NiO nanoparticle-decorated SnO$_2$ nanosheets for ethanol sensing with enhanced moisture resistance

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**Abstract**

In a high relative humidity (RH) environment, it is challenging for ethanol sensors to maintain a high response and excellent selectivity. Herein, tetragonal rutile SnO$_2$ nanosheets decorated with NiO nanoparticles were synthesized by a two-step hydrothermal process. The NiO-decorated SnO$_2$ nanosheet-based sensors displayed a significantly improved sensitivity and excellent selectivity to ethanol gas. For example, the 3 mol% NiO-decorated SnO$_2$ (SnO$_2$-3Ni) sensor reached its highest response (153 at 100 ppm) at an operating temperature of 260 °C. Moreover, the SnO$_2$-3Ni sensor had substantially improved moisture resistance. The excellent properties of the sensors can be attributed to the uniform dispersion of the NiO nanoparticles on the surface of the SnO$_2$ nanosheets and the formation of NiO-SnO$_2$ p–n heterojunctions. Considering the long-term stability and reproducibility of these sensors, our study suggests that the NiO nanoparticle-decorated SnO$_2$ nanosheets are a promising material for highly efficient detection of ethanol.

**Introduction**

Metal oxide semiconductors (MOX) have attracted substantial attention in the field of gas detection over the past few decades due to their ease of use and reproducible response to various gases$^{1-3}$. As a representative n-type MOX, SnO$_2$ has been extensively investigated and used for commercial gas detectors$^4$. To further improve the sensor performance, diverse SnO$_2$-based nanostructures, such as nanoparticles$^5$, nanosheets$^6$, nanowires$^7$, nanotubes$^8$, hollow spheres$^9$, and some hierarchical architectures$^{10-12}$, have been developed. In these reports, two-dimensional (2D) SnO$_2$ nanostructures exhibit a rather high catalytic activity on certain surface sites, which promotes their sensing performance$^1$. On the other hand, SnO$_2$-based sensors can also be substantially improved by the addition of appropriate dopants, such as Pd$^{13}$, Sb$^{14}$, Ce$^{15}$, and Ni$^{16}$. The gas sensing mechanisms related to doping effects, junction forming, surface catalytic effects, and synergistic effects have been explored to explain the improved sensor performance$^{17,18}$. Among them, NiO is often used as a catalyst, which may also form p–n heterojunctions between the interface of the NiO and the SnO$_2$$^{19,20}$. In particular, a p-type NiO enables an increase in the oxygen adsorption that can react with target gases$^{21}$.

According to previous studies, NiO-decorated SnO$_2$ nanostructures were synthesized by various methods with beneficial ethanol sensing effects. NiO/SnO$_2$ composite nanofibers prepared via electrospinning were used for ethanol detection, and a response up to 25.5 (100 ppm) was achieved at 300 °C, which was 12.7 times larger than that of the pure SnO$_2$ nanofibers$^{19}$. The ultrafine NiO/ SnO$_2$ nanoparticles obtained by thermal treatment of the precursor exhibited a fast sensing process with a response and recovery period of 2 s and 3 s, respectively$^7$. The 3D structures of Ni-doped SnO$_2$, such as hollow spheres$^{22}$, microflowers$^{20}$, or other hierarchical nanostructures$^{23}$, were produced by the hydrothermal method or chemical solution route, which successfully improved the response...
with excellent selectivity for ethanol detection. To date, ethanol testing is needed not only for drunk driving and alcohol brewing but also for the production of biochemical products. It is imperative that researchers carry out significant work on the sensitivity, selectivity, and long-term stability of ethanol sensors. However, it should be noted that the moisture resistance is often the most-overlooked aspect of gas sensors in actual use scenarios. On the other hand, NiO-doped SnO2 hierarchical nanostructures could be applied to reduce the influence of environmental humidity and demonstrate a fast response time and excellent gas response. Even so, it is still necessary to further clarify the state of the NiO (dopant or individual phase) added to SnO2 nanostructures because this may extend our understanding of their gas sensing mechanisms. It is also well known that NiO shows a high affinity for water molecule absorption.

This work reports the synthesis of NiO-decorated SnO2 nanosheets by a facile two-step hydrothermal process. The effects of NiO content on the structural, morphological, and gas sensing properties of SnO2 nanosheet-based sensors were analyzed in detail. The gas sensing results confirmed that the NiO-decorated sensors indeed exhibited highly sensitive and selective ethanol sensing properties, with excellent long-term stability and reproducibility. In particular, the 3 mol% NiO-decorated sensor had a remarkable enhancement in moisture resistance compared with the pure SnO2 sensor, which makes it more promising for practical application.

**Results and discussion**

**Structural and morphological characteristics**

As illustrated in Fig. 1a, SnO2 nanosheets can be easily decorated with NiO nanoparticles during the preparation procedure. First, precipitates were formed immediately when the SnCl2·2H2O was put into deionized water because of Sn2+ hydrolysis. The added NaOH also reacted with Sn2+ ions and accelerated its hydrolysis. Hence, the solution turned slightly white at first. The oxidation of the Sn(OH)2 precipitates occurred at conditions with a high pressure and high temperature of 180 °C. Following the so-called “oriented attachment” mechanism, excessive OH- ions preferred to attach on the (110) of rutile SnO2 and bind relatively weakly to (001). With the control of the pH value (pH = 13), the basic units gradually aggregated to form the SnO2 nanosheets and grew along the [110] direction. In the secondary hydrothermal process, urea was used to ensure the homogeneous precipitation of Ni(OH)2 on the surface of 2D SnO2 nanosheets. After annealing at 500 °C in air, the NiO nanoparticle-decorated SnO2 nanosheets were obtained.

The crystal structures of the pure and NiO-decorated SnO2 samples were analyzed by X-ray diffraction (XRD), as shown in Fig. 1d. All diffraction peaks observed in the
curves were indexed to tetragonal rutile SnO$_2$ (JCPDS No. 41-1445). However, the NiO phase cannot be detected in these XRD patterns even though the content of NiO reaches 10 mol%. A similar phenomenon was previously reported and was explained by the low content (the second phase can be observed by XRD experiments above 40 mol%) and small crystal size of the NiO $^{20,29}$. On the other hand, no shifts can be observed in the peaks of the NiO-decorated samples, indicating that the added Ni may not be incorporated in the SnO$_2$ lattice $^{30}$. The energy dispersive X-ray (EDX) spectrum of SnO$_2$-3Ni, shown in Fig. 1e, shows that the content of Ni was approximately 2.9%, which agrees well with the intended value (3 mol%). It should be noted that the peaks for Cu and C shown in Fig. 1e originated from the copper grid in the TEM specimen.

Figure 2a–c display the scanning electron microscopy (SEM) and the transmission electron microscopy (TEM) images of the pure SnO$_2$ sample. The nanosheets were in the size range of 100-500 nm with a smooth surface morphology. Compared with the pure SnO$_2$ nanosheets, the 3 mol% NiO-decorated nanosheets (Fig. 2d–f) had rough surfaces and diverse shapes, which might be due to the decoration of the NiO. More details for the morphologies of the SnO$_2$ samples with NiO decoration amounts of 1 mol%, 5 mol%, and 10 mol% are shown in Fig. S1. It can be clearly observed that the 2D nanosheet structure of pure SnO$_2$ was well maintained for all the samples.

To further confirm the decoration of the NiO nanoparticles, we investigated the SnO$_2$-3Ni nanosheets with high-resolution TEM (HRTEM), as shown in Fig. 2f. The HRTEM image demonstrates the presence of independent phases of NiO nanoparticles on the surface of the SnO$_2$ nanosheets. The lattice fringes with d-spacings of 0.242 nm and 0.335 nm were obtained, which match well with the (111) plane of NiO and the (110) plane of rutile SnO$_2$, respectively $^5$.

X-ray photoelectron spectroscopy (XPS) was conducted to further investigate the surface compositions and the

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**Fig. 2** Morphologies and chemical components of pure SnO and SnO$_2$-3Ni nanosheets. a SEM image and b, c TEM images of pure SnO$_2$ nanosheets, d SEM image, e TEM image and f HRTEM image of SnO$_2$-3Ni nanosheets, g XPS survey spectra of the pure SnO$_2$ and SnO$_2$-3Ni samples, h high-resolution core level Sn 3d spectra of pure SnO$_2$ nanosheets and SnO$_2$-3Ni, i high-resolution core level Ni 2p spectra of SnO$_2$-3Ni.
chemical states of the pure SnO2 and SnO2-3Ni nanosheets. The survey spectrum in Fig. 2g confirmed the presence of Sn, O, and C in both samples and Ni only for the SnO2-3Ni, where C is commonly known as an impurity component in XPS measurements. The high-resolution spectrum of Sn 3d is shown in Fig. 2h, and the peaks are consistent in the two samples. Two peaks of 855.3 eV and 872.9 eV were attributed to Ni 2p3/2 and Ni 2p1/2, respectively, and a spin-orbit splitting of 17.6 eV can be seen between the Ni 2p3/2 and Ni 2p1/2 peaks. The Ni 2p3/2 peaks were attributed to NiO or a Ni2+ pyramidal symmetry, according to previous literature reports.5,31. Based on the findings above, the core level Ni 2p spectra further confirmed the formation of NiO decoration on the SnO2 nanosheets.

Gas-sensing properties
To verify the optimum operating temperature, the responses of the sensors based on pure and NiO-decorated SnO2 nanosheets to 100 ppm ethanol were investigated from 200 to 320 °C, as shown in Fig. 3a. For all sensors, the response first increased, reached a maximum value at an optimum operating temperature, and decreased with increasing temperature. Obviously, the optimum operating temperature of all the sensors was approximately 260 °C. It is worth noting that all the NiO-decorated sensors exhibited significantly improved ethanol sensing properties compared with the pure SnO2-based sensor. In particular, the SnO2-3Ni sensor exhibited the best performance of the samples considered in this study, and a high response of 153 was achieved at 260 °C. We also noticed that an excessive amount of NiO decoration resulted in a decrease in the response. The responses of sensors based on SnO2, SnO2-1Ni, SnO2-3Ni, SnO2-5Ni and SnO2-10Ni (at 260 °C) were 28, 107, 153, 87, and 65, respectively.

Figure 3b displays the response of the pure SnO2 and SnO2-3Ni-based sensors to ethanol with concentrations ranging from 5 to 10000 ppm. The response of the pure SnO2 sensor had a significant increase at the ethanol concentration below 500 ppm and then tended to saturate at 2000 ppm. In comparison, the response of the SnO2-3Ni sensor increased rapidly in the range of 5–2000 ppm and then continued to increase with ethanol concentration up to 10,000 ppm, which suggests a higher maximum response.
acidity, ammonia, and toluene, respectively. In other words,
the responses of the SnO2-3Ni sensor were 153, 46.5, 18.0,
to ethanol among the six gases. For instance, the
response increased sharply once the sensor was exposed
to ethanol and returned to its original value after exposure
to air.

Another critical factor to meet the practical demands
required for gas sensors is the selectivity for different
gases. As shown in Fig. 3d, the sensor responses to various
gases were measured at 260 °C with a
fixed concentration of 100 ppm. All the sensors showed the highest response
to ethanol among the six gases. For instance, the
responses of the SnO2-3Ni sensor were 153, 46.5, 18.0,
13.9, 9.0, and 2.7 to ethanol, methanol, acetone, acetic
acid, ammonia, and toluene, respectively. In other words,
the SnO2-3Ni sensor demonstrated a good selectivity to
ethanol gas.

Reproducibility and long-term stability are important
requirements for the practical application of gas sensors. Figure 3e displays the response curve of the SnO2-3Ni
sensor towards 50 ppm ethanol and contains the measure-
ment of four continuous cycles at 260 °C. The response
curves were repeated well during the four cyclic
measurements, reflecting its good reproducibility. In
addition, the response values of all sensors were measured
for four weeks. As shown in Fig. 3f, all response values of
the sensors remained around their initial value with little
fluctuation during the 4-week measurement period. The
response of the SnO2-3Ni sensor was maintained at 143
after 4 weeks.

The effect of humidity is a major concern for the per-
formance and stability of SnO2-based gas sensors. As shown in Fig. 4a, the response of the sensor based on
SnO2-3Ni maintained 71% of its initial value when the
relative humidity increased from 20% to 80% RH, while
that of the sensor based on pure SnO2 decreased to 32%.
This comparison indicates that the resistance of a gas
sensor to a humid environment could be significantly improved with the help of NiO nanoparticles. To inves-
tigate the impact of humidity on the sensors based on
SnO2 nanosheets decorated with NiO, the SnO2-3Ni
sensors were analyzed by electrochemical impedance
spectroscopy (EIS) under various humidities at 260 °C (the optimum operating temperature) during the measure-
ment. As shown in Fig. 4b, the semicircles were
represented by an equivalent QR model (shown insert of Fig. 4b). The
value of R1 extracted from the semicircles was influenced
by humidity. Additionally, Q is a small phase element that
was almost constant during the investigation, and R2 is the
contact resistance during the measurement and far less
than that of R1. With increasing RH, R1 decreased when
the water molecule reacted with the absorbed oxygen species. The EIS plots in Fig. S2 show the same tendency,
which confirms our assumption and the QR model. The
major difference is that the resistance of the SnO2-3Ni
was much larger than that of the pure SnO2. As men-
tioned in Fig. 4a, the SnO2-3Ni sensor maintained a high
response to ethanol in an environment with high relative
humidity. However, Figure S3 also shows that the
moisture resistance of the SnO2-3Ni sensor was mainly
determined by its resistance change in air (R0). The EIS
plots can directly indicate a change in R0, to some extent,
and reflect the moisture resistance of the gas sensors.

**Gas-sensing mechanisms**

The gas-sensing mechanism of SnO2 (an n-type MOX)
has been generally explained as a resistance change
resulting from the gas absorption-dissociation on the
surface of the sensing material. The absorbed oxygen
molecules ionize to oxygen species (O$_2^-$, O$^-$, and O$^2^-$) by capturing the electrons from the conduction band of the SnO$_2$ in air. Once exposed to ethanol vapor, the ethanol molecules react with the absorbed oxygen species, which results in thin electron depletion layers that decrease the resistance. Figure 5 compares the ethanol sensing mechanisms of the NiO-decorated SnO$_2$ nanosheets with those of pure SnO$_2$ nanosheets. As previously reported, p–n heterojunctions at the interface between the NiO and SnO$_2$ bend the bands of p-type and n-type semiconductors in the depletion layers, resulting in the equalization of Fermi levels$^{5,16,32,33}$. In air, both electrons in the conduction band of SnO$_2$ and holes in the valance band of NiO ionize the absorbed oxygen molecules, which broadens the width of electron depletion layers on the surface of SnO$_2$ nanosheets and hole accumulation layers on the surface of NiO nanoparticles. It should be noted that the NiO-decorated sensors presented a higher sensor resistance in air ($R_a$) than that of pure SnO$_2$-based sensors at the same operating temperatures. When the sensors were exposed to ethanol gas, the electrons, resulting from the reaction between ethanol molecules and oxygen species, passed through the NiO/SnO$_2$ interface attributed to a p–n heterojunction. The electron depletion layer and hole accumulation layer became narrow, which led to a broader conductive channel in the SnO$_2$ nanosheets and decreased the sensor resistance ($R_g$).

We can also see that an excessive amount of NiO decoration led to a decrease in the response. The reason may be explained as follows. (1) An excessive amount of NiO further broadens the width of the electron depletion region between a NiO nanoparticle and the SnO$_2$ nanosheet, making it difficult to adjust the electron transfer in the SnO$_2$ nanosheets. (2) As a p-type MOX, an excessive amount of NiO also captures partial free electrons during the ethanol sensing process, which hinders the decrease in $R_g$. Consequently, an appropriate amount of NiO is of great importance to promote the sensor performance of NiO/SnO$_2$. On the other hand, the selectivity of the sensor is always affected by the operating temperature (or determined by the ratio of the absorbed oxygen species to the target gases). In this work, NiO-decorated SnO$_2$ sensors show a strong catalytic capacity to ethanol at 260 °C, which requires further discussion$^{34}$. In addition, NiO could act as a catalyst to facilitate the oxidation reaction on the surface of SnO$_2$ nanosheets$^{23,33}$. The amount of oxygen adsorbed on NiO is markedly larger than that of SnO$_2$ due to charge compensation through the oxidation of Ni$^{2+}$ to Ni$^{3+}$$^{26}$. Considering the more efficient carrier regulatory mechanisms with the help of NiO decoration, the NiO-decorated SnO$_2$ nanosheets indeed exhibited improved ethanol sensing properties.

When the sensor operated in a high RH environment, there were many oxygen species absorbed onto the NiO nanoparticles, which interacted with the water molecules, providing a good response to ethanol. Moreover, NiO was more capable of adsorbing water molecules than SnO$_2$$^{25,26}$. Therefore, the SnO$_2$ nanosheets decorated with NiO nanoparticles maintained an excellent ethanol sensing performance with little response loss in a high RH environment due to the NiO-SnO$_2$ p–n heterojunctions and the increased oxidation reaction facilitated by the NiO decoration.
Conclusions
In summary, tetragonal rutile SnO$_2$ nanosheets decorated with NiO nanoparticles were successfully prepared by a template-free two-step hydrothermal method. The SnO$_2$ nanosheets decorated with NiO nanoparticles exhibited excellent sensing performance towards ethanol detection. With an optimum NiO decoration amount of 3 mol%, a high response of 153 was achieved to 100 ppm ethanol gas at 260 °C, compared to 28 for the sensor with the pure SnO$_2$ nanosheets. All the sensors demonstrated good selectivity of ethanol to other reductive gases (methanol, acetone, acetic acid, ammonia, and toluene), good reproducibility, and excellent long-term stability. These findings were attributed to a p–n junction forming between the NiO nanoparticles and SnO$_2$ nanosheets. The SnO$_2$-3Ni sensor also exhibited high moisture resistance in a high RH environment. Hence, SnO$_2$ nanosheets decorated with NiO nanoparticles are promising candidates for ethanol sensing applications.

Materials and methods
Synthesis of NiO-decorated SnO$_2$ nanosheets
All the reagents were of analytical grade and were used without any further purification. NiO-decorated SnO$_2$ nanosheets were obtained by a two-step hydrothermal process, as illustrated in Fig. 1a. In the first step, 6 mmol SnCl$_2$·2H$_2$O was dissolved into 20 mL of deionized water. Then, the solution was adjusted to pH = 13 with 0.4 M NaOH solution. The mixture was stirred for 30 min and transferred into a 50 mL Teflon-lined stainless autoclave. The autoclave was sealed and kept in an oven at 180 °C for 12 h and cooled naturally to room temperature. The SnO$_2$ nanosheets were collected by centrifugation and successively washed with deionized water and absolute ethanol several times to remove any residual ions and finally dried at 80 °C overnight. In the second step, the as-obtained powder (0.1 g) was fully dispersed in 20 mL deionized water with sonication. A certain amount of nickel chloride (NiCl$_2$, 0.2 M) solution and urea (molar ratio NiCl$_2$: urea = 1:10) were added to the above suspension under continuous magnetic stirring. Then, the mixture was transferred into autoclave again and maintained at 80 °C for 6 h. The final product was collected and washed, as described previously, and calcined at 500 °C for 2 h in air. For comparison, SnO$_2$ nanosheets with different contents of NiO (1, 3, 5, and 10 mol%) were prepared and referred to as SnO$_2$-1Ni, SnO$_2$-3Ni, SnO$_2$-5Ni, and SnO$_2$-10Ni, respectively.

Characterization
X-ray diffraction (XRD) patterns were recorded on an X-ray diffractometer (Rigaku Smartlab) using Cu K$_\alpha$ radiation. The morphologies of the samples were characterized by scanning electron microscopy (SEM, Zeiss Gemini) and high-resolution transmission electron microscopy (HRTEM, FEI Tecnai G2 F30), where the high-resolution transmission electron microscope was equipped with energy dispersive X-ray spectroscopy (EDX). X-ray photoelectron spectroscopy (XPS) was carried out on ESCALAB 250Xi.

Fabrication and sensor measurement
Gas-sensing measurements were performed on a commercial WS-30B system (Weisheng Instruments Co., Zhengzhou, China). Figure 1b displays a schematic diagram of the ceramic tube device used in our gas sensing measurements. Two ring-shaped Au electrodes were pasted at each end of the Al$_2$O$_3$ tube as the testing electrodes, and each Au electrode was connected with two Pt wires. A Ni-Cr coil was placed inside the tube to control the operating temperature. Figure 1c displays a photograph of the as-fabricated sensor with SnO$_2$-based materials coated on the Al$_2$O$_3$ tube. In brief, the as-obtained products were mixed with a proper amount of binder (ethylcellulose: terpinol = 10:90 wt%) and pasted onto the Al$_2$O$_3$ tube. After drying at 80 °C, all sensors were heated at 400 °C for 2 h in air. During the test, the operating temperature varied from 200 to 320 °C at a constant humidity of 20% RH. The gas response is defined as $R_g/R_a$ ($R_a$: sensor resistance in air, and $R_g$: sensor resistance in the target gas). Impedance measurements were characterized by the E4990A impedance analyzer (Agilent Tech., Inc.). The heating power was supported by a PWS2721 DC Power Supply (Tektronix, Inc.). Different RH conditions were given by saturated salt solutions at room temperature; specifically, 11.3%, 23.1%, 33.1%, 43.2%, 55.9%, 69.9%, 75.5%, 85.1%, and 97.6% RH were generated by the saturated solution of LiCl, CH$_3$COOK, MgCl$_2$, K$_2$CO$_3$, Mg (NO$_3$)$_2$, KI, NaCl, KCl, and K$_2$SO$_4$, respectively.

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Author contributions
G. N., C. Z., and F. W. conceived and designed the experiments. G. N., C. Z., H. G., X. L., and F. W. performed the experiments. G. N., C. Z., H. G., X. L., and F. W. analyzed the data. G. N., C. Z., and F. W. wrote the paper. All authors discussed the results and commented on the manuscript.

Conflict of interest
The authors declare that they have no conflict of interest.

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References

1. Yamazoe, N., Sakai, G. & Shimanoe, K. Oxide semiconductor gas sensors. Catal. Surf. Asiat. 7, 63–65 (2003).
2. Wang, C., Yin, L., Zhang, L., Xiang, D. & Gao, R. Metal oxide gas sensors: sensitivity and influencing factors. Sensors 10, 2088–2106 (2010).
3. Barsan, N., Kozej, D. & Weimar, U. Metal oxide-based gas sensor research: How to? Sens. Actuators, B 121, 18–35 (2007).
4. Das, S. & Jayaraman, V. SnO2: A comprehensive review on structures and gas sensors. Prog. Mater. Sci. 66, 112–255 (2014).
5. Ding, H. et al. Preparation and gas-sensing property of ultra-fine NiO/SnO2 nanoparticles. RSC Adv. 2, 10324 (2012).
6. Sun, P. et al. Porous SnO2 hierarchical nanosheets: hydrothermal preparation, growth mechanism, and gas sensing properties. CrystEngComm 13, 3718 (2011).
7. Herrera, M., Maestre, D., Cremades, A. & Piqueras, J. Growth and Characterization of Mn Doped SnO2 Nanowires, Nanobelts, and Microplates. J. Phys. Chem. C 117, 8997–9003 (2013).
8. Yuan, J. et al. Facile fabrication of aligned SnO2 nanotube arrays and their field-emission property. Mater. Lett. 118, 43–46 (2014).
9. Zheng, C., Zheng, X., Hong, Z., Ding, X. & Wei, M. Template-free synthesis of SnO2 nanostructural hollow spheres covered by nanorods. Mater. Lett. 65, 1645–1647 (2011).
10. Yu, H. et al. Facile synthesis cedar-like SnO2 hierarchical micro-nanostructures with improved formaldehyde gas sensing characteristics. J. Alloy. Compd. 724, 121–129 (2017).
11. Wang, H. & Rogach, A. L. Hierarchical SnO2 nanostructures: recent advances in design, synthesis, and applications. Chem. Mater. 26, 123–133 (2013).
12. Zou, Y. et al. Highly efficient gas sensor using a hollow SnO2 Microfiber for Triethylamine Detection. ACS Sens. 2, 897–902 (2017).
13. Wang, Z., Li, Z., Jiang, T., Xu, X. & Wang, C. Ultra-sensitive hydrogen sensor based on Pd-loaded SnO2 electrospun nanofibers at room temperature. ACS Appl Mater. Inter 5, 2013–2021 (2013).
14. Suematsu, K., Sasaki, M., Ma, N., Yuasa, M. & Shimanoe, K. Antimony-doped tin dioxide gas sensors exhibiting high stability in the sensitivity to humidity changes. ACS Sens. 1, 913–920 (2016).
15. Lian, X. et al. Synthesis of Ce-doped SnO2 nanoparticles and their acetone gas sensing properties. Appl. Surf. Sci. 407, 447–455 (2017).
16. Wang, Y., Zhang, H. & Sun, X. Electrospray nanowebds of NiO/SnO2 p-n heterojunctions for enhanced gas sensing. Appl. Surf. Sci. 389, 514–520 (2016).
17. Miller, D. R., Akbar, S. A. & Morris, P. A. Nanoscale metal oxide-based heterojunctions for gas sensing: A review. Sens. Actuators, B 204, 250–272 (2014).
18. Kim, H.-J. & Lee, J.-H. Highly sensitive and selective gas sensors using p-type oxide semiconductors: Overview. Sens. Actuators, B 192, 607–627 (2014).
19. Liu, L. et al. Enhancement of ethanol sensing properties of NiO-SnO2 nanofibers. J. Am. Ceram. Soc. 94, 771–775 (2011).
20. Sun, G. et al. Synthesis and improved gas sensing properties of NiO-decorated SnO2 microflowers assembled with porous nanorods. Sens. Actuators, B 233, 180–192 (2016).
21. Rai, P. et al. Design of highly sensitive and selective Au@NiO yolk-shell nanoreactors for gas sensor applications. Nanosens. 6, 8292–8299 (2014).
22. Kim, H. R. et al. Ultra-fast responding and recovering C2H5OH sensors using SnO2 hollow spheres prepared and activated by Ni templates. Chem. Commun. 46, 5061–5063 (2010).
23. Gu, C. et al. Controlled synthesis of porous Ni-doped SnO2 microstructures and their enhanced gas sensing properties. J. Alloy. Compd. 692, 855–864 (2017).
24. Kim, H.-R. et al. The role of NiO Doping in reducing the impact of humidity on the performance of SnO2-based gas sensors: synthesis strategies, and phenomenological and spectroscopic studies. Adv. Funct. Mater. 21, 4456–4463 (2011).
25. Iwamoto, M., Yoda, Y., Yamazoe, N. & Selyama, T. Study of metal oxide catalyticity temperature programmed desorption 4. Oxygen adsorption on various metal oxides. J. Phys. Chem. C 82, 2564–2570 (1978).
26. Salou, M. et al. Initial oxidation of polycrystalline permealloy: Surf. Sci. 602, 2901–2906 (2008).
27. Li, Y. et al. Synthesis of SnO2 nano-sheets by a template-free hydrothermal method. Mater. Lett. 63, 2085–2088 (2009).
28. Zhao, C., Fu, J., Zhang, Z. & Xie, E. Enhanced ethanol sensing performance of porous ultrathin NiO nanosheets with neck-connected networks. RSC Adv. 3, 4018 (2013).
29. Yang, R., Gu, Y., Li, Y., Zheng, J. & Li, X. Self-assembled 3-D flower-shaped SnO2 nanostructures with improved electrochemical performance for lithium storage. Acta Mater. 58, 866–874 (2010).
30. Wang, C. et al. Ultrathin SnO2 nanosheets: oriented attachment mechanism, nonstoichiometric defects, and enhanced lithium-ion battery performances. J. Phys. Chem. C 116, 4000–4011 (2012).
31. Hidalgo, P., C., R. H. R., Coelho, A. C. V. & Gouvea, D. Surface segregation and consequent SO2 sensor response in SnO2-NiO. Chem. Mater. 17, 4149–4153 (2005).
32. Castro, R. H. R., Hidalgo, P., Muccillo, R. & Gouvea, D. Microstructure and structure of NiO–SnO2 and Fe2O3–SnO2 systems. Appl. Surf. Sci. 214, 172–177 (2003).
33. Sotano, L. et al. Surface effects in the Ni 2p x-ray photoemission spectra of NiO. Phys. Rev. B 75, 233417 (2007).
34. Chen, Y. et al. Superior ethanol-sensing properties based on Ni-doped SnO2 p-n heterojunction hollow spheres. Sens. Actuators, B 166-167, 61–67 (2012).
35. Lin, Z., Li, N., Chen, Z. & Fu, P. The effect of Ni doping concentration on the gas sensing properties of Ni doped SnO2. Sens. Actuators, B 239, 501–510 (2017).
36. Leng, X., Luo, D., Xu, Z. & Wang, F. Modified graphene oxide/Nafion composite humidity sensor and its linear response to the relative humidity. Sens. Actuators, B 257, 372–381 (2018).