Original Article

Enhancement mechanisms of ethanol-sensing properties based on Cr₂O₃ nanoparticle-anchored SnO₂ nanowires

Zhicheng Cai a, Sunghoon Park a, b, *

a Department of Software Convergence, Sejong University, 209 Neungdong-ro, Guwangjin-gu, Seoul, South Korea
b School of Intelligent Mechatronics Engineering, Sejong University, 209 Neungdong-ro, Guwangjin-gu, Seoul, South Korea

A R T I C L E   I N F O

Article history:
Received 2 October 2019
Accepted 22 October 2019
Available online 6 November 2019

Keywords:
SnO₂ nanowire
Cr₂O₃ nanoparticle
Ethanol gas sensor
Energy band diagram.

A B S T R A C T

Cr₂O₃ nanoparticle-anchored SnO₂ nanowires are synthesized to fabricate highly sensitive and selective ethanol gas sensor. SnO₂ nanowires are synthesized by vapor-liquid-solid method as a gas detection material, and Cr₂O₃ nanoparticles are anchored to SnO₂ nanowires to improve sensing properties. Anchoring Cr₂O₃ nanoparticles are synthesized to deep the SnO₂ nanowire sample to chromium oxide colloid gel, and anneal this sample at 500 °C, in a vacuum atmosphere. This hybrid structured sensor presents 4 times improved ethanol sensing response compared with as-synthesized SnO₂ nanowires when exposed to 100 ppm ethanol gas in 300 °C. Furthermore, sensing selectivity of ethanol versus other volatile organic compound (VOC) gas is also drastically improved. Generally, nanostructured SnO₂ is known as very sensitive material to chemical gas, but it is hard to apply to commercial gas sensor since its extremely low selectivity. However, using this hybrid structured sensor, highly sensitive and selective ethanol sensor can be fabricated. This improvement of ethanol sensing properties can be explained that variation of energy bandgap of homojunction between n-SnO₂ and n-SnO₂ and heterojunction between n-SnO₂ and p-Cr₂O₃ of nanowires. Furthermore, catalytic properties of this hybrid structure nanowire make selectivity of sensor improved.

© 2019 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Recently, many smart devices having new functions are developed with nanotechnologies [1–3]. Nanostructured metal oxides have been studied as chemical gas sensors in past decades owing to their unique properties [4–6]. Because their resistance changes with exposure to an oxidation or reduction gas, gas can be detected by this material-based sensor by measuring its resistance [7]. Because electrons in nanomaterials migrate as chemical gas, the ions are attached to or detached from the surface of the nanomaterials, and the carrier concentration of the nanomaterials varies. Owing to this variation in carrier concentration, the resistance of nano-
materials changes, and chemical gas can be detected [8]. This migration of carriers occurs near the surface and an extremely small range of nanomaterials can be affected. The range can be calculated by the Debye length [9]. In this sense, nanomaterials having a small diameter are suitable for application in chemical gas sensors [10]. Unlike bulk materials, the resistance of nanomaterials changes dramatically [11].

SnO₂ nanostructures have various unique properties possible to applying lots of smart devices, such as solar cells [12], transparent conducting oxides (TCO) [13], lithium storage cells for electrodes of rechargeable batteries [14], and chemical gas sensors [15]. Of these applications, its application as a chemical gas sensor presents the best prospect, as nanostructured SnO₂ is sensitive to chemical gas. Many studies have reported on using this nanomaterial as a chemical gas sensor [16–18]. Hence, many kinds of chemical gas can be detected by SnO₂ nanostructures, and ethanol gas can also be detected well using this nanomaterial. Sensors based on various kinds of SnO₂ nanomaterial, which have several microstructures and morphologies, have been studied, and are presented in Table 1. Researches presented in this table are modified their microstructures to amplify ethanol-sensing properties of an SnO₂ nanomaterial-based sensor with some additional processes such as modifying its microstructures [28], doping [29], and creating a core/shell structure [30]. According to the papers presented in Table 1, the ethanol-sensing properties are improved as additional processes are performed. However, its sensing response and selectivity must be further improved for application as a commercial gas sensor. Above all, selectivity is the most important inveterate problem for SnO₂ nanomaterial-based gas sensors [31]. Although gas sensors based on SnO₂ nanomaterial present a good response to chemical gas, the sensitivity of the material shows poor results because the material reacts with many kinds of chemical gas. For this reason, various methods have been used to overcome this problem [32–34].

Hybrid-structured nanomaterials are considered the principal method for fabricating highly sensitive and selective chemical gas sensors. Of these chemical gas sensors, nanowire-based sensors have commanded attention owing to their linear morphology, narrow diameter, high aspect ratio, and extremely large surface area [35]. Furthermore, nanoparticle-attached nanowires present an optimal structure for the fabrication of highly sensitive and selective chemical gas sensors. Because Cr₂O₃ nanomaterial is known to be sensitive to ethanol gas [36], and it also shows adequate selectivity to this gas [37], it is expected that highly sensitive and selective ethanol gas sensors could be fabricated using Cr₂O₃ nanoparticle-anchored SnO₂ nanowires (CSN). SnO₂ nanowires are used in highly sensitive sensors for various gases, but their selectivity is poor. In contrast, Cr₂O₃ nanomaterial presents good selectivity, but its sensitivity must improve for application in commercial ethanol gas sensors. Therefore, highly sensitive and selective ethanol gas sensors can be fabricated by anchoring Cr₂O₃ nanoparticles to SnO₂ nanowires. This hybrid-structured nanowire not only presents high selectivity, but also presents an improved sensing response to ethanol gas compared with as-synthesized SnO₂ nanowires (ASN).

In this study, methods for synthesizing CSN are presented, and their physical properties, chemical structure, and electrical-sensing properties are analyzed. Furthermore, ethanol gas-sensing mechanisms based on these nanowires are also discussed.

2. Experimental

CSN are synthesized via a two-step process. First, SnO₂ nanowires were synthesized by a vapor-liquid-solid (VLS) process. To synthesize SnO₂ nanowires, an interdigital electrode (IDE) chip is prepared. Two different electrode patterns with a 10 μm gap were printed on a 300 nm SiO₂/Si wafer substrate using a photolithography lift-off process. 10 nm Ti/50 nm Pt/3 nm Au layers were deposited on this IDE pattern-printed substrate. In the meantime, 1 g of Sn powder as a source material was loaded into an alumina crucible, and the IDE-patterned substrate chips were placed in front of the Sn powder. The crucible was inserted into the center of a horizontal tube furnace and tightly sealed. The chamber of the furnace was evacuated to 1 mTorr and heated to 900 °C for 90 min in an ambient vacuum. When the target temperature was reached, 99 sccm N₂ and 1 sccm O₂ gas were injected into the chamber, and the pressure inside the chamber was set to 1 Torr. This process proceeded for 10 min under constant temperature and gas supply. After 10 min, the chamber was cooled to room temperature without any gas supply. When the VLS process was finished, a white velvet-like film was found on the IDE pattern.

The second step of synthesizing CSN is as follows: 0.6 g of chromium (III) acetate hydroxide was dissolved in 50 ml distilled (DI) water. Then, 0.1 g of NaOH was added to this solution, and mixed at 300 rpm using a magnetic stirrer. After
30 min, the solution was transferred to a conical tube and centrifuged at 3000 rpm for 2 min. A colorless transparent solution without precipitate was removed, and the same amount of ethanol gas was added. It was then mixed using a 500 rpm magnetic stirrer for 1 h. After 1 h, this colloid gel solution was deep coated on the SnO$_2$ nanowire-deposited IDE chip. The chip was dried using an N$_2$ gun and annealed at 500 °C for 1 h in a 1 mTorr ambient vacuum without a gas supply.

The physical and chemical properties of CSN and ASN were analyzed using the following process. The morphologies of these samples were observed with scanning electron microscopy (SEM, Hitach S-8010), and their crystal structures were measured using 2θ mode X-ray diffraction (XRD, Philips X’pert Pro MRD). The morphology, nanostructure, and chemical structure of a single nanowire was analyzed with an energy dispersive X-ray spectroscopy (EDS)-equipped transparent electron microscope (TEM, Jeol-2100F). To measure the electrical properties of the samples, a custom-made gas sensing system was used.

Prepared IDE chip is attached sensing die, and installed sensing chamber connected with electrodes. The other end of the electrodes were connected to a source meter (Keysight B-2900A) to monitor and record the resistance of the sensors. During the sensing process, a 1 V bias was applied to the sensors, and resistance was measured every 0.5 s. A 200 sccm target and purging gas were injected in front of the IDE chip. This gas was exhausted naturally by the difference in pressure between the inside and outside of the chamber. Each gas was injected for 200 s and 300 s, respectively. 1, 2, 5, 10, 20, 50, 100 ppm ethanol gas was supplied to the sensors as a target gas to analyze the response of the sensors followed by ethanol concentration. The operational temperature was adjusted from 150 °C to 400 °C at 50 °C intervals to find the optimal temperature. The resistance values of the sensors were defined as $R_0$ and $R_4$ for the target gas (ethanol) and purging gas (synthetic air), respectively. The gas response (R) of the samples was defined as $R_4/R_0$.

### 3. Results and discussion

Fig. 1 (a) presents an SEM image of the as-synthesized SnO$_2$ nanowires, and its enlarged image is shown in Fig. 1 (b). According to these images, synthesized nanowires are linear and have an extremely large aspect ratio. In these images, the surface of the nanowire is quite smooth, and its diameter is from approximately 50 nm to 100 nm. The SEM image of a CSN and its enlarged SEM image are presented in Fig. 1 (a) and (b), respectively. The morphologies of the SnO$_2$ nanowires...
are similar to that shown in Fig. 1 (a) and (b), but small bumps can be observed on the surface of the nanowires. These bumps are Cr$_2$O$_3$ nanoparticles, and their diameters are from approximately 5 nm to 20 nm. Fig. 2 presents XRD patterns analyzing the ASN (black line) and CSN (red line) samples. Both samples include several diffraction peaks, such as (110), (101), (200), (111), (210), (211), (220), (002), (310), (112), (301), (202), and (321), and these peaks indicate that synthesized samples consist of tetragonally structured SnO$_2$ (JCPDS No. 88-0287). Unlike the ASN, the CSN pattern includes an additional peak at (110) of Cr$_2$O$_3$ (JCPDS No. 89-3079). This additional peak presents weak intensity, because the amount of Cr$_2$O$_3$ nanoparticles is much smaller than the SnO$_2$ nanowire.

The CSN TEM image is shown in Fig. 3 (a). According to this image, the morphology of SnO$_2$ nanowire is similar to that shown in Fig. 1 (c) and (d). However, in this image, anchored Cr$_2$O$_3$ nanoparticles appear more clearly than in the SEM images. Fig. 3 (b) presents an enlarged and high-resolution TEM image of the CSN presented in Fig. 3 (b). Neighboring fringe patterns are shown in this image, and the space gaps of the nanowire body are 3.35 Å, indicating the (110) lattice plane, and 2.64 Å, indicating the (101) lattice plane of SnO$_2$. Meanwhile, the space gaps of the anchored nanoparticles are 2.48 Å, indicating the (110) lattice plane, and 2.66 Å, indicating the (104) lattice plane of Cr$_2$O$_3$. Fig. 3 (c) presents the SAD pattern of the corresponding nanowire in the TEM sample. Regularly arranged bright patterns are observable, which indicate the (101) and (110) lattice planes of SnO$_2$, and some aperiodic and indistinct spots, which indicate that the (110) lattice plane of Cr$_2$O$_3$ is appended with the pattern. Although single Cr$_2$O$_3$ nanoparticles consist of a single crystal, a group of particles can be considered as a polycrystalline structure, and each crystal have different direction each other, so SAD patterns assigned Cr$_2$O$_3$ nanoparticles present irregular patterns. The amount of Cr$_2$O$_3$ is smaller than that of SnO$_2$, and the peak intensity of Cr$_2$O$_3$ is weaker than that of SnO$_2$. Fig. 4 (a) presents a scanning transparent electron microscopy (STEM) image of a corresponding nanowire. The EDS electron

---

**Fig. 2** - XRD patterns of ASN (black line) and CSN (red line).

---

**Fig. 3** - (a) Low-magnification and (b) Enlarged high-resolution TEM image of single Cr$_2$O$_3$ nanoparticle-anchored SnO$_2$ nanowire, and (c) selected area electron diffraction (SAD) image of corresponding nanowire.
mapping spectra of this image were analyzed. Fig. 4 (b)–(d) presents the results of the elemental profile of oxygen, tin, and chromium, respectively. According to these results, nanowires and nanoparticles consist of tin oxide and chromium oxide, respectively. No elemental diffusions can be observed in these images.

To find the optimal operating temperature, the ethanol-sensing properties of CSN and ASN-based sensors were examined under a supply of 100 ppm ethanol gas, as shown in Fig. 5 (a). During this experiment, the operating temperature was adjusted from 150 °C to 400 °C, at 50 °C intervals. Based on the results of this experiment, both samples presented their best sensing response at 300 °C, whereas the CSN-based sensor presented a superior sensing response compared with ASN at every temperature. In particular, at 300 °C, which presented the best sensing response for both sensors, the response of the CSN-based sensor was four times better than the sensing response of the ASN-based sensor. Fig. 5 (b) and (c) presents the dynamic response curves of CSN and ASN-based sensors at 300 °C as a function of the ethanol concentration, respectively. Ethanol gas in concentrations of 1, 2, 5, 10, 20, 50, and 100 ppm was supplied to the sensors to analyze the effect of ethanol concentration. The responses of both sensors increased as the ethanol concentration increased. Fig. 5 (d) presents the summarized sensing response of ASN and CSN-based sensors at 300 °C followed by ethanol concentration. Based on this graph, the response curves of both sensors increase linearly at this temperature. However, when the sensors were exposed to 100 ppm ethanol gas, the response of the CSN-based sensor was 20.11 times higher than the response when the sensors were exposed to 1 ppm ethanol gas, whereas present just only 5 times higher response in case of ASN based sensor. This difference in response was caused by the Cr2O3 nanoparticles anchored on the surface of SnO2 nanowire. With this structure, highly sensitive ethanol gas sensors can be fabricated.

Fig. 6 (a) presents the gas-sensing response of ASN and CSN-based sensors with various volatile organic compound (VOC) gases to analyze the gas-sensing selectivity of both sensors. Unlike the ASN-based sensor, the CSN-based sensor presents improved sensing selectivity toward ethanol gas. In particular, the acetone response of the ASN-based sensor presents results almost the same as the ethanol-sensing response, but in the case of the CSN-based sensor, the ethanol gas presented a response 3.4 times greater than the response of acetone gas. The source of improvement in the selectivity of the hybrid-structured sensor is not yet clear [38]. However, it might be explained by the synergistic effect of the highly
sensitive SnO$_2$ nanowires and the good ethanol selectivity of the Cr$_2$O$_3$ nanoparticles. Fig. 6 (b) presents the long-term stabilization of both sensors. To analyze this stabilization, the response of both sensors to 100 ppm ethanol gas was measured every 3 d for 1 mo. According to the results, both sensors presented a stable sensing quality during this period. The deviations in the CSN and ASN-based sensor were within 5%, and 3%, respectively, and these results show that the sensor can be used commercially.

The major mechanisms of ethanol gas sensing using CSN-based sensors are theorized as follows: One is the variation in potential energy barriers between the nanowires [39], and the other is the change in the depletion layer of the nanowire surface [40] when exposed to air and the target gas.

When nanowire sensors are placed in ambient air, the oxygen gas in the air is pulled and adsorbed on the surface of the SnO$_2$ nanowires by the electrostatic force changing oxygen molecules. Electrons in the SnO$_2$ nanowire are attracted to the adsorbed oxygen molecules and are absorbed by them thus changing the oxygen molecules to oxygen ions (O$_2^-$). Finally, these ions absorb more electrons, and decompose to O$^-$ or O$_2^-$ according to the following equations [41]:

\[ \text{O}_2(\text{gas}) \rightarrow \text{O}_2(\text{ads}) \]  
\[ \text{O}_2(\text{ads}) + e^- \rightarrow \text{O}_2^-(\text{ads}) \]  
\[ \text{O}_2^-(\text{ads}) + e^- \rightarrow 2\text{O}^- \]

---

Fig. 5 – (a) Gas sensing response of ASN and CSN exposed to 100 ppm ethanol gas with variation in the operating temperature, dynamic response curves of (b) ASN and (c) CSN as a function of the supplied ethanol gas concentration, and (d) ethanol sensing responses of corresponding samples as a function of the supplied ethanol gas concentration.

---

Fig. 6 – (a) Ethanol gas responses of ASN and CSN samples compared with that of a VOC gas, and (b) Long-term stabilizations of both gas sensor samples during month-long exposure to 100 ppm ethanol gas at 300 °C.
\[ \text{O}^– + e^- \rightarrow \text{O}^{2–} \]  
\[ \text{(4)} \]

In contrast, ethanol gas is supplied to the sensor, and ethanol gas is also adsorbed on the SnO₂ nanowire surface, and these adsorbed ethanol gases react with oxygen ions. As the result of this reaction, ethanol gas and oxygen ions change to H₂O and CO₂ gases. These gases detach from the nanowires and are exhausted outside of the chamber. In the meantime, electrons that are absorbed by oxygen ions revert to the nanowire body according to the following equations:

\[ \text{CH}_3\text{CH}_2\text{OH(ads)} + 6\text{O}^- (\text{ads}) \rightarrow 2\text{CO}_2(g) + 3\text{H}_2\text{O}(g) + 6e^- \]  
\[ \text{(5)} \]

\[ \text{CH}_3\text{CH}_2\text{OH(ads)} + 6\text{O}^{2–}(\text{ads}) \rightarrow 2\text{CO}_2(g) + 3\text{H}_2\text{O}(g) + 12e^- \]  
\[ \text{(6)} \]

The sensing mechanisms of ASN and CSN-based sensors can be explained to separate two parts: One is the change in the electrical properties at the homojunctions between the two nanowires, and the other is the change in electrical properties at the nanowire surface. First, the change in electrical properties at the homojunctions can be explained as follows. As is generally known, SnO₂ is an n-type semiconductor that uses electrons as electric carriers. Therefore, if the SnO₂ nanowires are exposed to air, and the electrons are extracted from the nanowire body, then the carrier concentration of the SnO₂ nanowire decreases and its Fermi level presents a downward tendency. Because two nanowires make a homojunction, this junction does not produce any energy band bending after equilibrium compared with before equilibrium, as shown in Fig. 7 (a) and (b). However, when it is exposed to air ambient, owing to the downward tendency of the Fermi level, the potential energy barrier grows \( (h_1) \), and the depletion layer between nanowires extends \( (W_1) \), as shown in Fig. 7 (c). Because nanowires act as a channel for a field effect transistor (FET) device, electrons from the source electrode must pass the barriers and depletion layers between nanowires to reach the drain electrode. For this reason, the resistance of the sensors should increase when they are placed in ambient air. In contrast, ethanol gas is supplied to these nanowires. Ethanol gas removes oxygen ions, and electrons revert to the nanowire body, and the Fermi level also returns to a near-initial state. At the same time, the potential energy barrier shortens \( (h_1) \) and the depletion layer is also reduced \( (W_1) \). As a result, electrons move easily from nanowire to nanowire, and the resistance of the sensors decreases, unlike the former case. This is one of the major mechanisms of SnO₂ nanowire-based ethanol gas sensors, and it occurs in almost the same way whether nanoparticles are anchored on the surface of the SnO₂ nanowires or not.

The second mechanism for ethanol sensing can be explained by the change in the surface depletion layer of the nanowires. Electrons are transferred through a conductance channel in this case, and the potential energy barrier can be ignored. In this case, only a change in the surface depletion area of the ASN and CSN body affects the resistance of the sensor. In the same manner as the former mechanism, the depletion layer of ASN is extended when the sensor is placed in ambient air, as shown in Fig. 8 (a). Therefore, because the conductance channel of the nanowires is reduced, the resistance of the sensor increases. In contrast, when ethanol gas is supplied to the sensor, the adsorbed oxygen ions are removed, the electrons absorbed by the oxygen ions revert back to the nanowire, and the surface depletion layer of the nanowire is reduced again. This widens the nanowire conductance chan-
Fig. 8 – Schematic images presenting the electric structure of as-synthesized single SnO$_2$ nanowire when (a) placed in air ambient and (b) exposed to ethanol gas.

...nel, as presented in Fig. 8 (b), and then the resistance of the ASN-based sensor decreases.

Unlike the ASN-based sensor, the surface depletion layer of the CSN is more complicated. Because Cr$_2$O$_3$ is a p-type semiconductor, p-n heterojunctions are generated at the nanowire surface. Because SnO$_2$ and Cr$_2$O$_3$ have different work functions, as presented in Fig. 9 (a), energy bending occurs between the heterojunctions, as presented in Fig. 9 (b). In this case, depletion layers are generated on both sides of the nanomaterials ($W_2$, $W_3$) as a result of contact. When the CSN is placed in ambient air, the depletion layer of the SnO$_2$ nanowire extends, whereas a hole-accumulation layer is generated ($W_3$) instead of a depletion layer at the surface of the Cr$_2$O$_3$ nanoparticles.

However, owing to the energy barrier at the grain boundary ($h_3$), the holes in the Cr$_2$O$_3$ nanoparticles are trapped, and cannot transfer to the SnO$_2$ nanowire. Because any carrier can be transferred between the nanowire and nanoparticles, only the depletion layer in the SnO$_2$ nanowire affects the resistance of the sensor. However, as a result of the heterojunctions, the depletion layer of the SnO$_2$ nanowire surface extends more than that of the ASN, and the resistance of the CSN-based sensor is larger than that of the ASN-based sensor. In other words, in the case of CSN, because the surface depletion layer of the SnO$_2$ nanowire body extends more when placed in ambient air, the conductance channel of the CSN is shortened and partially divided, as shown in Fig. 10 (a). Therefore, the resistance...
of the CSN-based sensor increases more when placed in ambient air. In contrast, when the CSN-based sensor is exposed to ethanol gas, the oxygen ions adsorbed on the nanowire and nanoparticle surface are removed, and the electrons absorbed by the oxygen ions revert back to the nanowire and nanoparticle bodies. In this case, as presented in Fig. 9 (d), the Fermi level of the CSN rises again, and the depletion layer \( W_3^- \) of the SnO\(_2\) nanowire and the hole accumulation layer \( W_3^+ \) of the Cr\(_2\)O\(_3\) nanoparticle are reduced. The depletion layer of the nanowire is reduced more, so the conductance channel of the CSN is widened, similar to the ASN. Even if the depletion layer of the SnO\(_2\) around the Cr\(_2\)O\(_3\) nanoparticles is slightly thicker, it could be negligible because the layer is much smaller than the whole width of the conductance channel, as presented in Fig. 10 (b). For this reason, the resistance of the CSN-based sensor decreases, similar to that of the ASN-based sensor. When the CSN-based sensor is placed in ambient air, its resistance presents a high value compared with the ASN-based sensor. In contrast, when it is exposed to ethanol gas, the resistance of the CSN-based sensor decreases, similar to that of the ASN-based sensor. Therefore, the response of the CSN-based ethanol sensor should be better than that of the ASN-based sensor.

4. Conclusion

In this research, SnO\(_2\) nanowires were synthesized, and Cr\(_2\)O\(_3\) nanoparticles were anchored on the nanowires to fabricate highly sensitive and selective ethanol gas sensors. As a result of anchoring Cr\(_2\)O\(_3\) nanoparticles on SnO\(_2\) nanowire, the sensing response was enhanced approximately four-fold compared with the ASN. Furthermore, its selectivity showed greater improvement. Low selectivity to various gases is an invertebrate problem for SnO\(_2\) nanowire-based gas sensors, but with this hybrid-structured nanowire, that problem is improved enough for the nanowire to be used in a commercial ethanol sensor. This sensing effect can be explained by a combination of two mechanisms. One concerns the potential energy barrier and depletion layer at the homojunction between the SnO\(_2\)–SnO\(_2\) nanowires. Another one is the variation in the surface depletion layer at the nanowire surface. Because changes in the electrical properties at the homojunction occur whether Cr\(_2\)O\(_3\) nanoparticles are anchored on the SnO\(_2\) nanowire surfaces or not, improvement in the sensing properties cannot be explained by this mechanism. However, because the change in the width of the surface depletion layer intensifies with the anchoring of Cr\(_2\)O\(_3\) nanoparticles on the surface of SnO\(_2\) nanowires, the improvement in the ethanol sensing properties can be explained by this mechanism. In this study, the ethanol-sensing properties of ASN and CSN are examined, and the mechanisms for their improved sensing are established using energy band bending.

Declaration of interests

None.
Fig. 10 – Schematic images presenting the electric structure of single Cr$_2$O$_3$ nanoparticle-anchored SnO$_2$ nanowire when (a) placed in air ambient and (b) exposed to ethanol gas.

Acknowledgment

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Education (2017R1D1A1B03034567).

REFERENCES


