Improvement in gas-sensing properties of TiO₂ nanofiber sensor by UV irradiation

Alireza Nikfarjam a,*, Nahideh Salehifar b

a Faculty of New Sciences & Technologies, University of Tehran, PO BOX: 14395-1561, Tehran, Iran
b Department of Electrical and Computer, Islamic Azad University, Science and Research Branch, Tehran, Iran

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1. Introduction

In the last few decades, researchers have realized that changes in the composition of gases around semiconductors can affect their electrical conductivities. Conductivity differs according to changes in the semiconductor’s electron density. Nowadays, metal oxide semiconductors such as TiO₂, In₂O₃, WO₃ and SnO₂ play a significant role in making gas sensors [1–6].

\[
\frac{1}{2} \text{mO}_2 + \{ \text{vacant site} \} + e^- \xrightarrow{K_1} \{ \text{O}_m \}
\]

\[
X + \{ \text{O}_m \} \xrightarrow{K_2} \{ \text{XO}_m \} + e^-
\]

The working mechanism of a gas sensor based on semiconductor metal oxides is as below:

\[
\{ \text{XO}_m \} \rightarrow \text{Desorption From Surface} \quad (1)
\]

Usually, metal oxide sensors are n-type semiconductors that first absorb oxygen from air, which acts as an electron receptor to form an ionic oxygen species that in turn decreases the electrical conductance. By introducing reducing gas atoms, they react with oxygen atoms which result in the emergence of electrons and the increase of electrical conductance. This effect could change nanoparticles’ type from n-type to p-type, or vice versa, which causes some changes in their conductivity [5–7].

Semiconductor gas sensors are widely used due to their small sizes, excellent responses, low costs, high stabilities, and ability to be integrated with electrical circuits [8,9].

In 1D metal oxide semiconductor nanostructures, such as nanowires, nanorods, nanobelts, and nanofibers, the surface-to-volume ratio is high; therefore, one-dimensional elements such as nanofibers are widely used in gas sensors [10–26]. Among various methods, the electrospinning (ES) procedure is highly regarded.
because of its simplicity and cheapness in making metal oxide fibers with high surface area and porosity. In this method, the polymer solution is transferred to polymer nanofibers through a high electric field. Changes in the composition of the polymer solution affect the fiber diameter, which is inversely proportional to the specific surface area. Sintering the fibers result in removal of the polymer to leave metal oxide fibers [15–17].

TiO₂ as an n-type semiconductor with special features, is widely applied in photocatalysts, photo/electrochromics, solar cell, and sensors. It has three crystalline phases: anatase, rutile, and brookite. Photocatalytic activity of a semiconductor is controlled by optical properties such as absorption coefficient in a specific spectrum, rate of oxidation, and reduction and rate of electron–hole recombination. In photon-semiconductor interactions, the most important limitation is band gap, which should be smaller than photon energy [20].

The gas-sensing properties of TiO₂ nanofibers were introduced previously [12]. In this research, since TiO₂ nanofiber exhibits strong photocatalytic activity, we focus on increasing the sensing performances through photoactivation. Moreover, the structure and crystalline phases of TiO₂ nanofibers in various calcined temperatures investigated improve the sensitivity and decrease the optimal temperature. All procedures were performed with and without UV irradiation. The stability, response time, and recovery time of the sensor were measured in different situations.

2. Materials and methods

2.1. Nanofiber deposition

Metal oxide nanofibers are synthesized by sol–gel and electrospinning methods. To produce the appropriate solution from the sol–gel method required for electrospinning, 0.5 g titanium tetraisopropoxid (C₁₂H₂₈O₄Ti, 97%) was added to 1 mL of ethanol (C₂H₅OH, 99.9%) and 1 mL acetic acid (CH₃COOH, 100%) and mixed for 15 min [8]. In another container, 2.5 mL ethanol with distinct weight ratios of PVP (9, 12, 19 and 26 wt%) was mixed for 45 min. This mixture was loaded into the first solution and mixed at the same speed for 3 h. The final solution was loaded into the syringe to join the electrospinning setup. Meanwhile, alumina ceramics with 1 mm thickness were sliced in 1.6 × 1 cm² and Pt interdigitated contacts with 600 nm thickness, 1 mm gap, and ten fingers with 1 cm length was DC sputtered through a shadow mask onto the ceramic substrate. Then alumina ceramic was stacked on aluminum foil, and a voltage of 18 kV was established between the needle of the syringe (anode) and the aluminum foil (cathode). The rate of electrospinning was 2 mL/min and the distance between the needle and aluminum foil was 25 cm. The nanofibers were calcined at 300–C, 500–C, 700–C, and 900–C. Heat treatment decomposed the polymer matrix to produce the metal oxide fiber between interdigitated contacts.

2.2. Gas sensing setup

To measure the gas-sensing properties of the sensor, we used a static test system that includes a data logger to collect data. A glass container and a number of electrical feed-throughs, gas inlet, gas outlet, a heater, mass flow controller (MFC) and thermometer which was located inside the chamber. Electrical feed-throughs are connected to a monitoring system with RS 232. A fireproof glass tube was also located directly on top of the sensor to serve as a flash-light. The UV lamp (Model SKU UVL-100) with 300–400 nm wavelength and 3.25 + 1 mW/cm² power was also used. The space between the UV light and gas sensor was 2 cm (Fig. 1).

2.3. Characterization techniques

XRD analysis was conducted by a Philips X’Pert MPD instrument operating with CuKα radiation (λ = 1.54178 Å) at 40 kV/30 mA. The...
FE-SEM images were taken by the Hitachi S4160 model Field Emission Scanning Electron Microscope. In this research, the response was obtained as the ratio of the sensor resistance in dry air to the sensor resistance in detected gas (\(R_{\text{air}}/R_{\text{gas}}\)). The response time is the time needed for the sensor’s resistance to undergo 90% modification and recovery time is the time needed for 60% change to get its initial value in the air. The gas-sensing performance was tested at H\(_2\) concentration of 5–200 ppm in the range of 50 °C to 300 °C.

3. Results

3.1. Structural analysis

The FESEM image of sintered TiO\(_2\) nanofibers with different PVP concentrations is presented in Fig. 2. The diameter of the nanofibers is approximately 50 ± 20 nm, 80 ± 20 nm, 130 ± 20 nm, and 200 ± 20 nm for 9, 12, 19 and 26 wt% of PVP, respectively. The results show that increases in nanofiber size could be attributed to increases in PVP concentration.

In continuous for showing details of the nanofibres structure, TEM image of calcined TiO\(_2\) nanofibers (prepared using 12 wt% PVP concentration) is displayed in Fig. 3. The sintered nanofibers surface at 5000 °C appeared almost smooth, and each individual nanofibers was quite uniform.

The concentration of PVP and heat treatment at different temperatures impact crystalline phase. The change in crystalline phase also affects the optical properties, stability, and the response of gas sensors based on TiO\(_2\) nanofibers. Fig. 4 shows the XRD pattern of TiO\(_2\) nanofibers calcined at 450, 500, 700, and 900 °C. For 500 °C, XRD peaks can be observed at about 2\(\theta\) = 27.28° (1 0 1) and 2\(\theta\) = 29° (1 1 0), which are relative to the anatase and rutile phase characteristics. The content of the anatase phase is calculated as:

\[
\frac{I_A}{I_R} + 1.26 I_R
\]

where \(I_A\) and \(I_R\) are the highest crest intensities of anatase and rutile, respectively. Temperature variation in the range of 400–1000 °C resulted in changing from the anatase phase into the rutile phase. The values obtained for the anatase phase are about 100%, 75%,

![Fig. 2. FESEM images of sintered TiO\(_2\) nanofibers at different PVP concentrations: (a) 26 wt%, (b) 19 wt%, (c) 12 wt%, (d) 9 wt% at 500 °C.](image)

![Fig. 3. TEM image of sintered TiO\(_2\) nanofibers at 12 wt% PVP concentration.](image)
25%, and 0% for the samples calcined at 450, 500, 700, and 900 °C, respectively.

Anatase phase TiO₂ is one of the best photocatalysts available today. However, according to the results obtained by spectrophotometer, the absorption of TiO₂ is maximized, when the ratio of anatase to rutile is about 3 to 1 (Fig. 5).

Moreover, the rutile phase has a lower band gap compared to that of the anatase phase. Therefore, by increasing the rutile phase, maximum absorption spectra are shifted to larger wavelengths (Table 1).

3.2. Hydrogen-sensing measurements

In this research, PVP was at distinct weight ratios of 9, 12, 19, 22 and 26 wt% and sintering temperature of 300 to 900 °C. The results (Fig. 6) revealed that in PVP concentrations of 12 wt% and sintering temperature of 500 °C, the sensor showed its highest response toward hydrogen gas (anatase: 77%, rutile: 23%).

The response of the TiO₂-nanofiber-based sensor in presence of different concentrations of hydrogen gas as a function of temperature was measured in both the dark and under UV illumination conditions. Results obtained for UV-irradiated and non-irradiated samples were compared and shown in Fig. 7(a) and (b). The values obtained for 25–200 ppm hydrogen gas are 1.8–10.1 and 18–96 for samples without and with UV irradiation, respectively. Furthermore, the UV irradiation changes the threshold of hydrogen gas concentration from 25 ppm to 5 ppm (Fig. 7(a)). Besides, UV irradiation causes considerable changes in operating temperature (the temperature in which, sensors show their maximum response at different gas concentrations) of about 100 °C toward lower values from about 290 °C to 190 °C (about one third of the initial value).

Response times in various temperature and different situations (UV illumination and without UV) of the pure TiO₂ nanofiber for 50 ppm H₂ are presented in Fig. 8. As the figure shows, with increasing temperature, the response and recovery times decrease. The response times were 12.3 and 2s and the recovery times were 22.5 and 6.9 s for pure TiO₂ and TiO₂/UV samples, respectively. When using UV irradiation, the response and recovery times are reduced by a factor of about 3–6.

Fig. 9 shows the response of the pure TiO₂ sample at 3, 6, and 9 months at. In addition, the effect of sintering temperature on stability of the sensor was investigated in this study. As the figures show, with increasing sintering temperature, the stability improves significantly and, at 900 °C after 9 months, the response remains almost constant due to the highly stable rutile phase of TiO₂, although the rutile phase has a lower photocatalytic effect and lower response toward ambient gas compositions. The results demonstrate that the response for the optimum sintering temperature of 500 °C drops by approximately 6% after 3 months, 15% after 6 months, and 23% after 9 months.

The TiO₂ nanofiber sensor was also tested for several gases to investigate the selectivity and the effect of UV irradiation in detecting other gases. Fig. 10 shows the response of the TiO₂ nanofiber sensor under dark and UV illumination conditions in the presence of 75 ppm for several gases. As the figure shows, the lowest response belongs to carbon monoxide with the sensitivity of 25, and the highest response belongs to ethanol with the sensitivity of 185.

In continuous we measured the time-dependent response of the samples to 75 ppm ethanol at optimum operating temperature with and without UV irradiation. Besides, absolute resistance changes are also shown in this Fig. 11. As shown in Fig. 11(a), the response of the TiO₂ nanofiber sensor to 75 ppm ethanol under dark condition is approximately 15. By UV illumination this amount is changed to about 185 (Fig. 11(b)). In addition response and recovery times

![Fig. 4. XRD pattern of pure TiO₂ nanofibers at different calcination temperatures: (a) 450 °C, (b) 500 °C, (c) 700 °C, (d) 900 °C.](image)

![Fig. 6. The response of pure TiO₂ nanofiber in 125 ppm H₂ without UV irradiation in different PVP concentrations and various calcination temperatures.](image)

![Fig. 5. The absorption spectrum of TiO₂ in various ratios of anatase to rutile.](image)
Fig. 7. The response of TiO$_2$ nanofiber sensor in presence of hydrogen gas as a function of temperature (a) without UV, (b) with UV irradiation, (c) comparison of two conditions at operating temperature.

Fig. 8. The response and recovery times of the TiO$_2$ nanofibers sensor in 50 ppm hydrogen gas as a function of temperature (a) with UV and (b) without UV.
Table 1
The effects of crystalline phase on maximum absorption of the nanofiber TiO₂.

<table>
<thead>
<tr>
<th>Anatase (%)</th>
<th>Anatase: 100%</th>
<th>Anatase: 75%</th>
<th>Anatase: 25%</th>
<th>Anatase: 0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ_{max}</td>
<td>350–360 nm</td>
<td>360–380 nm</td>
<td>390–400 nm</td>
<td>405–410 nm</td>
</tr>
</tbody>
</table>

Fig. 9. The stability of the TiO₂ nanofiber sensor under UV illumination at 150 ppm hydrogen gas at various sintering temperatures at 290 °C working temperature.

decreased from 15s to 4.5s and 20s to 7s, respectively. The time-dependent of the pure sensors at different C₂H₅OH concentrations is also displayed in Fig. 12. With the increase of ethanol concentrations, the response increases significantly. For 5–75 ppm ethanol gas, the response is approximately 2–15 and 15–185 without UV and with UV illumination, respectively.

3.3. The effect of thin Gold layer

In addition, we fabricated another sensor with TiO₂ nanofibers coated with an Au thin layer, using DC-sputtering method at various thicknesses of 1, 1.5, 2.5 and 3 nm. Table 2 shows the absorption spectrum of TiO₂ at various thicknesses of Au on TiO₂ nanofibers samples. The results revealed that by raising the thickness, λ_{max} is significantly increased; at a thickness of 2.5 nm, the red shift toward the visible spectrum is maximized (λ_{max} = 400 nm). Fig. 13 shows that the absorption spectra of pure TiO₂ sample and Au (2.5 nm)–TiO₂ samples are about 370 nm and 400 nm, respectively. The Au (2.5 nm)–TiO₂ sample showed about 20% growth in absorption intensity and approximately 30 nm red shift toward the visible spectrum compared to the pure samples. In continuous all Au covered samples are tested by UV with wavelength range of 390–410 nm.

The responses of the Au-sputtered TiO₂ nanofiber sensor at various thicknesses and different temperatures without UV to 200 ppm CO are presented in Fig. 14. The results revealed that with Au thickness of 2.5 nm and sintering temperature of 500 °C, the sensor exhibited the best performance. The response of nanofibers covered with 0.5 nm thickness of Au did not exhibit any significant enhancement compared to the pure samples.

The Au (2.5 nm)/TiO₂ nanofiber sensor is also tested for several gases to investigate the effects of UV (390–410 nm) irradiation and Au thin film on the selectivity of the sensor. Fig. 15 shows the response of the Au/TiO₂ nanofiber sensor under dark and UV (390–410 nm) illumination conditions in the presence of 25 ppm of several gases. The Au/TiO₂ nanofiber sensor exhibits a supreme response for CO, suggesting that it can be utilized for different practical applications. The results show Au is the best catalyst to detection of CO in comparison to other gases. Although the figure mentions that the highest response belongs to ethanol but the increasing rate of response in CO is the highest among other gases. In the following the responses of various samples at different operating temperatures for CO are shown and compared in Fig. 16. The responses are 200, 95, 50 and 10.1 and the operating temperatures are 170 °C, 190 °C, 230 °C and 290 °C for the Au/TiO₂/UV (390–410 nm), TiO₂/UV (360–370 nm), Au/TiO₂, and pure TiO₂ samples, respectively. As the figure shows, the response of Au/TiO₂/UV (390–410 nm) in comparison to the pure sample under dark condition is increased by a factor of about 20. In addition, the operating temperature is lowered to about 120 °C. The response and recovery times at various temperatures and in different situations (UV illumination and without UV) for pure and Au/TiO₂ nanofiber samples for 200 ppm CO are presented in Fig. 16(b) and 16(c). By increasing the temperature, the response and recovery times decrease. The response time at 170 °C is 32, 13, 9, and 2.5 s and the recovery time is 40, 23, 10, and 5 s for the pure TiO₂, TiO₂/Au, TiO₂/UV (360–370 nm), and TiO₂/UV (390–410 nm)/Au samples, respectively. By using UV irradiation and Au additive, the response and recovery times are reduced by a factor of about 12.8 and 8, respectively.

Besides, the results demonstrate that the response for Au/TiO₂ and pure TiO₂ samples fabricated in their optimum sintering temperature of 500 °C drops by approximately 3% and 25% after 9 months, respectively. This reveals that covering the nanofibers with a thin Gold layer enhances the stability more than 8 times. This is due to the high chemical stability of Gold layer. Besides, this layer acts as a barrier for entering undesired contaminations.

Liu et al. [11] observed that the TiO₂ nanofibers sensor is totally insensitive to H₂, CO, and CH₄. They found no changes in sensor resistance for 100 ppm H₂, CO, and CH₄, even at 300 °C operating temperature. However, in this study, not only did we improve the response of TiO₂ nanofibers’ sensor by optimizing the crystalline

Table 2
The absorption spectrum of Au–TiO₂ at various thicknesses of Au.

<table>
<thead>
<tr>
<th>Au (nm)</th>
<th>1</th>
<th>1.5</th>
<th>2.5</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ_{max}</td>
<td>380 nm</td>
<td>390 nm</td>
<td>400 nm</td>
<td>395–400 nm</td>
</tr>
</tbody>
</table>

Fig. 10. The response of the TiO₂ nanofiber sensor under dark and UV illumination conditions in 75 ppm for several gases.
structure and diameter of nanofibers to a response of 4.3 under the same condition of 100 ppm H₂ at 300 °C, but we also obtained a noticeably better response through a UV irradiation mechanism of 47 for 100 ppm H₂ at lower temperature of 190 °C; the latter exhibited a highly sensitive sensor (11 times) at a lower working temperature (110 °C decrement). So the TiO₂ nanofibers’ structure with these modifications and UV-assisting mechanism could be a strong candidate for various industrial applications.

![Fig. 11](image1.png)

**Fig. 11.** Time-dependent resistance and response (a) and (c) without UV, (b) and (d) with UV radiation in pure TiO₂ nanofibers sample toward 75 ppm of C₂H₅OH at operating temperature.

![Fig. 12](image2.png)

**Fig. 12.** Time-dependent response of the pure TiO₂ nanofibers sample at different ethanol concentrations (a) without UV (at 290 °C) (b) with UV (at 190 °C).
4. TiO$_2$ nanofiber gas-sensing mechanism

The sensing mechanism of the TiO$_2$ nanofibers sensor is principally similar to that of metal oxide films. The XRD and TEM images presented polycrystalline structure with grains connected to each other. This structure has an increased surface area as well as providing electronic transmission channels for electron transferring through the grains with grain boundary barriers between them. In addition, because electrosprinned fibers have random orientation, there are a huge number of fiber-to-fiber connections [24–26]. Passing electrons through these potential barriers is critical to the total current of the sensor. The O$_2$ molecules chemisorb and dissociate at high temperatures or lower temperatures with the corporation of UV illumination to form active ionic oxygen atoms [O$^-$] on the surface of the TiO$_2$ grains. Due to the high electron affinity oxygen, they extract electrons from the conduction band of n-type semiconductor to form [O$^-$] and develop a depletion or space-charge region on the grain surface and decrease the effective radius of the grains for electron transport (Fig. 17). This decreases the conductance of the fiber. When the sensor is exposed to hydrogen gas, with the corporation of heat and UV illumination, reaction between the ionic oxygen atoms [O$^-$] and hydrogen molecules takes place. This effect re-injects captured electrons to the depletion region and widens the effective core area and lowers the height and width of potential barriers for better electron transportation (Fig. 17). In this case, the conductance is proportional to the core area, i.e. the square of effective radius ($r-\lambda_0$), where “$r$” is the core radius and $\lambda_0$ is the thickness of the space charge region. The density of electronic charges on the surface, $N_r$, is equal to $n_0\lambda_0$, where $n_0$ is carrier concentration. On the other hand, $N_r=|O^-|$, where [O$^-$] is dissociated and ionized oxygen atoms concentration, adsorb on the surface and trap electrons due to their high electron affinity. The reducing agent (Hydrogen atoms) decreases [O$^-$] through surface reaction. So, reducing agent [R] changes, [O$^-$], $N_r$ and $\lambda_0$, which result in conductance variation [11–13].

Due to the photocatalytic effect of TiO$_2$, the UV light absorption increases the density of the ionic oxygen atoms at the surface of the TiO$_2$ nanofiber (O$_2$ + e$^-$ + UV → 2O$^-$), providing more active sites for its further reaction with hydrogen. Besides, under UV irradiation, hole–electron pairs are created with high reactivity on the TiO$_2$ surface. Another reason for increasing the response and decreasing the response time and operating temperature is reducing the activation energy between the TiO$_2$ surface and hydrogen gas under UV irradiation [27–30]. Both thermal and radiation mechanisms are important. However, UV illumination reduces the activation energy between the TiO$_2$ surface and hydrogen molecules, but very low temperatures could not supply this reduced activation energy.

Besides, we used Gold layer to improve the sensing performances.

TEM images of Au/TiO$_2$ nanofibers are the same as TiO$_2$ nanofiber samples where is shown in Fig. 3. It seems that gold as nanoparticles cover TiO$_2$ nanofibers. Gas molecules can penetrate to the nanofiber structure through the free spaces between the particles.

A potential barrier forms between TiO$_2$ nanoparticles and a schottky barrier forms between gold and TiO$_2$ nanoparticles. By absorbing oxygen molecules at the TiO$_2$/TiO$_2$ and TiO$_2$/Au interfaces, the heights of barriers growth due to the captured electrons from TiO$_2$ by oxygen molecules to form oxygen ion species (O$_2^-$, O$^{2-}$, O$^-$. When CO gas molecules enter, the reaction between oxygen ions and CO molecules tends to release electrons back in to the TiO$_2$ nanoparticles. Then barrier heights decrease to their initial values [31,32]. Fig. 18 shows Au/TiO$_2$ nanofiber cross section which represents neighboring grains electronic states before and after carbon monoxide exposure.

Gold is not only one of the best chemical catalysts for CO gas sensing which reduces the activation energy between TiO$_2$ grain surfaces and CO gas molecules, but also Gold in form of nanoparticles, through Localized Surface Plasmon Resonance (LSPR) effect, which could increases the absorption in visible light, enhances and shifts photo catalysis effect of the TiO$_2$ nanofiber sensors toward

![Fig. 13. The absorption spectrum of pure and Au covered TiO$_2$ nanofiber samples.](image1)

![Fig. 14. The response of Au sputtered TiO$_2$ nanofiber sensor in different thicknesses of Au as a function of temperature toward 200 ppm CO gas.](image2)

![Fig. 15. The response of the Au/TiO$_2$ nanofiber sensor under dark and UV (390–410 nm) illumination conditions in 25 ppm of several gases.](image3)
Fig. 16. The (a) response, (b) response time and (c) recovery time of TiO$_2$, TiO$_2$/UV (360–370 nm), Au/TiO$_2$ and Au/TiO$_2$/UV (390–410 nm) sensors as a function of temperature at different conditions of UV irradiation toward 200 ppm CO gas.

Fig. 17. The potential barrier develops between TiO$_2$ neighboring grains (a) before and (b) after hydrogen exposure.
grains reduced a sensors. visible sensing of general, through temperature parallel illumination. deposited significant nm Conclusions Charge Besides, sensor. electron light LSPR gives and GNPs sensor and GNPs and surface band perturbing major effect and GNPs GNPs and between GNPs are dominant mechanisms for the electron flow.

One of our main goals in adding gold catalyst is to provide an optical sensor can work in visible spectrum which can activate by sun light without any artificial source of light. For this purpose we used LSPR effect of GNPs to absorb and activate by visible light illumination. By covering the sample with GNPs, we observed about 30 nm red shift toward visible light from 370 nm to 400 nm. This has a significant role in using visible light instead of UV ray [37].

5. Conclusions

In this study, in PVP concentration of 12 wt% and sintering temperature of 500 °C, the sensor showed its highest response. In general, by UV irradiation, the response was enhanced up to 9 times for 25 ppm H₂ gas, and the response and recovery times were reduced by a factor of 3–6. Furthermore, UV irradiation changed the threshold detection of hydrogen gas concentration from 25 ppm to 5 ppm. UV irradiation also caused considerable changes in operating temperature of about 100 °C toward lower values. The UV enhancement of gas-sensing properties can be attributed to the reducing of activation energy between the TiO₂ surface and hydrogen gas. In addition, the sensor was tested for several gases under dark and UV illumination conditions in the presence of 75 ppm gas. The highest response obtained for ethanol exhibited sensitivity of 185 in addition response and recovery times decreased from 15 s to 4.5 s and 20 s to 7 s, respectively. For 5–75 ppm ethanol gas, the response is approximately 2–15 and 15–185 without UV and with UV illumination, respectively.

Then we coated a thin layer of Au on the pure TiO₂ nanofibers sample and tested their sensing for CO. The sample with 2.5 nm Au layer shows the best performance among samples with different thicknesses of Au. By covering the sample with a thin Au layer we observed about 30 nm red shift toward visible light from 370 nm to 400 nm. By using UV (390–410 nm) irradiation and Au catalyst layer, the response for CO in comparison to the pure sample under dark condition is increased by a factor of about 20 and the response and recovery times are reduced by a factor of about 12.8 and 8, respectively.

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Alireza Nikfarjam was born in Tehran in 1975. He obtained his BSc and MSc degrees in electronics both in Iran in 1998 and 2001, respectively. In 2007 he obtained his PhD in microelectronics from K. N. Toosi University of Technology. He joined the Sharif University of Technology in 2009 as Post-Doctoral researcher to work on nano-sensors. Then he joined the Faculty of New Sciences and Technologies of University of Tehran in 2011 as assistant professor. His research interests are semiconductor micro/nano-devices especially gas sensors, MEMS&NEMS and Organic Electronics.

Nahideh Salehifar was born in Hamburg on 1989. She received her BSc and MSc degrees in electronics from University of Tabriz and Science & research center of Islamic Azad University both in Iran in 2009 and 2012, respectively. Her research interests are Renewable Energy Technologies, Metaheuristic Optimization Problem, Power Electrical System Analysis, Electrical Insulation, Gas sensors by nanofibers, Catalyst and Reactor Research, CFD and Math. Modeling.