A high-sensitivity hydrogen gas sensor based on carbon nanotubes fabricated on SiO₂ substrate

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ABSTRACT

In this study, an inexpensive simple method for the fabrication of efficient hydrogen (H₂) gas sensor based on carbon nanotubes (CNTs) was presented. The CNTs were synthesized using microwave oven and deposited onto SiO₂ substrate by a dielectrophoretic method. The as-grown CNTs showed an n-type behavior because CNTs possess the characters of both metallic and semiconductor when placed between the two electrodes, meanwhile, the current was directed mostly by metallic tubes. Upon exposure to H₂ gas at room temperature, the CNTs exhibited high sensitivity up to 315% at 140 ppm H₂, and relatively good sensitivity of 40% at a very low H₂ gas concentration of 20 ppm. To the best of our knowledge, this is the first work involving the fabrication of CNTs for detecting a low H₂ gas concentration of 20 ppm at RT with high sensitivity comparing with other previous studies.

GRAPHICAL ABSTRACT

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1. Introduction

Great efforts have been devoted to the development of novel nanostructured materials with specific properties for gas sensors with high performances such as selectivity and sensitivity. Since their discovery in 1991, carbon nanotubes (CNTs) have attracted scientific interest due to their remarkable mechanical, chemical, and electronic properties in addition to their semiconductive/metalllic character depending on their diameter [1,2]. These unique characteristics make them a promising material for various applications including nanoelectronics, field emission devices, and multifunctional composite materials [3].

The application of CNTs for gas sensing has been widely investigated because of their large surface area due to their nanoscale regime and hollow geometry [4,5]. Some previous studies confirmed that CNTs-based gas sensors could be fabricated by electrophoresis [6,7].

Surface functionalization of CNTs via reflux treatment using some extreme acids, such as HNO3, resulted in the enhancement of surface area and modified morphological characteristics and thereby increased the ability to adsorb target gases [5,8].

Hydrogen (H2) is an essential component in numerous applications such as hydrogenation processes, petroleum transformation, welding, chemical production of substances, cryogenic cooling, rocket engines. Nowadays, fossil fuels are considered polluting agents, therefore utilization of H2 as a clean energy carrier in fuel cells has gained great importance. It is a colorless and odorless gas. Therefore, early detection of H2 gas because it is colorless and odorless. The studies have shown that if the concentration of H2 in the air is higher than 4% it will be highly explosive and easily flammable [9].

The fabrication of sensors with high sensitivity for H2 detection represents a major challenge in the development of H2-based technology. CNTs are successfully being employed as active sensing materials for the detection of H2 [10-14]. Moreover, the human senses do not detect H2 gas because it is colorless and odorless. Therefore, early detection of H2 is very important to ensure the safe operation of the H2-based energy equipment or fuel cell vehicles, since H2 leaks may cause deadly explosive accidents [9].

Most of the recent studies on composite sensors were based on their response towards NO2 and NH3 gases [6] However, there are few reports on the response of such CNT composite sensors towards H2. Furthermore, metals (Pd and Pt) and metals oxides (TiO2, SnO2, WO3) were added to CNTs in order to improve their sensitivity for H2 detection [4,11,12,15].

However, the fabrication of a gas detector by using multi-walled carbon nanotube was reported by Jung et al. [16] The results revealed a sensitivity of about 13% under 18,000 ppm of H2 gas at room temperature, and the response time was 20 s.

Moreover, functionalized multiwall carbon nanotubes were used to fabricate H2 gas sensors by Dhell et al. [8] The sensitivity of the sensors after 7 min of exposure were approximately 0.9, 0.13, and 0.14% for 500, 3500, and 5000 ppm of H2 gas respectively, and the recovery time of these sensors was 95 s.

In this paper, a simple method for the synthesis of CNTs using a conventional microwave oven and a novel nanoelectronic gas sensor fabricated from CNTs for H2 detection, are reported. The as-fabricated sensor was tested in the open air and at the presence of H2 with several operating temperatures.

The novelty of this research work consists of a cost-effective dielectrophoretic DEP deposition method for CNTs exhibiting good gas sensing characteristics at lower operating temperature, low recovery time, higher sensitivity at low gas concentration with a much faster response rate in an open environment.

The as-fabricated CNTs-based sensor showed good reversible and reproducible responses towards H2 in the temperatures range of 25–100 °C over a period of 55 min. This high performance was attributed mainly to the high surface to volume ratio of CNTs and increased H2 adsorption onto functionalization CNTs surface. The developed facile fabrication method in addition to the highly sensitive CNTs-based H2 gas sensor would reduce the cost and the operating power consumption as well.

2. Experimental part

2.1. Materials and samples preparation procedure

Pristine multi-walled carbon nanotubes (MWCNTs) were produced by a new method using a microwave oven. Different ratios (30:70), (20:80), (80:20), and (50:50) of ferrocene and graphite flattened in a ceramic boat, then irradiated using microwave oven for 5 s; CNTs with an average outer diameter of 55 nm were obtained [16].

The CNTs as-produced by microwave oven were treated in nitric acid (HNO3, 2.6 M) and stirred at RT for 14 h followed by ultrasonication for 1 h. After that, centrifugation at 10,000 rpm for 1 h was performed to obtain a supernatant, then resuspension the solution in deionized water. The last process was repeated several times until the pH of the solution reaches 7. The as-obtained CNTs were dried in an electric furnace at 70 °C for 24 h. The acid treatment can extremely facilitate the CNT by
insertion of chemical functional groups (-COOH and -OH) to the ends and sidewalls of CNTs resulting in the enhancement of their hydrophilicity [17].

2.2. Characterization techniques

The microstructure of the as-grown CNTs was characterized by field emission scanning electron microscope (FESEM) using Carl Zeiss Leo-Supra 50VP. Raman spectra were recorded at RT in the range 1100–1800 cm⁻¹ using an excitation wavelength of 633 nm of He-Ne laser to check the graphitic crystalline quality.

2.3. Fabrication of sensor

In order to fabricate a metal-semiconductor-metal (MSM) gas sensor, a 300 nm layer of SiO₂ was deposited onto Si wafer by wet oxidation (Figure 1(a)). Palladium (Pd) contact finger of thickness 100 nm was deposited via a metal mask on SiO₂ substrate using RF magnetron sputtering system (A500 Edwards), see Figure 1(b). The electrode fingers are 0.35 mm wide and 3.4 mm long with a gap of 0.40 mm in space. These electrodes have been electrically contacted to AC power supply by copper wires using silver paste.

For the preparation of CNTs solution, 3 mg of multi-wall CNTs synthesised by microwave oven and functionalized using HNO₃ acid were dispersed in 20 ml of Ethanol solution. Then followed by sonication for 60 min to disperse and stabilize the CNTs dispersion in solution. The concentration of CNTs solution was about 150 mg ml⁻¹. The CNTs solution of 0.5 ml was dropped between Pd electrodes under an AC electric field of 10 V at 50 Hz. The solution that was dropped on the substrate between electrodes was approximately 10 µl of carbon-ethanol solution using a micropipette. The schematic diagram of CNTs deposition on Pd electrode using AC dielectrophoresis is shown in Figure 1(c). The inset of Figure 1(c) shows the micro-image of the as-fabricated sensing device.

2.4. Experimental sensing set-up

The gas-sensing properties of CNT were performed for the detection of H₂, using a commercial sensing system equipped with a Keithley 2400 source meter. The sensor response under a constant applied voltage of 0.05 V was tested by measuring current-voltage curves, while the total flow rate was kept constant at 1000 sccm. The sensor was put in a homemade chamber, and the two Pd-electrodes of the sensor were connected to a computer-controlled by Keithley 2400 source-meter, as shown in Figure 2. Then the sensor was exposed to dilute H₂ gas concentration in the range 20–140 ppm at various operating temperatures. The mixture ratio of the main gasses (H₂/N₂) and dry air, were varied in order to control the gas concentration through the two gas flow controllers.

Figure 3 shows FESEM images of CNTs synthesized using different graphite/ferrocene mixture ratios. The tendency of agglomeration and the appearance of stacked bundles confirm the synthesis of CNTs, having diameters of about 55 nm as shown in Figure 3(a)–(d).

Figure 4 shows Raman spectra for as-grown CNTs. Two distinctive peaks are observed; the (D) band at 1330 corresponding to defects present in the hexagonal sp² carbon lattice of graphene layer and (G) band at 1580 cm⁻¹ ascribed to graphitic well-ordered carbon atoms. Meanwhile, the G-to-D
peaks intensity ratio \( \frac{I_D}{I_G} \) is usually considered as a measure of the well-ordered or relative amount of defects present in CNTs.

In order to obtain structural properties of the as-grown CNTs, the evaluated \( \frac{I_D}{I_G} \) values from Raman spectra are summarized in Table 1. The lowest \( \frac{I_D}{I_G} \) value that appears for CNTs obtained with 70:30 graphite/ferrocene ratio, This value indicates a high crystalline quality with fewer defects, thus, the highest sensitivity for hydrogen gas.

The D-to-G peaks intensity ratio \( \frac{I_D}{I_G} \) has often been linked to the structural purity of graphitic materials with the crystal domain size. When the intensity of G band is higher than D band, this implies an improvement of crystal quality. CNTs usually contain a graphene layer formed at the edges with a higher quantity of structural defects. The intensity of D band suggests the presence of defects in the graphene structure. By referring to the double resonance theory, the excited electrons scattered by crystal defects are responsible for the wave generation [18].

3. Results and discussion

The CNT based on \( \text{H}_2 \) gas sensor was introduced into the chamber at RT and to evaluate the gas-sensing characteristics, the \( \text{H}_2 \) concentration was controlled by the MFC (mass flow controller), meanwhile, the flow rate of the gas mixture was set at 1000 ppm.

The sensitivity of the sensor is defined as the relative variation of the electrical resistance using the following equation [19]:

\[
\text{Sensitivity} \, (\%) = \frac{R_{\text{gas}} - R_{\text{air}}}{R_{\text{air}}} \times 100 \tag{1}
\]

where \( R_{\text{air}} \) and \( R_{\text{gas}} \) are the maximum resistances of CNTs when exposed to \( \text{H}_2 \) ambiance and air ambiance, respectively.

The above expression, can also be expressed in terms of electrical current produced in CNTs under the operation of a DC bias voltage [20]:

\[
\text{Sensitivity} \, (\%) = \frac{I_{\text{gas}} - I_{\text{air}}}{I_{\text{air}}} \times 100 \tag{2}
\]
herein, $I_{\text{gas}}$ and $I_{\text{air}}$ are the maximum current recorded after the H$_2$ exposure and the current measured in pure air, respectively.

From the above equations, it is clear that the sensitivity can be associated with the quantity of electron charge transfer, the nature of the surface interaction of the gas and CNTs. Furthermore, it is important to highlight that CNTs have four possible positions whereby H$_2$ gas molecules can be adsorbed: internally, in external grooves, in interstitial channels, and on external surfaces [21].

Figure 5 illustrates the variation of CNTs-based sensor sensitivity when exposed to consecutive pulses of 140 ppm H$_2$ gas at different operating temperatures (RT, 50, 75, and 100 °C). This figure displays the actual time response of the sensor over a period of 55 min with excellent repeatability, especially at high temperatures. The repeatability improvement with operating temperature rising can be attributed to readily desorb of the H$_2$ molecules by lowering the binding energy of CNTs.

On the other hand, the current of the sensor returns to its original value after exposure to air at RT. This is a prominent feature for this device compared to previous studies which demonstrated an inability to return to the original value at RT [22,23].

The sensitivity of the sensor based on CNTs as defined by Eq. (1), at RT under an applied voltage of 0.05 V is shown in Figure 5(a). It is clear that at room temperature and under the H$_2$/balance N$_2$ of 140 ppm exposure, the device displays a very high sensitivity of 315% (Figure 5(a)), which is much higher than previously reported values from the literature [4,5,8,10–13,15,17,24–29].

Figure 6 illustrates the responses of the sensor when exposed to various H$_2$ concentrations in the range 20–140 ppm at different operating
temperatures. It can be observed that the CNTs-based sensor displays a fast response even when exposed to a low H$_2$ concentration of 20 ppm and achieved a sensitivity of about 40% at RT (Figure 6(a)). Besides, it was also found that the sensor response was repeatable and stable regarding its response changes without recording any major signal variations.

Recently, I. Sayago et al. [28] reported that H$_2$ gas can be detected using MWCNTs functionalized with Pd exhibited a sensitivity of only 20% for H$_2$ concentration of 30,000 ppm at temperature 250°C with response and recovery time of 1800 and 3600s, respectively. It is obvious that the present CNTs-based sensor exhibited much better sensitivity and more ability to detect several ppm of H$_2$ gas at RT comparing with previous studies.

The fast response of the as-prepared CNTs-based H$_2$ gas sensor can be attributed to the large surface-to-volume ratio CNTs, which increases H$_2$ adsorption sites and facilitates the diffusion of H$_2$ molecules through CNT. After replacing the test gas with air, the gas sensor returns back rapidly to its baseline. The recovery time of the present CNT-based gas sensor is 19 s at RT, which is very small compared to the significant recovery time reported for some other CNTs-based sensors in some previous studies [5,12,13].

Furthermore, a relationship between the sensitivity and H$_2$ concentrations was also obtained, as shown in Figure 7(a). It was noticed that the sensitivity depended on the concentration of H$_2$ molecules, which gradually increases, though not totally linear in response with the increase in gas concentration, reaching saturation around 90 ppm, especially at 100°C. The maximum sensitivity detected with 140 ppm H$_2$, was 415% at 100°C.

Moreover, Figure 7(b) exhibits a linear relationship between sensitivity and operating temperatures in the presence of 140 ppm of H$_2$ gas, where the increase in the operating temperature from RT to 100°C leads to an increase in the sensitivity. This is because higher temperatures facilitate the dissociation of H$_2$ molecules absorbed and thus enhance the adsorption of gas molecules on CNTs gas sensor, which decreases the response time [20,22].

The repeatability of this sensor for low H$_2$ concentration (140 ppm) indicates that, the sensitivity of the sensor does not weaken after repeated exposure to H$_2$, which proves that the sensing characteristics are reproducible.

The dependence of response time, which is another important characteristic of the sensor, and the temperature is shown in Figure 7(c). The results indicated that higher temperature favors faster response; when the sensor was heated to 100°C, the response time became shorter as 70 s.

In general, the relationship between the electrical conductivity of semiconductors and the ambient temperature is expressed by the following equation [23]:

$$\sigma = \sigma_0 e^{(-E_a/K_B T)}$$

where $K_B$ is the Boltzmann constant, $E_a$ is the activation energy and $T$ is the ambient temperature in Kelvin.

Figure 8 shows a logarithmic plot of the sensitivity versus reciprocal of operating temperature (1/T), the activation energy of the CNTs-based sensor can be evaluated from the slope of the Arrhenius plot.
Figure 5. Sensitivity and cyclic response of CNTs-based gas sensor under exposure to a dilute H₂ atmosphere (140 ppm) at different sensor temperatures: (a) RT, (b) 50 °C, (c) 75 °C, and (d) 100 °C.

Figure 6. Sensitivity of CNTs-based gas sensor under exposure to a dilute H₂ gas with different concentrations (20 to 140 ppm) at different temperatures: (a) RT, (b) 50 °C, (c) 75 °C and (d) 100 °C.
The obtained value was about 16 meV, which was much smaller compared to the activation energy value of 230 meV obtained for Pd-functionalized multi-layer graphene nanoribbons (MLGNs) network as reported by Jason et al. [31] and also much smaller than other of some previous CNTs-based sensors research works [32,33].

However, low activation energy is an indication that the present CNTs-based gas sensor has a high response for H2 gas with superior sensitivity.

It is important to highlight that the conductivity was increased with H2 adsorption then decreased upon turning off H2 gas flow meanwhile exposed to air. This behavior can only occurs when charge carriers in CNTs are of n-type, which is not in agreement with some previous studies, where CNTs were reported to be p-type.

This can be clarified as follows. CNTs deposited between the two electrodes were a mixture of 2 types of CNTs, metallic and semiconductor, forming junctions and crossings within the channel. Since the resistance of the semiconducting tubes is large, it can be stated that the measured current was directed mostly by the metallic tubes [34,35].

Notably, CNTs network in the gas sensor had a prevalent semiconductor behavior, although the network was possibly composed of a mixture of both semiconductor to metallic characters with different CNTs diameter.

It was observed that the present CNTs-based sensor had much higher sensitivity, and was operated at low applied voltage of 0.05 V with a total power consumption of around 3.5 μW at RT, which was the lowest as compared with other values of previously reported for other sensors [10,22,36,37]. This value was very much smaller than the lowest ideal value of 100 mW, hence this sensor with ultra-low power consumption is suitable for use in remote areas where the power sources might be very limited.

The mechanisms of sensing behavior of CNTs depend on the chemisorption and physisorption of H2. Chemisorption involves atomic H2 adsorption on CNTs surface while physisorption involves the adsorption of molecular H2 on CNTs surface.

In the meantime, Pd electrode plays a catalytic function during the chemisorption process to dissociate H2 molecules to H atoms [13,14,24,36]. The increased conductivity of CNTs-based gas sensor during exposure to H2 dilute gas can be explained by the following: H2 molecules are considered as a reducing agent that delivers an electron to CNTs. In the present gas sensor, H2 can play a role as an electron donor to CNT. Consequently, the electrons will be transported from H2 to CNTs during exposure to H2 gas. This process results in increasing the number of electrons leading to the reduction of CNTs resistivity meanwhile increase conductivity [13,14,24].

In the reverse process, when oxygen is present, the adsorbed atomic H2 combines with O2 to form hydroxyl groups (reaction 2), which will further combine with adsorbed H2 to form water that can depart the CNTs-based sensor (reaction 3). Thus, the oxygen in the air plays the role as a recovery agent, on Pd electrodes and CNTs surfaces. When H2 gas flow is switched off, this process leads to sensor reversibility and thus recovering CNTs electrical properties [20,22,38].

The main possible reactions that can describe H2 absorption and recovery stages are [5,17,39]:

 Response:

\[ H_2 \rightarrow 2H_{on\, \text{Pd\, electrode}} \rightarrow 2H_{on\, \text{CNT}} \] (4)

 Recovery:

\[ 2H + O_2 \rightarrow 2(OH)_{on\, \text{CNT}} \] (5)
\[ H + (OH) \rightarrow H_2O \] (6)

It is worth noting that the group of hydroxides resulting from the reaction of oxygen with absorbed
H₂ facilitates its recovery and this is consistent with the short recovery time of 19 s.

4. Conclusion

In this study, we demonstrated that high sensitive, efficient, and inexpensive CNTs-based H₂ gas sensor can be easily fabricated by a simple dielectrophoresis deposition of CNTs onto SiO₂ substrates. The CNTs synthesis can be achieved by a one-step and simple method under microwave irradiation and using a graphite/ferrocene mixture. The n-type behavior of CNTs was attributed to the presence of a metallic CNTs network which directs the current in a CNTs-based gas sensor. Notably, the sensor offers an excellent response toward H₂ in the range 20–140 ppm level comparable with the highest values reported in some previous studies in the literature (Table 2). It was found that CNTs-based sensor achieved high sensitivity of about 315% at 140 ppm.
level of $H_2$ concentration at RT with faster response/recovery times of 19/70 s. Furthermore, it is also shown that the CNTs-based gas sensor has a good sensitivity of 40% for the low concentration of 20 ppm level of $H_2$ at RT.

On the other hand, successive thermal treatments significantly improve the sensor sensitivity and the sensor response was reproducible without supplementary assistance such as an additional metal decoration or a vacuum system. The successful utilization of CNTs in gas sensing based on novel nanostructure and its capability to detect a very low concentration of $H_2$ in the range of 20–140 ppm favors the development of enhanced $H_2$ gas sensors with high performance. Also, the present sensor operates at RT with ultra-low power consumption in the range of 3.5 μW, hence it is suitable for use in remote areas with limited power sources.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References
1. Qi P, Vermesh O, Grecu M, et al. Toward large arrays of multiplex functionalized carbon nanotube sensors for highly sensitive and selective molecular detection. Nano Lett. 2003;3(3):347–351.
2. Nguyen H-Q, Huh J-S. Behavior of single-walled carbon nanotube-based gas sensors at various temperatures of treatment and operation. Sens Actuators B. 2006;117(2):426–430.
3. De Volder MF, Tawlick SH, Baughman RH, et al. Carbon nanotubes: present and future commercial applications. Science. 2013;339(619):535–539.
4. Jaggi N, Dhall S. Hydrogen gas sensing properties of multiwalled carbon nanotubes network partially coated with SnO2 nanoparticles at room temperature. Analysis. 2014;74:9999801.
5. Kong J, Chapline MG, Dai H. Functionalized carbon nanotubes for molecular hydrogen sensors. Adv Mater. 2001;13(18):1384–1386.
6. Lee J-H, Kim J, Seo HW, et al. Bias modulated highly sensitive NO2 gas detection using carbon nanotubes. Sens Actuators B. 2008;129(2):628–631.
7. Gohier A, Chançon J, Chenevier P, et al. Optimized network of multi-walled carbon nanotubes for chemical sensing. Nanotechnology. 2011;22(10):105501.
8. Dhall S, Jaggi N, Nathawat R. Functionalized multiwalled carbon nanotubes based hydrogen gas sensor. Sens Actuators A. 2013;201:321–327.
9. Hübert T, Boon-Brett L, Buttner W. Sensors for safety and process control in hydrogen technologies. Vol. 14. CRC Press; 2016.
10. Sippe-Oakley J, Wang H-T, Kang BS, et al. Carbon nanotube films for room temperature hydrogen sensing. Nanotechnology. 2005;16(10):2218–2221.
11. Sun Y, Wang HH. Electrodeposition of Pd nanoparticles on single-walled carbon nanotubes for flexible hydrogen sensors. Appl Phys Lett. 2007;90(21):213107.
12. Majumdar S, Nag P, Devi PS. Enhanced performance of CNT/SnO2 thick film gas sensors towards hydrogen. Mater Chem Phys. 2014;147(1–2):79–85.
13. Kumar MK, Reddy ALM, Ramaprabhu S. Exfoliated single-walled carbon nanotube-based hydrogen sensor. Sens Actuators B. 2008;130(2):653–660.
14. Guo K, Jayatissa AH. Hydrogen sensing properties of multi-walled carbon nanotubes. Mater Sci Eng C. 2008;28(8):1556–1559.
15. Gong J, Sun J, Chen Q. Micromachined sol–gel carbon nanotube/SnO2 nanocomposite hydrogen sensor. Sens Actuators B. 2008;130(2):829–835.
16. Natheer AA, Ibrahim K, Hassan Z, et al. Cost-effective single-step carbon nanotube synthesis using microwave oven. Mater Res Express. 2017;4(8):085602.
17. Kumar MK, Ramaprabhu S. Palladium dispersed multiwalled carbon nanotube based hydrogen sensor for fuel cell applications. Int J Hydrogen Energy. 2007;32(13):2518–2526.
18. Tuinstra F, Koenig J. Characterization of graphite fiber surfaces with Raman spectroscopy. J Compos Mater. 1970;4(4):492–499.
19. Buttner WJ, Post MB, Burgess R, et al. An overview of hydrogen safety sensors and requirements. Int J Hydrogen Energy. 2011;36(3):2462–2470.
20. Kadhim IH, Hassan HA. Room temperature hydrogen gas sensor based on nanocrystalline SnO2 thin film using sol–gel spin coating technique. J Mater Sci Mater Electron. 2016;27(5):4356–4362.
21. Zhao J, Buldum A, Han J, et al. Gas molecule adsorption in carbon nanotubes and nanotube bundles. Nanotechnology. 2002;13(2):195–200.
22. Abdullah Q, Yam F, Hassan J, et al. High performance room temperature GaN-nanowires hydrogen gas sensor fabricated by chemical vapor deposition (CVD) technique. Int J Hydrogen Energy. 2013;38(32):14085–14101.
23. Hu C, Wang W, Liao K, et al. Systematic investigation on the properties of carbon nanotube electrodes with different chemical treatments. J Phys Chem Solids. 2004;65(10):1731–1736.
24. Ding D, Chen Z, Rajaputra S, et al. Hydrogen sensors based on aligned carbon nanotubes in an anodic aluminum oxide tem plate with palladium as a top electrode. Sens Actuators, B. 2007;124(1):12–17.
25. Wongchoosuk C, Wisitsoraat A, Phokharatkul D, et al. Multi-walled carbon nanotube-doped tungsten oxide thin films for hydrogen gas sensing. Sensors (Basel). 2010;10(8):7705–7715.
26. Lu Y, Li J, Han J, et al. Room temperature methane detection using palladium loaded single-walled carbon nanotube sensors. Chem Phys Lett. 2004;391(4–6):344–348.
27. Zilli D, Bonelli P, Cukierman A. Room temperature hydrogen gas sensor nanocomposite based on Pd-decorated multi-walled carbon nanotubes thin films. Sens Actuators B. 2011;157(1):169–176.
28. Sayago I, Terrado E, Lafuente E, et al. Hydrogen sensors based on carbon nanotubes thin films. Synth Met. 2005;148(1):15–19.
29. Jung D, Han M, Lee GS. Gas sensor using a multi-walled carbon nanotube sheet to detect hydrogen molecules. Sens Actuators A. 2014;211:51–54.
30. Kim D, Pikhitsa PV, Yang H, et al. Room temperature CO and H2 sensing with carbon nanoparticles. Nanotechnology. 2011;22(48):48501.
31. Johnson JL, Behnam A, Pearton S, et al. Hydrogen sensing using pd-functionalized multi-layer graphene nanoribbon networks. Adv Mater. 2010;22(43):4877–4880.
32. Cantalini C, Valentini L, Armentano I, et al. Carbon nanotubes as new materials for gas sensing applications. J Eur Ceram Soc. 2004;24(6):1405–1408.
33. Wada Y, Fujita Y, Takei K, et al. Suspended single-walled carbon-nanotube field-effect transistor for gas sensing application. Jpn J Appl Phys. 2015;54(6S1):06FB01.
34. An KH, Jeong SY, Hwang HR, et al. Enhanced sensitivity of a gas sensor incorporating single-walled carbon nanotube–polypyrrole nanocomposites. Adv Mater. 2004;16(12):1005–1009.

35. Vijayaraghavan A, Kanzaki K, Suzuki S, et al. Metal-semiconductor transition in single-walled carbon nanotubes induced by low-energy electron irradiation. Nano Lett. 2005;5(8):1575–1579.

36. Abdullah Q, Yam F, Hassan Z, et al. Hydrogen gas sensing performance of GaN nanowires-based sensor at low operating temperature. Sens Actuators B. 2014;204:497–506.

37. Gelamo R, Rouxinol F, Verissimo C, et al. Low-temperature gas and pressure sensor based on multi-wall carbon nanotubes decorated with Ti nanoparticles. Chem Phys Lett. 2009;482(4–6):302–306.

38. Mubeen S, Zhang T, Yoo B, et al. Palladium nanoparticles decorated single-walled carbon nanotube hydrogen sensor. J Phys Chem C. 2007;111(17):6321–6327.

39. Trinchi A, Kandasamy S, Wlodarski W. High temperature field effect hydrogen and hydrocarbon gas sensors based on SiC MOS devices. Sens Actuators B. 2008;133(2):705–716.