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Room-Temperature Carbon Monoxide Detection Using Decorated CNT/Ag Sheet Gas Sensors

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Abstract

This work presents the development of a carbon nanotube/silver (CNT/Ag) sheet gas sensor designed for rapid and reliable carbon monoxide (CO) monitoring. The sensing platform is based on conductive carbon nanotube sheets functionalized with silver (Ag) nanoparticles to form a hybrid nanostructured network with enhanced surface activity and electrical transport properties. Surface treatment methods were employed to improve nanoparticle dispersion, interfacial adhesion, and charge transfer between the CNT matrix and Ag nanophase. The sensing mechanism relies on changes in the electrical resistance of the CNT/Ag sheet upon exposure to CO gas. Adsorption of CO molecules on the Ag nanoparticle surfaces alters local electron density and modulates charge transport pathways within the interconnected CNT network, producing a measurable electrical response. Sensor performance was evaluated using a four-point probe configuration at room temperature, demonstrating quantitative detection capability without the need for elevated operating temperatures. The CNT/Ag sheet sensor exhibited reasonable sensitivity, fast response and recovery behavior, and stable operation under ambient conditions. The flexible sheet architecture, combined with the intrinsic conductivity of CNTs and catalytic activity of Ag nanoparticles, provides a lightweight and scalable sensing platform suitable for portable environmental monitoring, industrial safety systems, and smart wearable technologies. These results highlight the potential of CNT/Ag hybrid materials as next-generation gas sensors for efficient and low-energy gas detection capability.

1. Introduction

Carbon monoxide (CO) is a hazardous and colorless gas generated from incomplete combustion processes in automobiles, power systems, domestic heating devices, and a wide range of industrial operations [1, 2]. Lacking both odor and irritating properties, CO exposure can occur without immediate warning, making it one of the most dangerous airborne toxicants in residential, commercial, and manufacturing environments [3, 4]. Even at relatively low

concentrations, CO can bind strongly to hemoglobin, reducing oxygen transport in the bloodstream and leading to headaches, dizziness, fatigue, impaired judgment, and, at higher levels, severe poisoning or death [5]. These risks underscore the critical need for reliable sensing technologies capable of rapid, continuous, and precise CO monitoring.

Conventional CO sensors are commonly based on metal oxide semiconductors, electrochemical cells, or catalytic combustion devices [6–8]. Despite their widespread adoption, these technologies face key limitations including high operating temperatures, high power consumption, long recovery times, limited flexibility, and environmental instability [9–11].

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Advancements in wearable electronics, portable safety systems, smart buildings, and distributed environmental monitoring networks have driven a growing demand for sensors that operate at room temperature while maintaining high sensitivity, mechanical durability, and low energy consumption [12–16].

Nanostructured materials have emerged as promising candidates for next-generation gas sensing because their high surface-area-to-volume ratio enables strong interactions with gas molecules and amplified electrical responses [8, 17, 18]. Among these materials, carbon nanotubes (CNTs) have attracted exceptional attention due to their unique combination of electrical conductivity, chemical stability, low density, flexibility, and outstanding mechanical strength [19–21]. Structurally, CNTs form one-dimensional graphitic networks that can efficiently transport charge carriers while also providing accessible adsorption sites for chemical species [22–24]. Outstanding thermal stability and a minimal temperature coefficient of resistivity enable CNTs to handle extremely high current densities, even though their baseline electrical conductivity does not surpass metallic conductors [25]. These properties make CNT assemblies highly attractive for applications requiring lightweight conductors, robust interconnects, actuators, flexible superconductors and electrically active sensing platforms [26, 27].

Despite their advantages, pristine CNTs may exhibit limited selectivity and moderate response toward certain gases because of relatively inert graphitic surfaces [28]. To overcome this challenge, functionalization strategies have been widely explored to modify CNT surface chemistry and introduce catalytically active sites [29–32]. Decorating CNT networks with metallic nanoparticles boosts sensing performance by enhancing gas adsorption, facilitating charge transfer, and creating localized active regions [33–36]. In particular, silver (Ag) nanoparticles are attractive not only for improving the sensor sensitivity but also for reducing operating temperature owing to their unique catalytic activity [37, 38]. Furthermore, their relative affordability compared to other noble metals, along with their suitability for scalable solution-based processing, renders Ag a promising functional modifier [39–41].

When Ag nanoparticles are integrated onto CNT sheets, a hybrid sensing architecture is created in which the CNT framework serves as a continuous conductive pathway, while Ag nanoparticles act as active interaction centers for CO molecules [42, 43]. Upon CO exposure, adsorption on the Ag surface modifies local electron density and perturbs charge

transport across the CNT–Ag network. These changes can be detected as measurable variations in electrical resistance, enabling real-time gas sensing.

In this study, we demonstrate proof-of-concept on the development and characterization of CNT/Ag sheet gas sensors for room-temperature CO detection. The study investigates the role of CNT surface treatment, Ag nanoparticle adhesion, and conductive network design in improving sensor response and reproducibility. Electrical measurements are performed using a four-point probe technique to accurately monitor resistance changes during gas exposure. By combining the intrinsic conductivity of CNT sheets with the catalytic functionality of Ag nanoparticles, this work aims to establish a scalable and energy-efficient sensing platform for environmental safety, industrial hazard prevention, and next-generation smart sensing technologies.

2. Experimental Methods and Procedure

CNT sheets were extracted from a chemical vapor deposition (CVD)-grown vertically aligned CNT forest. The synthesized forest consisted of CNTs with an average diameter of approximately 10 nm and a height of 280 μm , corresponding to a volumetric forest density of 63.8 mg cm^{-3} [44, 45]. With its highly aligned structure and 45% porosity, this architecture is well-suited for sheet extraction [44].

The CNT sheets were chemically functionalized through a mixed acid treatment to introduce oxygen-containing groups onto the CNT surface. Saleh [46] presented the effect of treatment temperatures ranging from 60 to 140 $^{\circ}\text{C}$ on the acidity of CNTs oxidized using a 3:1 volumetric ratio of 95% sulfuric acid (H_2SO_4) and 75% nitric acid (HNO_3). The study found 100 $^{\circ}\text{C}$ as the optimum temperature for maximizing surface acidity without compromising the mechanical integrity of the CNTs. The acid solution used in this study consisted of 15 mL of 0.5 M H_2SO_4 and 5 mL of 1 M HNO_3 was used, corresponding to a 3:1 (v/v) ratio. The CNT sheets were treated at 50 $^{\circ}\text{C}$ for 4 h, followed by repeated washing with deionized water until neutral pH was reached and drying in a convection oven at 70 $^{\circ}\text{C}$ for approximately 12 h to achieve controlled oxidation, which introduced uniformly distributed functional groups such as carboxyl ($-\text{COOH}$) and hydroxyl ($-\text{OH}$) on the CNT surface.

For Ag deposition, 5 mg of AgNO_3 was used as the Ag precursor, with PVP serving as the stabilizing agent. The synthesis mixture consisted of 5 mg CNT, 5 mg AgNO_3 , and 100 mg PVP in 1.5 mL of DMF.

The mixture was heated at approximately 160 °C for 1 h in a sealed autoclave reactor. After cooling to room temperature, the resulting CNT/Ag composite was washed by centrifugation twice with deionized water, followed by a final wash with approximately 45 mL of ethanol to remove residual PVP, unreacted precursor, and other soluble residues. The washed composite was then dried at approximately 60 °C. Based on the initial amount of AgNO_3 , the maximum theoretical amount of elemental Ag available for deposition was ~3.18 mg. Assuming complete conversion and deposition of Ag, this corresponds to a nominal Ag content of ~38.8 wt.% in the CNT/Ag composite. This procedure resulted in CNTs uniformly decorated with Ag nanoparticles, forming an active sensing material suitable for integration into flexible gas-sensing devices.

Sensor Fabrication: The CNT/Ag composite sheets were deposited onto insulating primed zirconium oxide (ZrO_2) textile cloth substrates. The ZrO_2 textile cloths were cleaned via sonication for 10 min each in acetone and isopropanol, then immersed in a 0.2 wt.% polyethyleneimine (PEI) water:ethanol (1:1) solution for 20 min. Subsequently, the cloths were dipped once in ethanol to remove excess PEI and dried at 70 °C for 10 min. Electrical contacts were attached using conductive Ag paste at designated electrode positions. The use of Ag paste significantly reduced contact resistance at the probe–sample interface and improved measurement reproducibility. For accurate resistance measurements, a four-point probe arrangement was implemented to minimize contact resistance effects. The active sensing region was defined between the voltage probes, where changes in conductivity were monitored during gas exposure.

Structural and Morphological Characterization: The morphology and surface distribution of Ag nanoparticles on the CNT sheets were examined

using a JEOL-JSM 7100F field-emission scanning electron microscopy (SEM). High-magnification imaging was used to evaluate nanoparticle size, dispersion, and interconnectivity within the CNT network. Additional characterization techniques, including X-Ray Diffraction (XRD) and Raman spectroscopy, were used to assess CNT structural integrity and Ag crystallinity after processing.

Gas Sensing Measurements: Gas sensing experiments were conducted in the sealed test chamber shown in Fig. 1. The system was equipped with controlled gas inlet and outlet lines. CO at a concentration of 1,000 ppm was supplied into the chamber at a gas flow rate of 100 mL/min. A CO concentration of 1,000 ppm was used as it is within a standard measuring range for existing air quality guidelines [47].

All measurements were performed at room temperature at a relative humidity of 53%. The electrical resistance of the CNT/Ag sheet sensor was continuously recorded using an Ossila Four-Point Probe System, which allows rapid and precise thin-film resistivity measurements by isolating voltage sensing from current injection to reduce contact resistance [48]. The fabricated sensors were evaluated in terms of sensitivity, repeatability, response/recovery behavior, and baseline stability over multiple sensing cycles.

The four-point probe head make electrical contact with the sample, enabling precise conductivity measurements while minimizing contact resistance effects. This configuration is particularly important for highly conductive nanostructured materials, where small resistance changes must be accurately detected during gas exposure [49].

As CO molecules adsorb onto the Ag-functionalized CNT network, the electrical properties of the sensing layer are altered, and these changes are continuously monitored by the measurement system. The software interface records conductivity

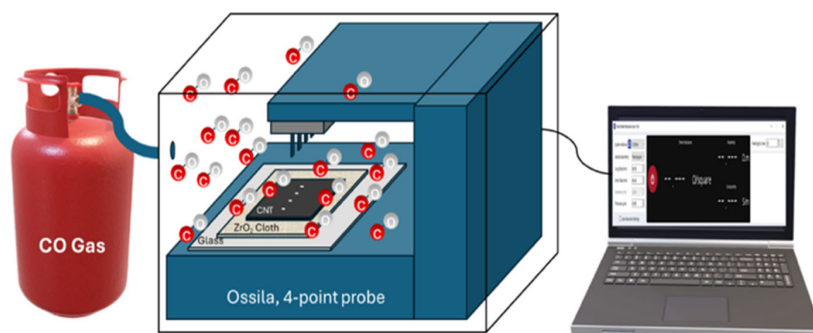


Fig. 1. The schematic diagram of experimental setup used to evaluate CO sensing performance of the CNT/Ag-based sensor using a four-point probe measurement system. The surrounding red and gray symbols represent CO molecules diffusing through the chamber atmosphere and interacting with the sensor surface.

variations as a function of time, allowing evaluation of sensor sensitivity, response and recovery behavior, repeatability, and room-temperature sensing performance. This setup provides a controlled and reliable platform for studying gas–surface interactions in CNT-based hybrid sensors.

The sensor response was calculated using the relative conductivity change by using the conductivity response relation: $S(\%) = \frac{\sigma_{CO} - \sigma_{air}}{\sigma_{air}} \times 100$, where σ_{air} is room temperature sensor conductivity under air; σ_{CO} is room temperature sensor conductivity under CO. Response time (t_{res}) was defined as the time required to reach 90% of the total conductivity change after CO introduction, whereas recovery time (t_{rec}) was defined as the time required for the conductivity to return to within 10% of the initial baseline conductivity following CO removal.

2. Results

Figure 2 shows a schematic illustration of decorated CNT sheets functionalized with Ag nanoparticles. The pristine CNT sheet consists of an interconnected conductive network of entangled

multi-walled carbon nanotubes (MWCNTs). After functionalization, Ag nanoparticles are uniformly distributed and anchored onto the CNT surfaces and junctions, enhancing electrical conductivity and providing active sites for gas adsorption. The enlarged and cross-sectional views highlight the role of Ag nanoparticles in improving charge transport and sensing performance for CO detection.

XRD Analysis and Phase Evolution: Figure 3 represents a comparison of the XRD patterns of pristine CNTs, acid-treated CNTs, and Ag-decorated acid-treated CNTs, together with the reference diffraction peak positions for graphitic carbon (C) and metallic Ag. The diffraction patterns provide insight into the structural evolution of the CNTs following chemical functionalization and Ag nanoparticle deposition. The diffraction pattern of the pristine CNTs (black curve) exhibits broad diffraction peaks indicates the nanocrystalline and partially disordered structure characteristic of amorphous CNTs. Following acid treatment (red curve), the characteristic carbon diffraction peaks remain at nearly the same positions, indicating that the graphitic framework of the CNTs is largely preserved after chemical functionalization.

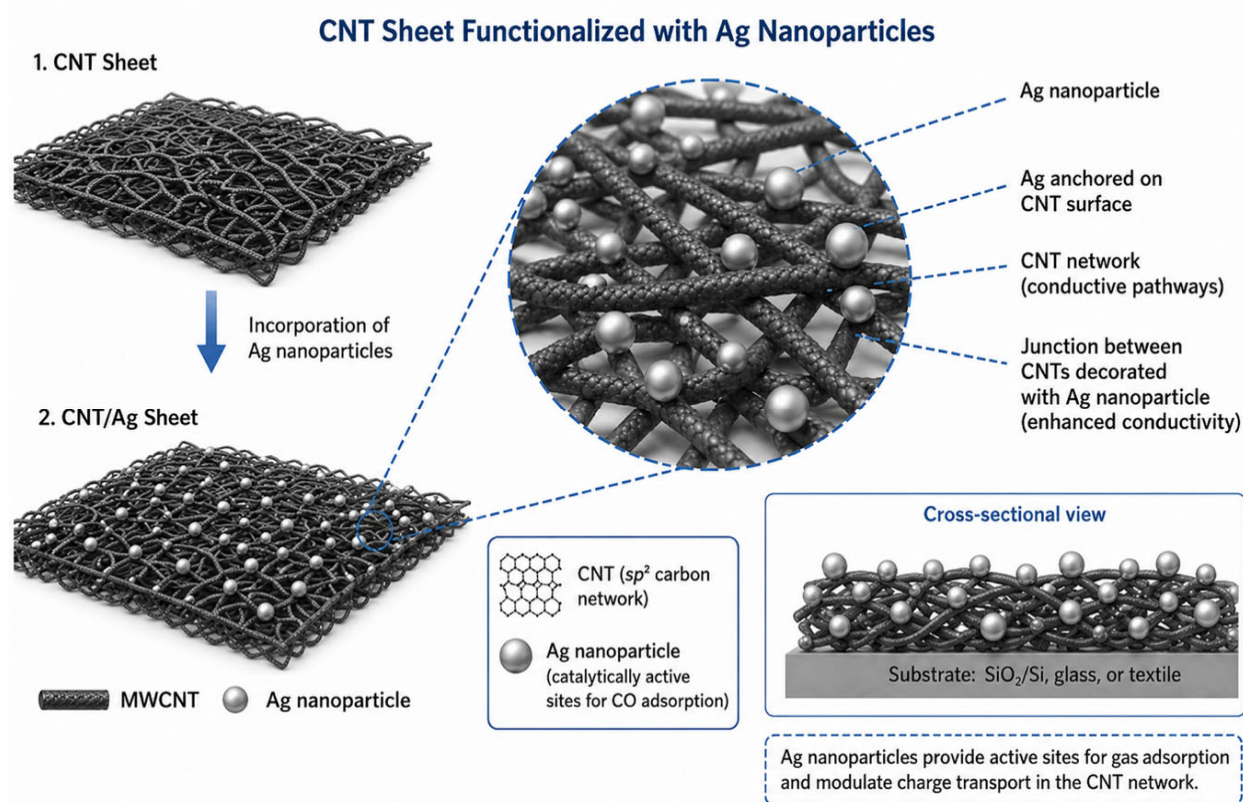


Fig. 2. Schematic illustration of a carbon nanotube (CNT) sheet functionalized with silver (Ag) nanoparticles. CNT sheet features a conductive network of interwoven multi-walled carbon nanotubes (MWCNTs). Upon functionalization, Ag nanoparticles become uniformly anchored to the CNT surfaces enhancing electrical conductivity and providing active sites for gas adsorption.

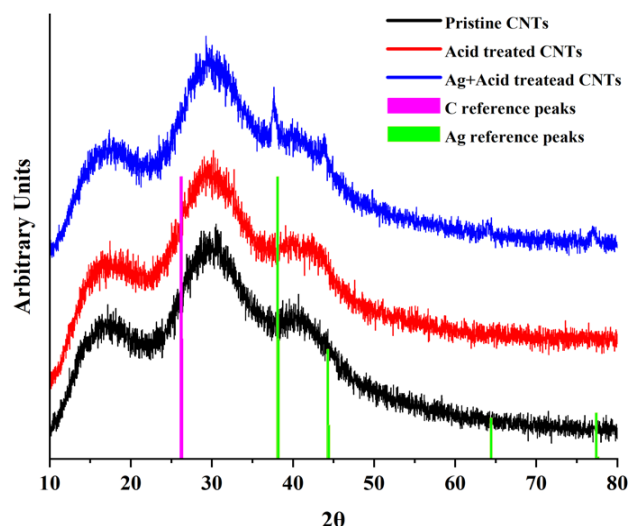


Fig. 3. X-ray diffraction (XRD) patterns of pristine CNTs, acid-treated CNTs, and Ag-decorated acid-treated CNTs.

However, noticeable changes in peak intensity and broadening are observed, suggesting the introduction of structural defects and oxygen-containing functional groups on the CNT surface. These defects increase the degree of disorder while providing active sites for subsequent nanoparticle attachment. The diffraction pattern of the Ag-decorated acid-treated CNTs (blue curve) shows the preservation of the graphitic carbon peaks together with the appearance of additional diffraction peaks corresponding to crystalline metallic Ag. The Ag reference peak positions, indicated by the green vertical lines, are located near $2\theta \approx 38.1^\circ$, 44.3° , 64.4° , and 77.4° , which are indexed to the (111), (200), (220), and

(311) crystallographic planes of face-centered cubic (fcc) Ag. The presence of these peaks confirms the successful formation and deposition of crystalline Ag nanoparticles on the CNT surface. Overall, the XRD results demonstrate that acid treatment modifies the CNT surface without destroying its graphitic structure, while subsequent Ag deposition results in the formation of crystalline Ag nanoparticles that coexist with the CNT framework. The combination of preserved graphitic conductivity and uniformly distributed metallic Ag nanoparticles is expected to enhance charge transfer, increase the density of active adsorption sites, and improve the sensitivity and response of the CNT-based CO gas sensors.

Surface Morphology and Microstructure: The SEM observations indicate that Ag nanoparticles exhibited significantly improved interfacial interactions and stronger adhesion on acid-treated CNT sheets compared with untreated CNT surfaces. Figure 4 illustrates the morphological evolution of CNT sheets following Ag nanoparticle functionalization. The pristine CNT sheet in Fig. 4a exhibits a porous and highly interconnected network of entangled nanotube bundles. After acid treatment and Ag deposition, bright nanoscale features appear on the CNT surfaces in Fig. 4b, corresponding to Ag nanoparticles anchored along individual nanotubes and at bundle junctions. Furthermore, Ag nanoparticles shown in Fig. 4b were more uniformly distributed and more firmly attached throughout the acid-treated CNT network, with reduced particle agglomeration and enhanced coverage at nanotube junctions, compared to the untreated CNTs shown in Fig. 4c.

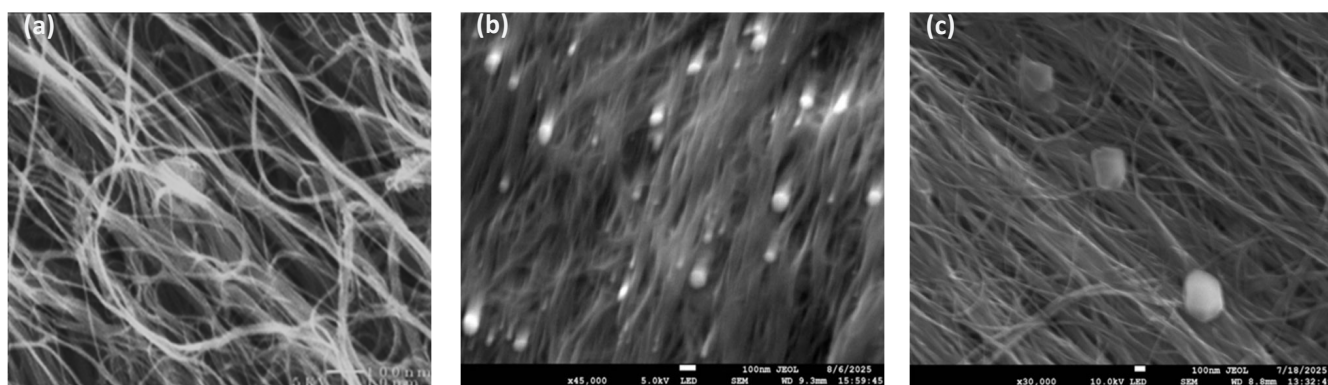


Fig. 4. SEM images showing the surface morphology of CNT sheets before and after Ag nanoparticle functionalization at different magnifications; (a) – pristine CNT sheet, consisting of an interconnected network of entangled nanotube bundles with a porous fibrous structure; (b) – Ag-functionalized CNT sheets, where bright contrast features represent deposited Ag nanoparticles distributed along CNT surfaces and junction regions. The micrographs indicate successful nanoparticle incorporation with increasing particle density and broad surface coverage, while preserving the conductive CNT network architecture; (c) – Ag nanoparticles on the non-treated CNT sheets, which possess relatively inert graphitic surfaces.

Their presence at inter-tube contact points is particularly important because these regions strongly influence electrical transport through the network [50]. The combination of the conductive CNT scaffold and catalytically active Ag nanoparticles creates a hybrid architecture well suited for gas sensing applications. In contrast, untreated samples typically exhibited less homogeneous particle deposition, leading to fewer active sensing regions, and reduced nanoparticle coverage. The combination of a high-surface-area CNT scaffold and nanoscale Ag catalytic domains creates a large number of accessible adsorption sites for CO molecules.

The enhanced nanoparticle adhesion observed after surface treatment indicates that oxygen-containing functional groups promoted nucleation and stabilization of Ag on the carbon surface. These modifications improved interfacial contact between the metallic nanoparticles and the CNT framework, which is essential for efficient charge transfer during sensing. The presence of nanoparticles at inter-tube contact points is particularly important because these regions strongly influence electrical transport through the network. In contrast, non-treated CNT sheets, which possess relatively inert graphitic surfaces, demonstrated weaker nanoparticle attachment and less homogeneous deposition as presented in Fig. 4c.

Raman Spectroscopy Analysis: The full Raman spectra of the pristine and acid-treated CNT sheets presented in Fig. 5a. The Raman spectra provide important insight into the structural changes induced by chemical functionalization. The radial breathing mode (RBM) is typically observed in single-walled carbon nanotubes (SWCNTs), whereas in multi-walled carbon nanotubes (MWCNTs) this mode is generally not well resolved due to interlayer interactions and structural complexity. In MWCNTs, the Raman response in the low-frequency region is often manifested as a broad envelope arising from the superposition of multiple unresolved RBM contributions.

Following acid treatment, this broad feature observed in pristine CNTs becomes slightly narrower, and in some cases, discrete narrow peaks begin to emerge (peak near $\sim 139\text{ cm}^{-1}$) shown in Fig. 5b. The appearance of such features may be attributed to structural modifications, partial isolation of nanotube shells, or changes in intertube interactions induced by chemical treatment. A similar RBM peak has been reported in SWCNTs [51]. However, due to peak broadening and overlap effects, the precise linewidth of these individual modes remains difficult to determine accurately [52].

The region between 500 cm^{-1} and 1000 cm^{-1} shown in Fig. 5c that consists of intermediated frequency modes (IMF). This region is silent for the pristine CNTs and exhibits two small lines, one located at about 800 cm^{-1} , with a width of about 40 cm^{-1} and the other at 908 cm^{-1} , with a width of the order of 50 cm^{-1} . The appearance of two additional Raman features in the acid-treated CNT sheets, one near $\sim 800\text{ cm}^{-1}$ ($\sim 40\text{ cm}^{-1}$ width) and another near $\sim 908\text{ cm}^{-1}$ ($\sim 50\text{ cm}^{-1}$ width) is a direct consequence of chemical functionalization and defect generation induced by the acid treatment. First, strong acid oxidation introduces oxygen-containing functional groups such as C–O, C–OH, C=O, and COOH onto the CNT sidewalls and at defect sites [53, 54]. These groups break the ideal sp^2 symmetry of the graphitic lattice and activate Raman modes that are normally weak or forbidden in pristine CNTs [55, 56]. Vibrational modes associated with C–O stretching and deformation commonly appear in the $\sim 800\text{--}950\text{ cm}^{-1}$ region, which explains the emergence of these peaks [57].

Second, acid treatment creates structural defects and sp^3 -hybridized carbon sites. These defects relax Raman selection rules and allow additional phonon modes to become active. The peaks around $\sim 800\text{ cm}^{-1}$ and $\sim 908\text{ cm}^{-1}$ can therefore be attributed to defect-activated modes, including out-of-plane vibrations and localized distortions of the carbon lattice.

Third, partial functional group clustering or edge formation (openings in CNT walls) can also contribute to these features. The relatively broad linewidths ($40\text{--}50\text{ cm}^{-1}$) indicate a distribution of bonding environments, rather than a single well-defined crystalline vibration, which is consistent with heterogeneous oxidation. The spectral range between 1000 and 2000 cm^{-1} shown in Fig. 6(a) and includes the D Raman line, associated with the defects in CNTs. For the pristine CNTs the D line is located at 1313 cm^{-1} , with a width of $\sim 60\text{ cm}^{-1}$. The D resonance for the acid treated is located essentially at the same position (actual position is 1317 cm^{-1}) as in the pristine sample and has a width of 60 cm^{-1} .

Szroeder et al. [58] reported position for the D line in MWCNTs is 1345 cm^{-1} . It is concluded that the acidic treatment has a negligible effect on the D band and that the position and widths of the D lines are consistent with the literature. The G resonance, assigned to graphitic structures, is located at 1611 cm^{-1} and a width of $\sim 90\text{ cm}^{-1}$. The position of this line is close to the theoretical value [52] of 1615 cm^{-1} for bundles of SWCNTs. The acid treated sample shows the G line at 1612 cm^{-1} with a width of $\sim 80\text{ cm}^{-1}$. The G mode is also named High Energy

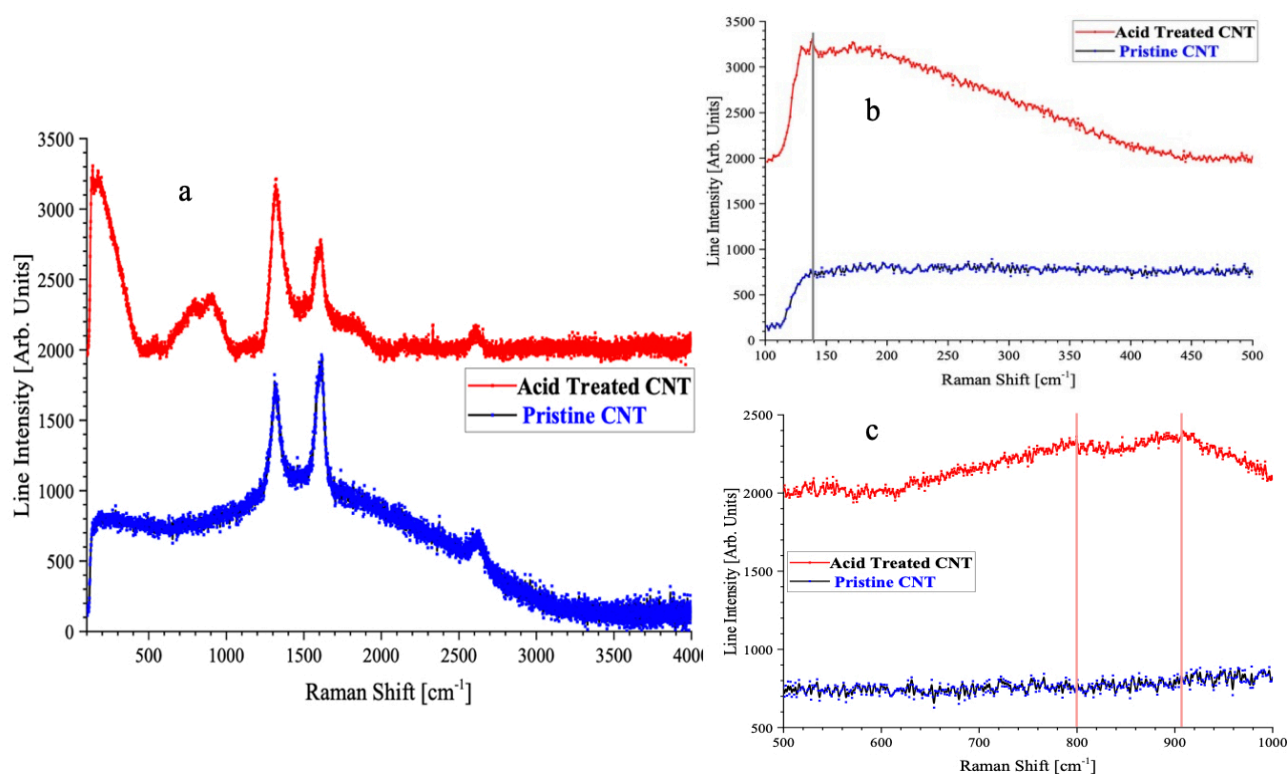


Fig. 5. (a) – Full Raman spectra of pristine and acid-treated carbon nanotube (CNT) sheets showing the characteristic D, G, and 2D bands. (b) – Raman spectra in the range between 100–500 cm^{-1} ; and (c) – Raman spectra in the range between 500–1000 cm^{-1} .

Mode or Tangential mode [52]. The G resonance exhibits an apparent asymmetry in both pristine and acid-treated CNTs. The structure of the G band suggests the presence of a weaker and a narrow component, which may include a semiconducting character in both samples [59]. This line was reported as being located between 1600 cm^{-1} in MWCNTs, for the 532 nm excitation wavelength. The recorded G bands are broader suggesting an enhanced degree of structural disorder. A weak and very broad line ($\sim 60 \text{ cm}^{-1}$) is observed in acid-treated CNTs at $\sim 1822 \text{ cm}^{-1}$. For the pristine CNT sheets, the relatively lower intensity ratio of the D band to the G band ($I_D/I_G \sim 0.93$) indicates a comparatively well-ordered graphitic structure with fewer defect sites. The acidic treatment enhances this factor up to 1.24, demonstrating the introduction of additional defects and functional groups onto the CNT surface. These defects are typically associated with oxidation-induced oxygen-containing species such as hydroxyl, carbonyl, and carboxyl groups formed during acid treatment.

The 2000–4000 cm^{-1} region shown in Fig. 6b is represented by Raman double resonances including the G' band, which is the second-order overtone of the D band [59]. The line is located at 2620 cm^{-1} ,

with a width of about 100 cm^{-1} . The position and width of this line are not affected by the acidic treatment. Similar lines were reported [60] at 2619 cm^{-1} in MWCNTs with a width of $\sim 54 \text{ cm}^{-1}$. The increased width may express a higher concentration of defects.

The increase in defect density is beneficial for subsequent nanoparticle functionalization because these newly created active sites promote stronger interfacial interactions, improved wettability, and enhanced anchoring of Ag nanoparticles onto the CNT sheets. Slight peak shifts and broadening observed after treatment may also indicate local strain, charge transfer effects, or partial disruption of the graphitic network. Overall, the Raman results confirm that acid treatment successfully modifies the CNT surface chemistry while preserving the fundamental CNT structure, making the treated sheets more suitable for advanced sensing and composite applications.

CO Gas Sensing Performance and Electrical Conductivity: Figure 7 presents the real-time electrical conductivity response of pristine CNT and the acid-treated CNT/Ag sensors deposited on ZrO_2 textile cloths during repeated CO exposure cycles. Conductivity is plotted as a function of time, where the blue data points represent the sensor baseline in the absence of CO, and the red data points correspond

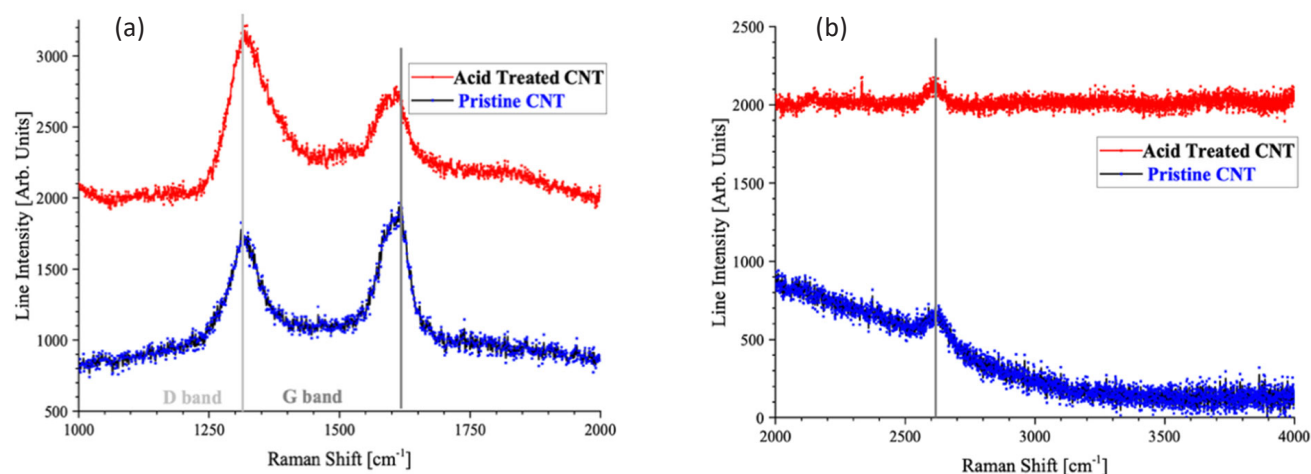


Fig. 6. (a) – Raman spectra in the range between 1000–2000 cm^{-1} and (b) – Raman spectra in the range between 2000–3000 cm^{-1} of pristine and acid-treated carbon nanotube (CNT) sheets showing the characteristic D, G, and 2D bands.

to the sensor response during CO exposure. The periodic conductivity transitions demonstrate that the modified sensor can repeatedly detect and recover from gas exposure at room temperature. While pristine CNTs exhibit a baseline conductivity of 9,032 S/m, which decreases to 8,120 S/m upon CO exposure before saturating without recovery, the acid-treated CNT/Ag sensor displays a positive sensing response. Starting from a baseline conductivity of 3,235 S/m, its conductivity increases relative to 1% upon CO introduction per cycle, demonstrating reversible and repeatable detection. This behavior is attributed to adsorption of CO molecules on the Ag nanoparticle surfaces, which modifies the local electronic environment and enhances charge trans-

port through the interconnected CNT network. The conductive CNT scaffold rapidly transmits these interfacial changes throughout the sensing layer, resulting in a measurable increase in conductivity. The repeated and distinguishable conductivity shifts observed over multiple cycles confirm good sensor reproducibility, stable electrical contacts, and reversible gas interaction. Although minor fluctuations are present in the signal, the overall trend remains consistent, demonstrating the capability of the CNT/Ag hybrid sensor for continuous and quantitative CO monitoring. These results support the effectiveness of combining acid-treated CNT sheets with Ag nanoparticles to achieve room-temperature gas sensing performance.

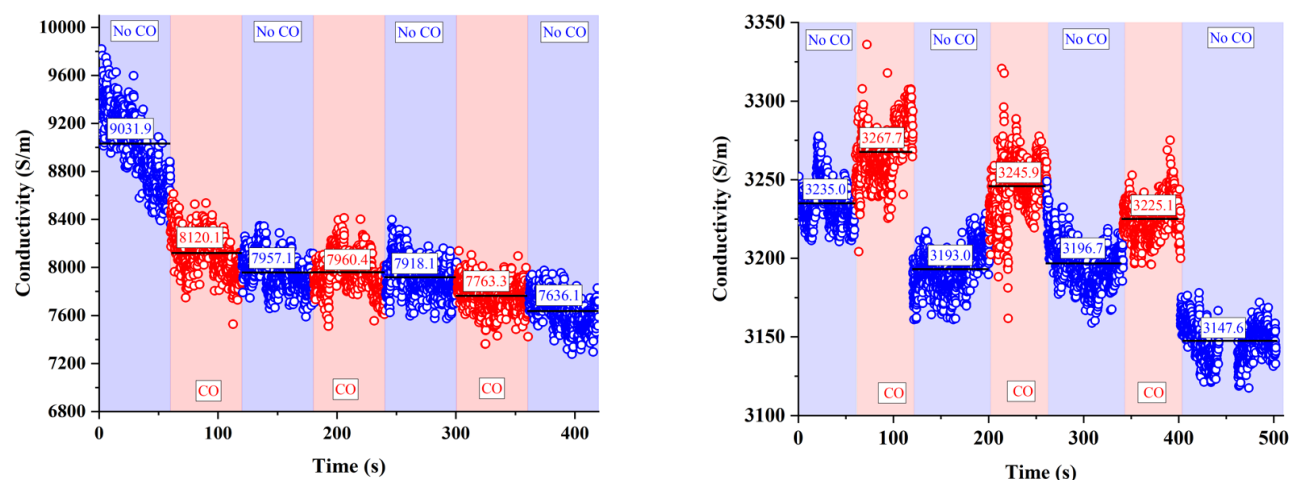


Fig. 7. Dynamic conductivity response of (a) pristine CNT and (b) an acid-treated CNT/Ag sensors supported on a zirconium oxide textile cloth during cyclic carbon monoxide (CO) exposure (1,000 ppm) at room temperature and relevant humidity of 53%. The blue data points represent the baseline conductivity measured in the absence of CO, while the red data points correspond to conductivity during CO exposure.

3. Discussion

The increase in conductivity during CO exposure is primarily attributed to surface adsorption and charge-transfer interactions at the Ag nanoparticle and CNT interface. Horastani et al. [61] demonstrates a gas-free Ag-Pd/CNT80 system initially functions as a high-resistance in the spin-down channel. CO molecules preferentially adsorb onto the Ag-Pd sites, which act as energetically favorable catalytic binding centers. Upon adsorption, charge transfer occurs where the CO molecule accepts electronic charge at spin up electrons from the hybrid structure. This spin-selective charge transfer modifies the band structure, thereby switching the material into a higher conductive state. In many CNT-based sensors, the nanotube network behaves as a p-type semiconducting system under ambient conditions due to oxygen adsorption from air [62–64]. When CO interacts with the Ag-functionalized surface, it can reduce charge scattering at nanotube junctions or modify hole transport pathways through the CNT sheet. This lowers the effective junction resistance and facilitates more efficient movement of charge carriers across the conductive network. Because electron transport in CNT sheets strongly depends on inter-tube contacts, even small changes at these junctions can produce significant macroscopic conductivity variations. A second contribution arises from the role of Ag nanoparticles as conductive bridges between neighboring CNT bundles. CO adsorption can change the electronic coupling at these nanoparticle-decorated contact points, improving tunneling probability or decreasing contact resistance. The porous morphology of the CNT sheet further enhances the response by allowing rapid gas diffusion to a large number of active sites. The combined effect of catalytic adsorption, interfacial charge transfer, and junction resistance modulation results in the observed conductivity increase during CO exposure. After removal of CO, desorption restores the initial electronic state, and the conductivity returns toward baseline values.

Based on the data in Fig. 7b, the sensor response (sensitivity, S) was calculated using the conductivity response relation. Baseline conductivity in air was $\sigma_{air} \approx 3235$ S/m, while average conductivity during CO exposure was $\sigma_{CO} \approx 3246$ S/m. These results indicate that CO adsorption increased the conductivity, by approximately 0.34%.

Electrical measurements showed that Ag functionalization reduced the overall resistance of the CNT sheets compared with untreated CNT networks.

This decrease is attributed to the high intrinsic conductivity of metallic Ag and the formation of additional conductive bridges across nanotube junctions. In porous CNT sheets, electron transport is often limited by contact resistance between adjacent bundles. Acid treatment also contributed indirectly to improved conductivity by removing impurities and enhancing nanoparticle attachment. However, excessive oxidation may introduce structural defects into the graphitic network as shown by Raman spectra and partially degrade conductivity. Therefore, optimization of treatment conditions is necessary to balance surface activation with preservation of the CNT conductive structure. The best-performing sensors were obtained when sufficient functional groups were introduced without excessive damage to the nanotube framework.

Upon exposure to CO at room temperature, the CNT/Ag sheet sensors exhibited measurable and repeatable changes in electrical resistance. The response magnitude increased with increasing CO concentration, demonstrating the potential for quantitative gas detection. Functionalized CNT/Ag sheets consistently produced larger responses than pristine CNT sheets, confirming the beneficial role of Ag nanoparticles in enhancing gas sensitivity. The sensing behavior is associated with adsorption of CO molecules on the Ag nanoparticle surfaces, followed by modulation of charge distribution at the Ag–CNT interface. These local electronic changes alter carrier transport through the interconnected network, producing a resistance shift that can be monitored in real time. Because CNT sheets contain many percolative pathways, even localized interfacial changes can generate a detectable macroscopic electrical signal.

The CNT/Ag sensors demonstrated relatively fast response and recovery behavior under ambient conditions. Rapid response is attributed to the accessible porous architecture of the CNT sheet, which allows gas molecules to diffuse efficiently throughout the sensing layer. Recovery occurred after purging with clean air or inert gas, indicating that the adsorption process was at least partially reversible under room-temperature operation. Although the sensor returned close to baseline after repeated cycles, slight baseline drift may occur over extended testing due to residual adsorption, humidity effects, or gradual surface rearrangement of nanoparticles. Such behavior is common in nanostructured chemiresistive sensors and can be mitigated through calibration, environmental control, or periodic regeneration steps.

Repeated exposure cycles demonstrated good reproducibility of the sensing response, indicating stable electrical contacts and durable interaction between Ag nanoparticles and the CNT matrix. The mechanical flexibility of the sheet architecture also suggests suitability for portable or wearable sensor platforms where bending or lightweight integration is required. Long-term stability is expected to depend on nanoparticle adhesion, oxidation resistance, and environmental storage conditions. Proper encapsulation or protective packaging could further enhance operational lifetime in practical deployments.

The overall sensing performance strongly depended on the relationship between material structure and electrical transport. Uniform nanoparticle dispersion increased the number of catalytic sites, while strong CNT interconnectivity preserved efficient charge conduction. Excessive Ag loading could potentially block pores, reduce accessible surface area, or create metallic short-circuit pathways that suppress sensitivity. Conversely, insufficient loading would limit catalytic enhancement. These observations indicate the existence of an optimal nanoparticle concentration that maximizes response while maintaining stable conductivity. Similarly, the porous morphology of the CNT sheet played a critical role by enabling rapid gas diffusion and high surface accessibility. The hybrid architecture therefore combines three complementary advantages: (i) conductive CNT transport pathways, (ii) catalytic Ag adsorption sites, and (iii) lightweight flexible sheet geometry.

Analysis of the dynamic conductivity response revealed a sensor sensitivity of about 0.34% toward CO exposure at room temperature. The CNT/Ag sensor exhibited rapid response and recovery times of ~25 s and 35 s, respectively. Adsorption–desorption analysis suggested fast reversible gas interaction kinetics associated with the high surface area, while the conductivity enhancement mechanism was attributed to CO-induced charge transfer and reduced junction resistance at Ag-functionalized CNT interfaces. Although the observed conductivity response (~0.34%) is lower than that reported for some high-temperature metal oxide gas sensors, the CNT/Ag hybrid sensor demonstrates effective room-temperature CO detection with rapid reversible response, low power requirements, and mechanically flexible architecture. The measured sensitivity compares favorably with many CNT-based chemiresistive sensors operating under ambient conditions and confirms the effectiveness of

Ag nanoparticle functionalization in enhancing interfacial charge-transfer interactions. In comparison, commercial CO gas sensors, typically based on metal-oxide semiconductors such as SnO_2 or electrochemical sensing platforms, generally exhibit response times ranging from ~30 s to several minutes depending on operating temperature, device architecture, and target concentration. Recovery times for commercial sensors are often longer, commonly in the range of ~60–180 s or more, particularly for room-temperature operation where desorption kinetics are slower [65]. Therefore, the CNT/Ag sensor shows a competitive or improved dynamic performance, especially in recovery behavior. The reduced recovery time suggests more efficient desorption of CO molecules, likely due to weaker adsorption energy and improved electron transport within the conductive CNT/Ag hybrid structure. This faster baseline restoration is advantageous for real-time monitoring applications where rapid cycling between exposure and recovery is required.

The enhancement in conductivity upon CO exposure is understood to be driven by interfacial charge transfer and the subsequent modulation of contact resistance at the Ag-decorated CNT junctions. Pristine CNT networks suffer from high junction resistance where nanotubes overlap, creating a bottleneck for electron transport. When Ag nanoparticles are integrated into these junctions, they act as highly active catalytic sites that selectively adsorb CO. This influx of electrons cascades into the intersecting CNT networks, narrowing the width and lowering the height of the localized Schottky barriers at the Ag-CNT interfaces. This barrier reduction facilitates quantum tunneling and smoother carrier transport across the inter-tube crosslinks, ultimately decreasing the junction resistance and causing a sharp macroscopic increase in the overall sensor conductivity. Figure 8 illustrates the proposed CO sensing mechanism in Ag nanoparticle-decorated CNT junction networks together with the corresponding energy band evolution. In the pristine CNT–CNT junction shown in Fig. 8a, direct contact between neighboring CNTs provides relatively smooth carrier transport with minimal junction resistance and no pronounced Schottky barrier formation. The valence band edge (E_v) remains close to the Fermi level (E_F), consistent with the p-type semiconducting behavior commonly observed in CNT networks under ambient conditions.

After incorporation of Ag nanoparticles between adjacent CNTs (Fig. 8b), localized metal–semiconductor junctions are formed at the Ag–CNT interfaces. Due to work-function differences between Ag

and the CNTs, charge redistribution occurs, leading to the formation of Schottky barriers (Φ_b) and depletion regions (W_b). These interfacial barriers hinder charge transport across the CNT junctions and increase the overall junction resistance of the sensing network.

Upon exposure to CO gas (Fig. 8c), CO molecules preferentially adsorb onto the Ag nanoparticles because of their strong catalytic activity and high surface affinity toward CO molecules. Since CO behaves as a reducing gas, electron donation occurs at the Ag surface, increasing the electron density of the Ag nanoparticles and shifting the Ag Fermi level upward. This interfacial charge transfer modifies the local band alignment at the CNT/Ag junctions, resulting in a reduction of the Schottky barrier height and narrowing of the depletion width.

The reduced barrier width facilitates enhanced carrier tunneling and more efficient charge transport across neighboring CNT junctions. Consequently, the junction resistance decreases significantly, leading to an increase in the macroscopic electrical conductivity of the CNT/Ag sensing network. The observed rapid conductivity enhancement and fast dynamic response are therefore attributed to the combined effects of catalytic CO adsorption on Ag nanoparticles, Fermi-level modulation, and Schottky barrier reduction at the CNT–Ag interfaces.

Compared with many metal oxide CO sensors that require elevated temperatures for activation, the CNT/Ag sheet sensor operated effectively at room temperature, reducing power consumption and simplifying device integration. The use of flexible carbon-based sheets also provides advantages in

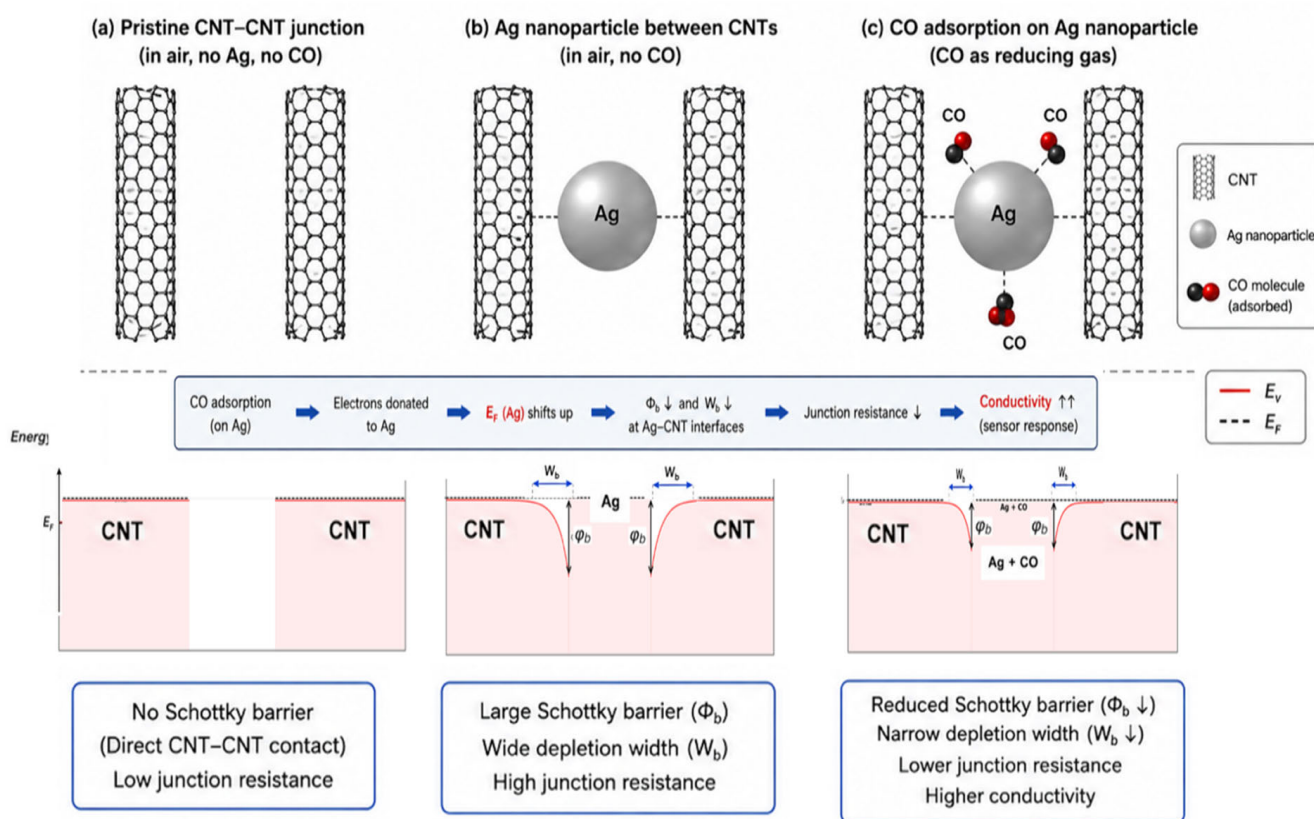


Fig. 8. Schematic illustration of the CO sensing mechanism in Ag nanoparticle-decorated CNT junctions and the associated energy band modulation. Panel (a) shows a pristine CNT–CNT junction without Ag nanoparticles or CO adsorption, where direct CNT contact results in low junction resistance and no significant Schottky barrier formation. Panel (b) illustrates the introduction of Ag nanoparticles between neighboring CNTs under ambient conditions. The Ag–CNT interfaces create localized Schottky barriers (Φ_b) and depletion regions (W_b), which increase the junction resistance and hinder carrier transport. Panel (c) demonstrates the effect of CO adsorption on Ag nanoparticles. As a reducing gas, CO donates electrons to Ag, causing an upward shift in the Ag Fermi level (E_F). This electron transfer reduces both the Schottky barrier height and depletion width at the Ag–CNT interfaces, facilitating carrier tunneling and improving charge transport across the CNT network. Consequently, the junction resistance decreases, and the overall electrical conductivity of the sensor increases significantly.

weight, scalability, and compatibility with wearable or distributed sensing systems. While further optimization may be required to improve selectivity under mixed-gas or humid environments, the present results demonstrate that CNT/Ag hybrid sheets are promising candidates for next-generation low-power CO monitoring technologies. Future studies will focus on further optimization and mechanistic understanding of the CNT/Ag sensing platform, with particular emphasis on systematically controlling the Ag concentration and nanoparticle loading. The effects of Ag loading on CO adsorption, charge transfer, sensitivity, response and recovery kinetics, and long-term stability will be investigated to identify the optimal sensor composition. Comprehensive gas adsorption–desorption measurements using appropriate probe gases will also be performed to characterize the specific surface area, pore-volume distribution, pore-size distribution, and accessibility of the CNT/Ag porous network. These measurements will help distinguish the total porosity from the fraction of the pore structure that is accessible to gas molecules and contributes to CO sensing. The relationships among Ag loading, accessible surface area, pore characteristics, CO adsorption, and electrical response will be systematically evaluated to establish more comprehensive structure–property–sensing correlations. In addition, future work will investigate the effects of humidity, temperature, and potential interfering gases to further improve sensor selectivity, reproducibility, and long-term operational stability. These studies will provide deeper insight into the underlying CO sensing mechanisms and guide the development of optimized, scalable, and portable CNT/Ag sensors for reliable room-temperature CO monitoring.

5. Conclusions

Acid treatment introduces oxygen-containing functional groups such as hydroxyl, carbonyl, and carboxyl species on CNT surfaces, which increase defect density and activate additional vibrational modes in Raman spectra, including features in the $\sim 800\text{--}950\text{ cm}^{-1}$ region associated with C–O-related bonding and structural disorder. The results demonstrate that Agnanoparticle functionalization significantly improves the sensing performance of CNT sheets toward CO. Enhanced sensitivity, stronger gas response, rapid dynamics, and repeatable room-temperature operation were achieved through the synergistic interaction of the CNT network and Ag catalytic nanophase. These findings

support continued development of CNT/metal hybrid architectures for advanced environmental and safety sensing applications. Repeated gas introduction results in a clear and reproducible increase in conductivity relative to the baseline, demonstrating a positive sensing response toward CO. The periodic conductivity transitions indicate stable response and recovery behavior over sensing cycles. At room temperature, the CNT/Ag sensor achieved 0.34% sensitivity to CO, with fast response ($\sim 25\text{ s}$) and recovery ($\sim 35\text{ s}$) times. Adsorption–desorption tests confirmed rapid, reversible gas kinetics. This increased conductivity stems from CO-induced charge transfer and lower junction resistance at the Ag-functionalized CNT interfaces. These results confirm that the acid-treated CNT/Ag hybrid structure provides effective charge transport modulation upon interaction with CO molecules, highlighting its potential for quantitative room-temperature gas sensing applications.

CRedit authorship contribution statement

Sara Sharifi: Visualization, Methodology, Investigation, Formal analysis, Editing. **Andrea P. Carvajal:** Visualization, Methodology, Investigation, Formal analysis, Editing. **Mkhitar Hobosyan:** Methodology, Investigation, Formal analysis, Review & Editing. **Mircea Chipara:** Methodology, Investigation, Formal analysis, Editing. **Nicholas Dimakis:** Review & Editing, Methodology, Formal analysis. **Matthew D. Lochridge:** Review & Editing, Conceptualization. **Anvar Zakhidov:** Methodology, Conceptualization, Supervision, Review & Editing. **Karen S. Martirosyan:** Writing, Review & Editing, Conceptualization, Investigation, Supervision, Methodology, Validation, Data curation.

Declaration of competing 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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