): this yielded high sensitivity across a wide strain range, with gauge factors increasing from ~1.8 at 50% strain to ~37 at 500% strain [8]. By contrast, higher CNT loadings (3–4 wt%) resulted in much lower gauge factors (~2 or less at high strain) due to the network being denser and more robust (less change in connectivity under strain) [8]. Such results highlight the fundamental trade-off between conductivity and sensitivity governed by percolation, and illustrate why controlling CNT network morphology is key to sensor performance.

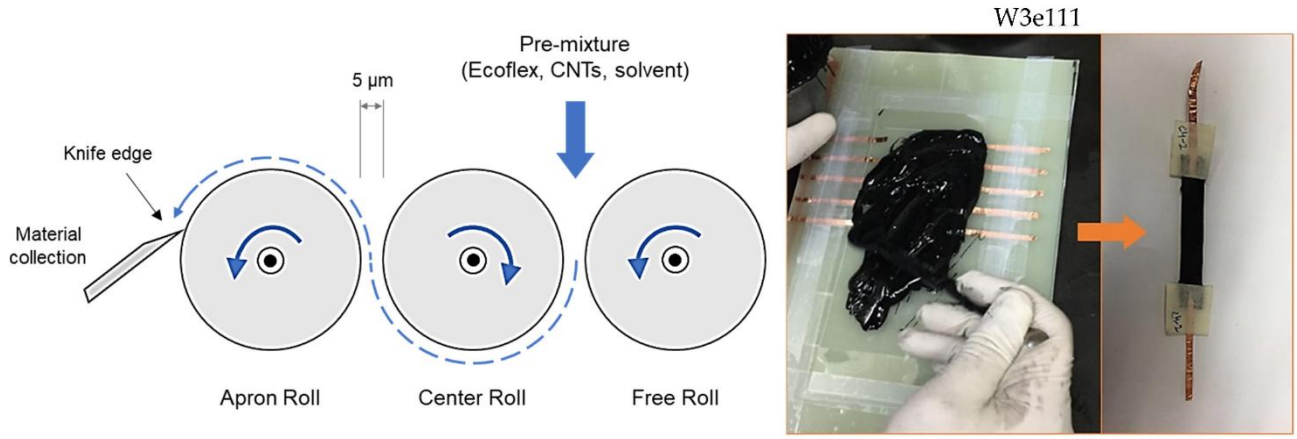

Fig. 1. Preparation of CNT-embedded sensors: (a) Schematic of mixture passing from three-roll milling machine; (b) prepared specimen [8]. Reproduced from ref. [8] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License).

In this review, we provide a comprehensive and application-oriented overview of CNT-based sensors, with a particular emphasis on how their percolation behavior and nanoscale charge transport mechanisms underpin performance. We connect fundamental sensing principles with real-world implementation, highlighting recent progress and remaining challenges in tunability, selectivity, and scalable manufacturing.

2. Fabrication Techniques

Given that CNTs are produced as powders or suspensions, a common route to create CNT sensor films is through solution processing [23-27]. CNTs can be dispersed in solvents (often with the aid of surfactants or polymer binders) and then deposited onto substrates by techniques such as drop-casting, spin-coating, spraying, or vacuum filtration. For example, a homogeneous CNT thin film can be spray-coated by moving a spray nozzle over a substrate while depositing a CNT ink [28]. According to Figure 2, Spray deposition allows control of film thickness by adjusting the number of passes or the ink concentration; as the volume sprayed increases, a visible network of CNTs forms and eventually yields a percolated film (e.g., ~8 nm thick film formed at a certain spray volume) [28]. Vacuum filtration through a membrane is another method to create uniform CNT networks, which can then be transferred to flexible substrates. Solution deposition is relatively simple and has been used to fabricate both resistive sensors and transistor channels. However, achieving uniform dispersion is critical – techniques like ultrasonication with dispersants and in situ mixing help minimize CNT agglomerates [8]. Post-deposition, techniques like annealing or plasma treatments are sometimes employed to improve film conductivity (by removing residual surfactants or promoting intertube contact) [28, 29]. For instance, an O_2 plasma etching can burn off polymer residue and shorten CNT junction distances, thereby reducing resistance. Overall, solution-based deposition is versatile and widely used for making films on various substrates (flexible plastics, papers, etc.), though achieving uniformity and repeatability of the CNT network remains challenging at large scale. In particular, surface energy plays a critical role in ensuring high-quality CNT coatings; however, accurate characterization of surface properties at the nanoscale remains difficult and warrants further research [30-32].

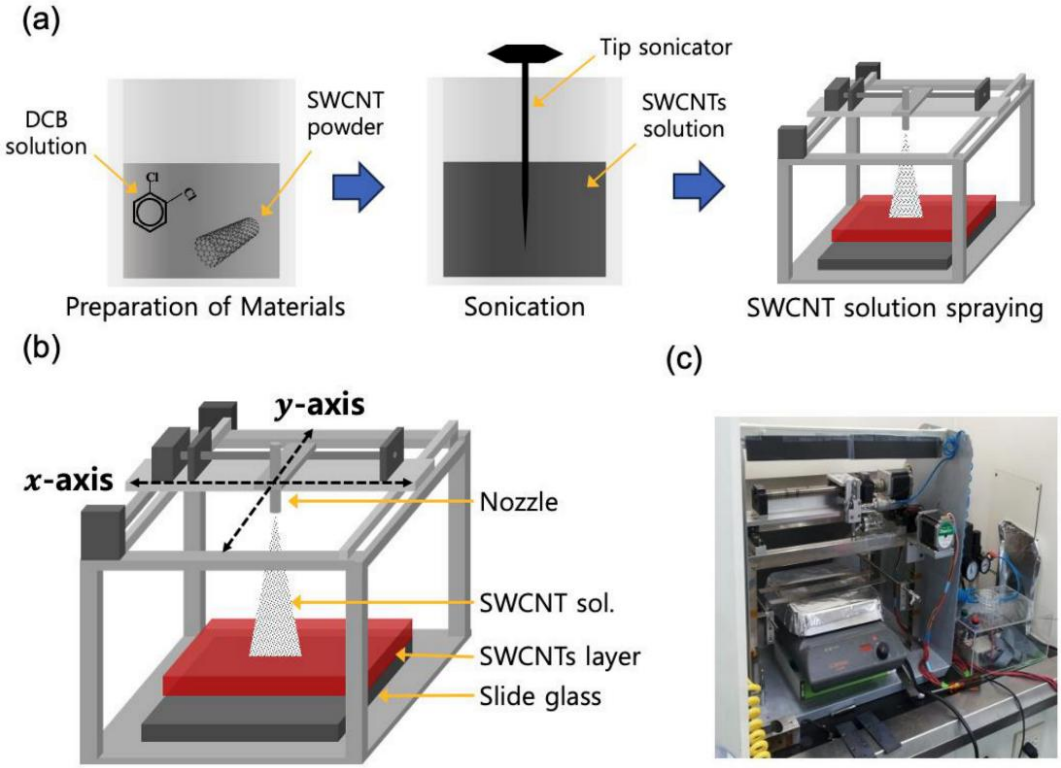

Fig. 2. (a) Schematic of the SWCNTs solution preparation process. Homemade spray device with spray nozzle movable in *x*-, *y*-, and *z*-axes. (b) Schematic diagram and (c) a photograph of the spray device [28]. Reproduced from ref. [28] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License).

Printable CNT-based inks have opened the door to patterning sensors directly onto surfaces with fine control [33-35]. Screen printing involves using a stencil to transfer a CNT paste onto substrates; it's a rapid method suitable for relatively thick films and has been used for strain gauges and electrodes. Inkjet printing offers higher resolution and material efficiency by ejecting tiny droplets of CNT ink in a defined pattern [6]. CNT inks can be printed in interdigitated patterns to serve as chemiresistors. Inkjet printing's advantages are digital design (no mask needed), additive deposition only where needed, and compatibility with flexible electronics fabrication. Challenges include formulating stable CNT inks (preventing nozzle clogging, maintaining dispersion) and ensuring sufficient film thickness via multiple print passes. There are reports of combining printed CNT layers with other materials – e.g., printing a composite PEDOT:PSS–CNT ink – to improve film uniformity and adhesion [29].

Many CNT sensors are realized as composites where nanotubes are embedded in a bulk polymer or elastomer matrix to form a flexible sensing material. To fabricate these, CNTs are typically mixed with the liquid polymer precursor or dissolved polymer, and then the mixture is cured or solidified. Composite sensors often require patterning of electrodes or specific shapes [36-39]. This can be done by molding (pouring the CNT–polymer mix into a mold of the desired sensor shape or thin-film) or by cutting the cured composite into sensor elements. Alternatively, one can fabricate a layered structure, such as a sandwich of pure elastomer/CNT composite/pure elastomer, to encapsulate the CNT network for better stability [1].

Carbon nanotubes (CNTs) can be synthesized through a variety of techniques, among which arc discharge, laser ablation, and chemical vapor deposition (CVD) are the most commonly employed. Historically, arc discharge [40-43] and laser ablation [44-47] have been favored for producing high-quality single-walled (SWCNT, Figure 3 (b) left) and multi-walled carbon nanotubes (MWCNT, Figure 3 (b) right), due to their ability to yield structures with excellent crystallinity. However, the CVD method has emerged as a promising alternative owing to its controllability over nanotube dimensions and growth conditions [48-50]. A schematic representation of the CVD process is illustrated in Figure 3 (a).

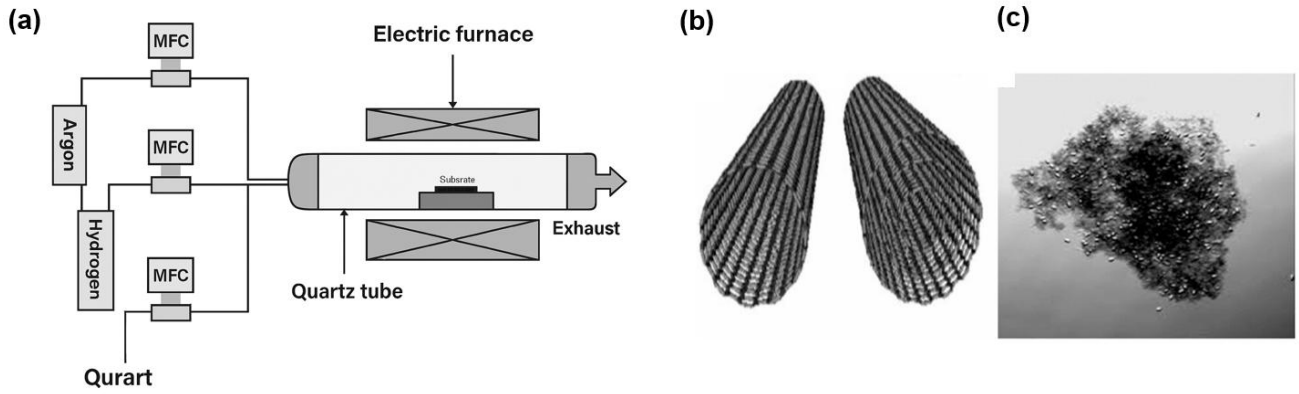

Fig. 3. (a) Schematic structure of CNTs. (b) SWCNTs (left) and MWCNTs (right); (c) visible of CNTs in naked eyes [51]. Reproduced from ref. [51] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License).

Unlike arc discharge and laser ablation, which typically require extreme temperatures and vacuum conditions, CVD offers a more cost-effective and scalable route by enabling synthesis under relatively mild thermal and pressure environments. Although the CNTs fabricated via CVD tend to exhibit lower crystallinity than those grown by physical methods, the CVD technique demonstrates

clear advantages in terms of material purity and functional performance. Furthermore, CVD remains the only method capable of fabricating structurally controlled CNT architectures with high spatial precision. The versatility of CVD lies in its capacity to utilize hydrocarbon precursors in various physical states—solid, liquid, or gas—and to support growth on a broad range of substrates. It also facilitates the formation of CNTs in diverse morphologies, including powders, thin and thick films, vertically or randomly aligned arrays, and even complex geometries positioned selectively on patterned surfaces. Importantly, process parameters such as temperature, gas flow rates, and reaction time can be finely tuned to achieve the desired CNT properties [39].

Jiadong *et al.,* [52] reported a facile, cost-effective approach for fabricating CNT-based chemical sensors operable at room temperature. Vertically aligned CNT arrays (CNTA) were synthesized via thermal chemical vapor deposition (CVD) and integrated with silk fibroin to enable substrate delamination without aggressive acid or sonication treatments. Leveraging the CVD-based CNT synthesis outlined earlier, this work demonstrates how the same thermal CVD process can be directly employed to fabricate high-performance chemical sensors. Subsequent in situ polymerization of aniline on the CNT arrays produced polyaniline (PANI)-functionalized sensors that exhibited markedly enhanced detection of ammonia (NH_3) and hydrogen chloride (HCl) vapors. The chemically modified arrays also responded reproducibly to organic vapors such as menthol, ethyl acetate, and acetone. Despite exhibiting detection limits comparable to prior reports, this method stands out for its simplicity, low fabrication cost, and energy efficiency. Additionally, the sensors demonstrated rapid response and recovery times—achieving 90% of full-scale response in under 20 s – while maintaining a linear relationship between relative sensitivity and analyte concentration, enabling precise quantification of trace vapors. These characteristics underscore the route's practical potential for scalable, low-energy sensor production [52].

Many studies [52-59] have proven that laser exposure is also a useful method for manufacturing CNT-based applications. The electrical conductivity and sensitivity characteristics of the sensor were enhanced through laser exposure, which facilitated the formation of stable carbon nanotube (CNT) networks.

Nikitina *et al.,* proposed a fabrication approach in which multi-walled carbon nanotubes (MWCNTs) dispersed in a PDMS elastomer matrix are first patterned via screen printing and then subjected to laser irradiation to enhance the conductivity of the resulting composite [60]. The process enables the development of flexible strain sensors suitable for gesture recognition, achieving low resistance (~3 kΩ), high sensitivity (gauge factor ≈10), and rapid response time (1 ms) when a low concentration (3 wt%) of MWCNT is used. As illustrated schematically (Figure 4), the procedure starts with uniform mixing of MWCNT and PDMS in a 3:97 weight ratio, followed by degassing under vacuum. The mixture is deposited into a mold using a screen-printing method and sandwiched between two PDMS protective layers, forming a multilayered sensor with a total thickness of 1 mm. After curing, the sensor is exposed to controlled laser scanning. This laser exposure locally heats the composite, promoting the formation of inter-nanotube junctions and creating a denser and more efficient conductive network.

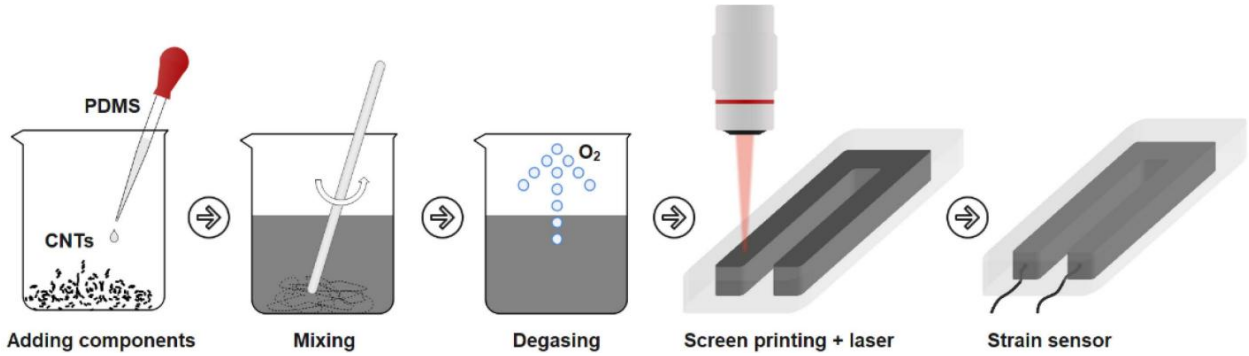

Fig. 4. (a) Schematic diagram of sensor manufacturing [60]. Reproduced from ref. [60] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License)

Microscopic images (Figure 5) show the structural transformation induced by the laser step. Before irradiation, CNTs tend to aggregate into large, irregular clusters. After laser exposure, these clusters become more evenly distributed and fragmented into smaller units. At higher magnification, direct bonding points between adjacent nanotubes become apparent, suggesting that the laser treatment facilitates localized connection and simplifies the network topology, thus improving electrical conductivity and mechanical responsiveness [60].

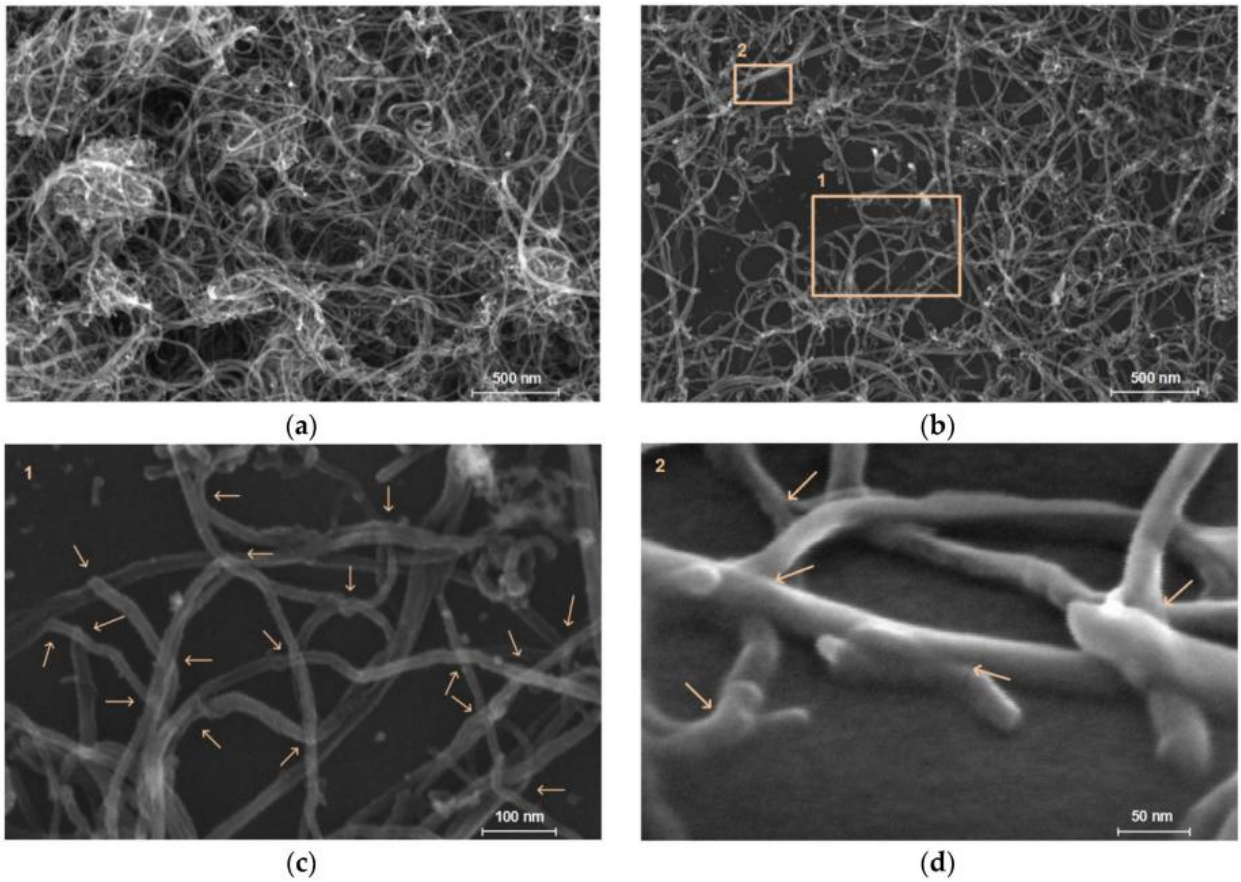

Fig. 5. Internal structure of the sensors with enlargement mode ×120,000: (a) fabricated without laser exposure and (b) with laser exposure. Enlarged areas of laser-irradiated sensors: (c) Area 1 with enlargement mode ×500,000, (d) Area 2 with enlargement mode ×1,000,000 and at 52◦ angle. The arrows indicate the welded areas of the nanotubes formed by the laser exposure [60]. Reproduced from ref. [60] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License).

3. Applications

CNT-based sensors find use in a broad array of applications owing to their flexibility in design and high sensitivity. In this section, we highlight three primary application areas: (1) wearable and flexible sensors (for human motion and health monitoring) and (2) gas and chemical sensors (for environmental and safety monitoring).

One of the most exciting applications of CNT sensors is in wearable electronics and human-health monitoring. The flexibility and skin-like compliance of CNT-based materials make them ideal for integrating with the human body or clothing to capture motion, strain, or physiological signals. A classic example is a flexible strain sensor for detecting joint or muscle movement. Wearable CNT sensors are not limited to strain; they have also been explored for pressure, tactile sensing, and even electrophysiological signal recording. CNT networks on thin films can act as pressure sensors by compressing the network and changing resistance when pressed (useful in electronic skin to sense touch or pressure distribution). Another area is flexible electrodes: CNT films are conductive and can make good skin-contact electrodes for ECG or EMG measurements. Unlike rigid metal electrodes, CNT-based electrodes can be dry (no gel needed) and conformal, with added benefits of lower biofouling [2].

By integrating a percolating CNT network into the material or coating, the entire material becomes a sensor (Figure 6) that can yield information about strain distribution or the occurrence of cracks [11]. Under elastic strain, the resistance increases due to the piezoresistive mechanisms. If a microcrack forms, it can cause a more significant, often irreversible jump in resistance because it physically severs some percolation pathways. Thus, by embedding electrodes and measuring resistance, one can detect both continuous deformation. The advantage of CNT sensors is their minimal impact on the host material's mechanical properties at the low loadings used [11].

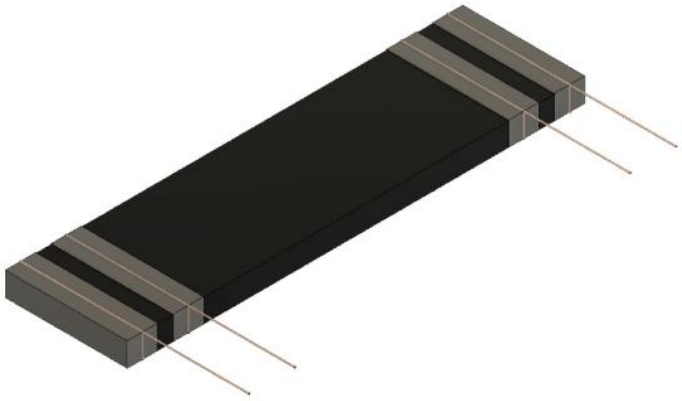

Fig. 6. Schematics of electrode disposition in electrical conductivity measurements [11].

CNTs' sensitivity to molecular adsorption has been widely exploited in gas sensors, chemical detectors, and even biosensors. The fundamental principle is that the conductance of a CNT (or a network of them) changes when certain molecules attach to its surface. Figure 7a shows a comb-pattern interdigitated electrode sensor (C-type) printed on a PET plastic substrate using a CNT nanoparticle ink; this device was designed for hazardous substance (HNS) detection in liquids. Figure 7b is an SEM image of the printed CNT film, revealing a tangled network of CNT bundles on the surface [18]. This sensor was shown to detect diluted ammonia and various chemical solvents; it exhibited measurable resistance changes when a droplet of chemical was introduced, allowing determination

of concentration based on calibration [18]. The example in Figure 7 typifies a flexible CNT chemical sensor – it is lightweight, bendable, and exploits CNTs' chemical sensitivity and conductivity for environmental monitoring.

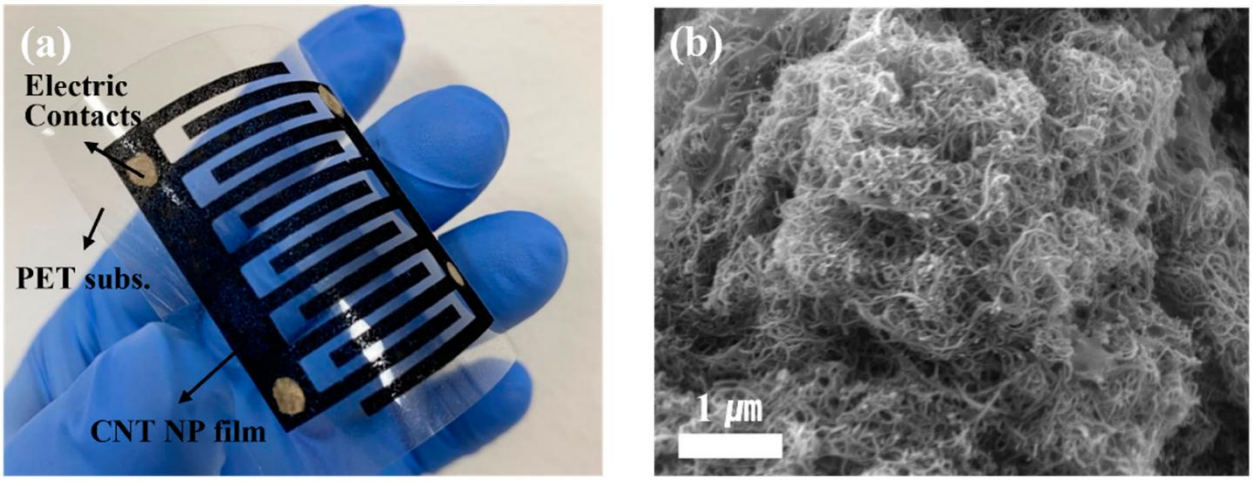

Fig. 7. (a) CNT film printed on a PET substrate, (b) FE-SEM image of PCF surface [18].

CNT-FET-based biosensors have emerged as promising platforms for the rapid and label-free detection of biomarkers such as miRNA, exosomal proteins for breast cancer, and carcinoembryonic antigen (CEA) for lung cancer, thereby facilitating early diagnosis and personalized therapeutic strategies. These devices offer superior sensitivity and real-time detection capabilities, positioning them as compelling alternatives to conventional diagnostic methods. In a study by Li *et al.,* [51], tumor-derived exosomal miRNAs were shown to play pivotal roles in the initiation and progression of cancer, highlighting their potential as biomarkers for early detection and therapeutic monitoring. To address the ongoing challenge of achieving simple, label-free, and highly sensitive detection, the researchers developed an advanced FET biosensor platform. This novel device was constructed using a polymer-purified semiconducting CNT film with excellent electronic characteristics and employed a floating-gate architecture, diverging from conventional sensor designs. A thin yttrium oxide dielectric layer was integrated into the device, and its surface was functionalized with gold nanoparticles, which served as anchoring sites for molecular probes. A thiol-modified DNA probe was covalently attached to these nanoparticles, enabling the specific hybridization with target miRNA sequences and facilitating electrical signal modulation upon binding. The resulting platform demonstrated outstanding analytical performance, combining ultra-high detection sensitivity with precise molecular specificity. Clinical validation using human plasma samples confirmed the device's ability to distinguish breast cancer patients from healthy controls with statistical significance, underscoring its diagnostic utility. These results support the CNT-FET biosensor as a viable and non-invasive diagnostic tool based on exosomal miRNA profiling.

The prompt and accurate identification of infectious diseases is crucial for curbing outbreaks and delivering timely medical intervention. While conventional diagnostic approaches such as PCR remain effective, they are limited by their reliance on specialized laboratory infrastructure and lengthy processing durations. In contrast, CNT-FET biosensors present a portable and highly sensitive alternative for detecting pathogens, including SARS-CoV-2 (COVID-19) and bacteria like Salmonella and Staphylococcus, which are responsible for foodborne illnesses. Their capacity to deliver real-time diagnostic results makes them particularly well-suited for point-of-care settings and outbreak

response scenarios. In response to the urgent need for widespread diagnostic testing during the COVID-19 pandemic, Zamzami *et al.,* [52] developed an economical and rapid electrochemical biosensing system based on CNT-FET technology (Figure 8). This platform was engineered to digitally detect and quantify SARS-CoV-2 viral antigens in human saliva samples. The sensor was fabricated by accurately depositing carbon nanotubes onto silicon substrates, followed by the site-specific functionalization with anti-SARS-CoV-2 S1 antibodies using a pyrene-based linker system.

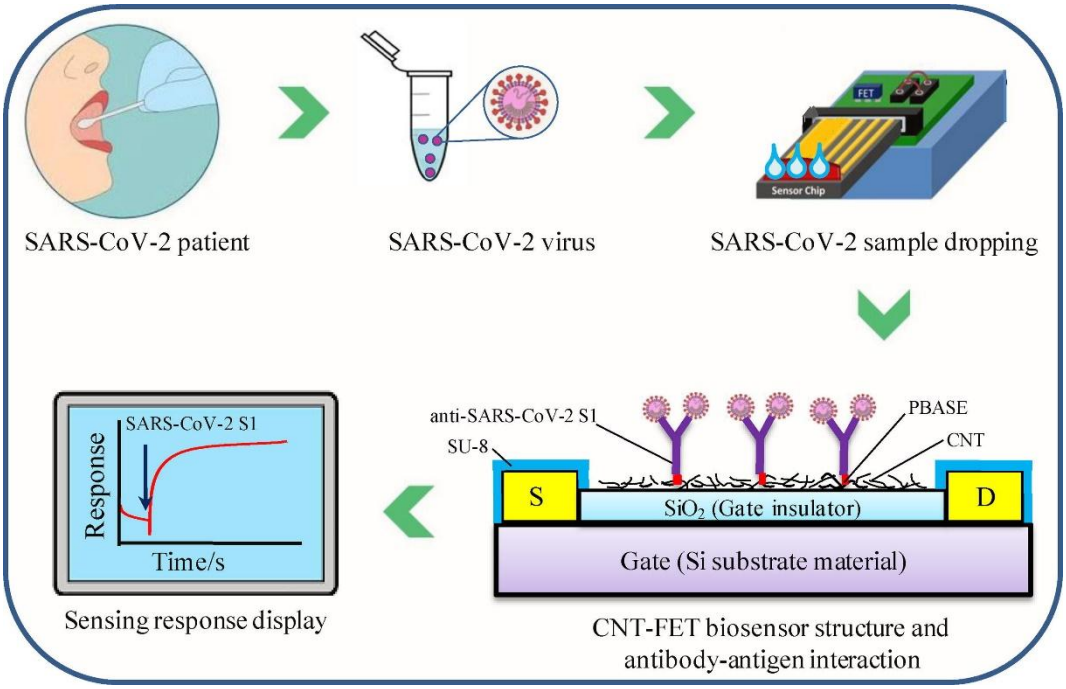

Fig. 8. Schematic diagram of CNT-FET biosensor and SARS-CoV-2 S1 testing steps. SWCNT as a sensing nanomaterial and anti-SARS-CoV-2 S1 immobilized on the CNT via PBASE (linker). The CNT-FET biosensor sense the SARS-CoV-2 spike protein based on the corresponding effects on the electrical signal properties [52]. Reproduced from ref. [52] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License).

Performance evaluation confirmed that the biosensor could selectively detect the target viral antigens without cross-reactivity toward structurally similar coronavirus proteins. Analytical testing further demonstrated an outstanding level of sensitivity across a wide dynamic range under optimized buffer conditions. Notably, the platform maintained its high performance even in complex biological environments, indicating strong potential for use in decentralized and point-of-care diagnostics. Compared to traditional techniques, the CNT-FET system offers substantial improvements in speed, simplicity, and testing scalability. Overall, these findings support its applicability as a powerful tool for large-scale screening during public health crises demanding rapid viral detection [52].

In addition to these applications, active research has been conducted on CNT-based gas sensors [61-71]. Loghin *et al.,* [61] developed a fully transparent gas sensor in which both the interdigitated electrodes and the sensing layer are composed of spray-deposited single-walled carbon nanotube (SWCNT) networks on a flexible Kapton substrate. This all-CNT architecture enables the elimination of noble metal contacts while maintaining optical transmittance above 60% in the visible range, positioning the device as a promising candidate for transparent and flexible sensing platforms. According to Figure 9, increasing the number of spray layers from 20 to 40 leads to a monotonic decrease in both sheet resistance and optical transmittance. The authors define semi-transparent

films as those with transmittance above 60%, and explore the trade-off between conductivity and transparency by introducing figure of merit. While thinner films initially offer higher FoM values, the optimal balance between low series resistance and sufficient transparency is found at 30 layers, corresponding to a film thickness of approximately 74 nm. At this point, the device achieves around 65 % transmittance at 550 nm and a sheet resistance of approximately 120 Ω sq^{-1}, satisfying the authors' practical criteria for transparent electrode design.

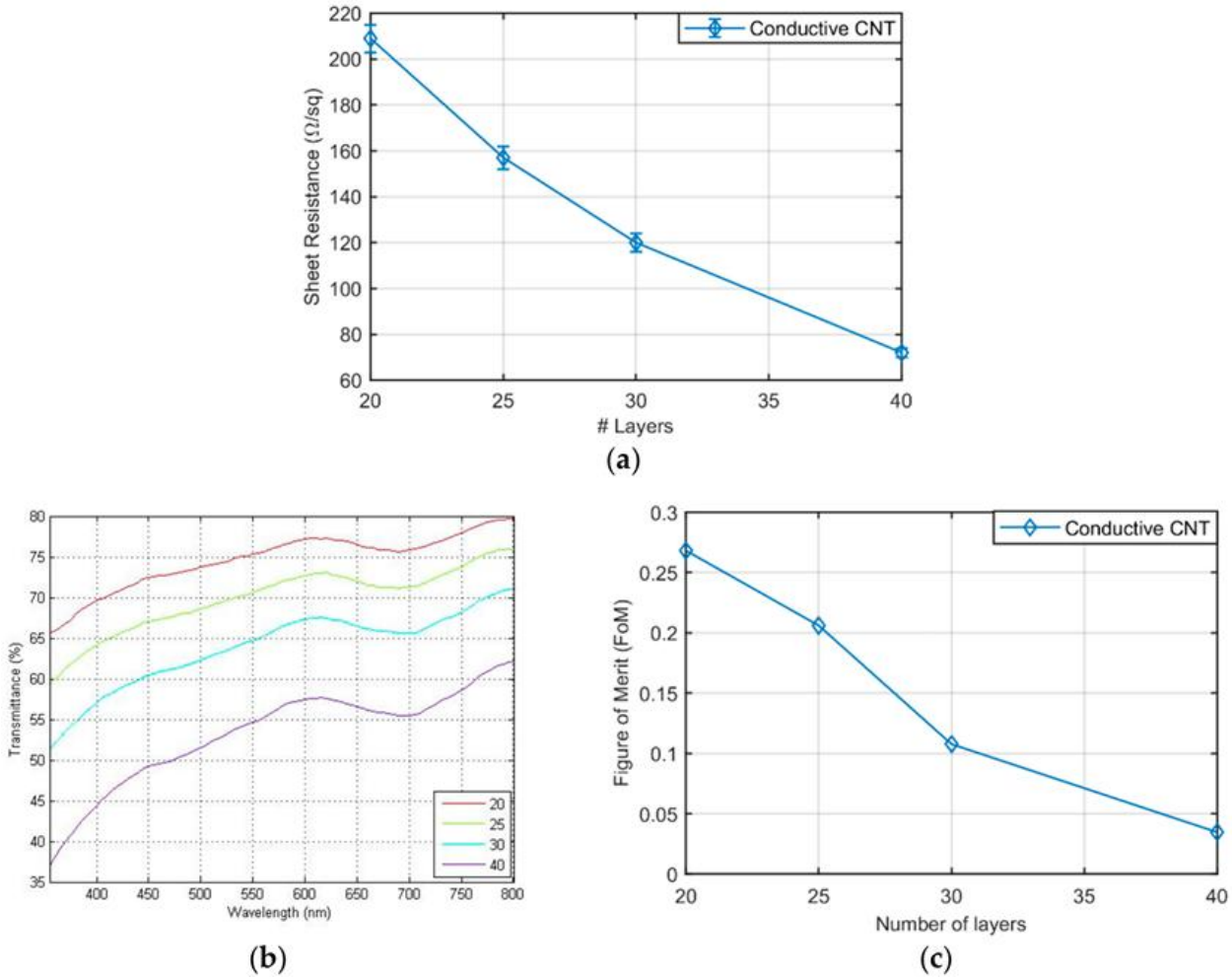

Fig. 9. (a) Sheet resistance of carbon nanotube (CNT) films with regard to the number of CNT layers sprayed. Corresponding to 48 nm, 60 nm, 74 nm and 97 nm film thickness, for 20, 25, 30 and 40 layers, respectively; (b) optical transmittance of CNT layers for electrodes definition; (c) electro-optical figure of merit as a function of the number of layers [61]. Reproduced from ref. [61] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License).

Figure 10 presents the gas sensing performance of the fully CNT-based device, demonstrating fast, reversible responses to NH_3 exposures ranging from 10 to 100 ppm. The calibration curves remain linear across this range for all electrode spacings tested – 50, 100, and 200 µm – highlighting the robustness of the sensor's electrical response. Notably, the sensor with a 200 µm spacing shows the highest sensitivity (0.248 %ppm^{-1}), as the larger spacing increases the relative contribution of the sensing layer's resistance to the total device resistance. This effect is not observed in control devices using evaporated gold electrodes, where the electrode resistance is negligible. A direct comparison between CNT and Au electrodes of identical geometry reveals nearly overlapping calibration curves,

confirming that CNT electrodes can substitute metal contacts without compromising sensitivity, response time, or recovery characteristics [61].

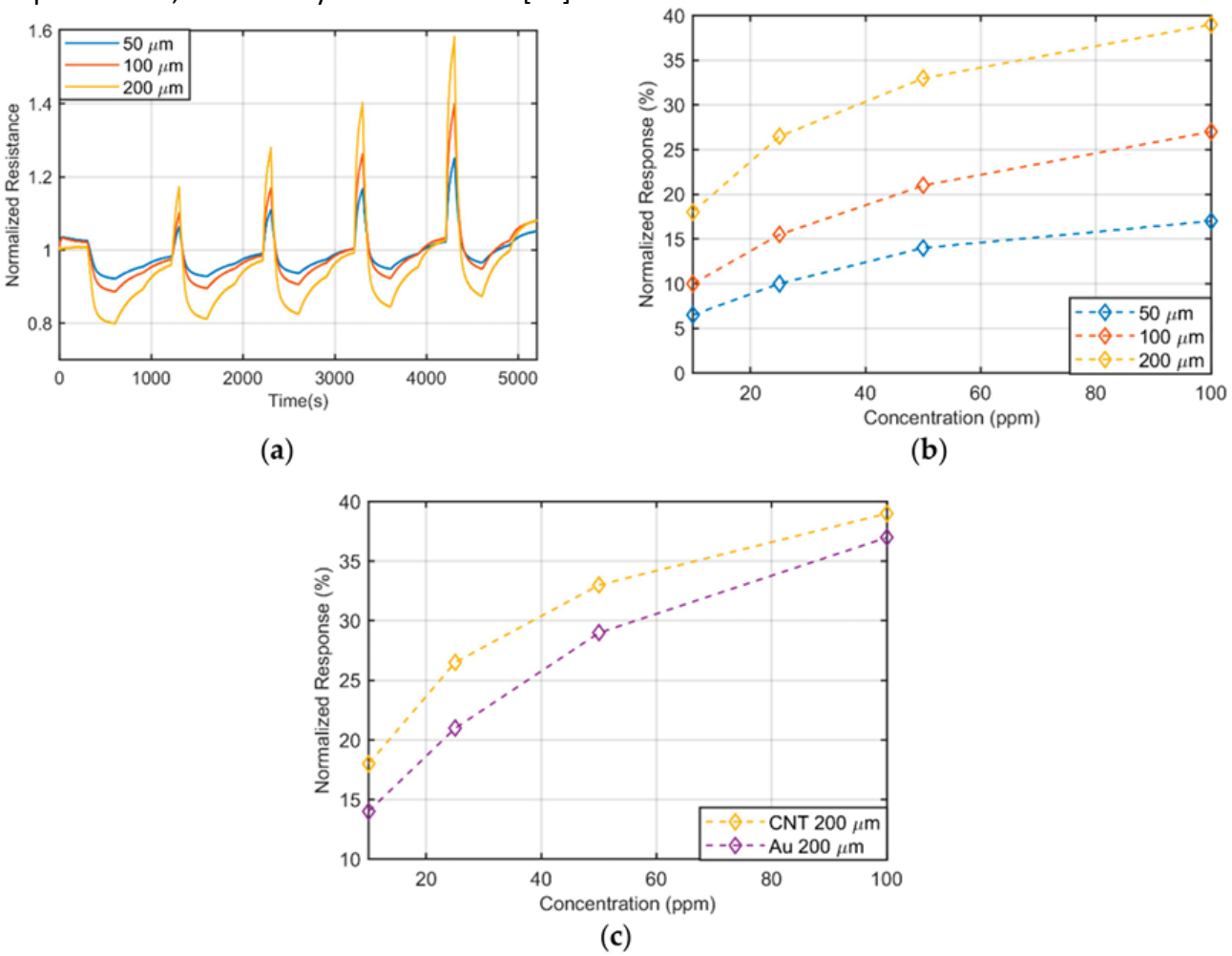

Fig. 10. (a)Time response of fully transparent sensor to NH3; (b)calibration curves of fully transparent sensor for NH3; (c) calibration curves towards ammonia for 200 m spacing for Au and CNT electrodes [61]. Reproduced from ref. [61] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License).

Like the applications introduced earlier, CNT-based sensors are often implemented in a multilayer structure with a polymer or composite-based matrix, resulting in complex electromechanical behavior. For precise numerical analysis of such composite structures, an analysis technique that integrates higher-order geometric representation and electromechanical modeling is required. Milić *et al.,* [72] proposed a framework for analyzing the electromechanical response of piezoelectric laminated shells by combining Isogeometric FE Analysis (IGA) and Reissner-Mindlin shell theory, which also suggests theoretical scalability for predicting the structural behavior of CNT-based piezoelectric composite sensors.

4. Conclusion

In this review, we explored the unique advantages of CNT-based sensors, from their fundamental sensing mechanisms to their fabrication and practical applications. CNTs, with their exceptional mechanical strength, electrical conductivity, and high surface area, have shown great promise as the core material for next-generation sensors that are not only lightweight and flexible but also highly

responsive to mechanical strain and chemical environments. We highlighted how CNT networks respond sensitively through mechanisms like piezoresistivity and tunneling, and how controlling the percolation behavior plays a key role in tuning sensor performance. Various fabrication methods—such as solution processing, printing, and composite molding—offer versatility in device design and enable integration into different substrates and form factors. Applications are already broad and growing, ranging from wearable sensors for health and motion tracking to environmental monitors that detect trace gases. These examples demonstrate how CNTs can bridge the gap between nanomaterials and real-world sensing needs. At the same time, some challenges remain—such as improving signal stability, selectivity, and large-area uniformity—but ongoing research into materials engineering and device optimization is steadily addressing these issues. Looking ahead, CNT-based sensors are well-positioned to become essential components in smart and connected technologies, offering sensing capabilities that conventional materials simply cannot match.

Author Contributions

Conceptualization, S.C. and B.H.; writing—original draft preparation, S.C. and B.H.; writing—review and editing, S.C. and B.H.; visualization, S.C. and B.H.; supervision, B.H.; project administration, B.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The study did not report any data.

Conflicts of Interest

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 paper.

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