Gate-controlled gas sensor utilizing 1D–2D hybrid nanowires network

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Highlights
1D SnO₂ Nanowire–2D SnSe₂ Heterostructure-based Gas Sensor

Selectivity for NO₂ gas at room temperature

Improve the sensing characteristics through a large effective reaction area

Controlling the gate bias enhances carrier movement and improves sensing performance

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Gate-controlled gas sensor utilizing 1D–2D hybrid nanowires network

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SUMMARY
Novel gas sensors that work at room temperature are attracting attention due to their low energy consumption and stability in the presence of toxic gases. However, the development of sensing characteristics at room temperature is still a primary challenge. Diverse reaction pathways and low adsorption energy for gas molecules are required to fabricate a gas sensor that works at room temperature with high sensitivity, selectivity, and efficiency. Therefore, we enhanced the gas sensing performance at room temperature by constructing hybridized nanostructure of 1D–2D hybrid of SnSe2 layers and SnO2 nanowire networks and by controlling the back-gate bias ($V_g = 1.5$ V). The response time was dramatically reduced by lowering the energy barrier for the adsorption on the reactive sites, which are controlled by the back gate. Consequently, we believe that this research could contribute to improving the performance of gas sensors that work at room temperature.

INTRODUCTION
The control of the reaction sites and charge concentration of a sensing material is a critical factor that determines gas sensing performance at room temperature. Metal oxide semiconductors have been used as a representative sensing material for chemiresistive gas sensors due to their good chemical stability and sensitivity. However, their relatively low intrinsic conductivity gives rise to high operating temperature (above 100°C–200°C), which hinders the use of these materials in an energy-efficient gas sensor (Ahn et al., 2009; Cao et al., 2014; Choi et al., 2008). Thus, optimization of the reaction sites for the carrier transfer and its concentration is crucial to achieve low-temperature operation.

Two-dimensional (2D) semiconductors have attracted significant interest for active sensing materials. Their ultrathin thickness contributes a high specific surface area and a large number of reactive sites for charge transfer between gas molecules and the sensing material (Dey, 2018; Donarelli and Ottaviano, 2018; McAlpine et al., 2007; Shalev, 2017; Yan et al., 2020). Based on these structural features, low operating temperature (near room temperature) has been reported for sensors based on 2D materials, especially transition metal dichalcogenides (TMDs), such as MoS2, WS2, and SnSe2 (Cho et al., 2015, 2016; Choi et al., 2017; Cui et al., 2020; Dey, 2018; Kang et al., 2019; Moumen et al., 2021; Ricciardella et al., 2017; Liu et al., 2021). However, there are several challenges that should be addressed, such as irreversible sensing behavior, slow response and recovery time, and high oxidation rate at high operating temperature (Camargo Moreira et al., 2019; Li et al., 2012; Yan et al., 2018). Therefore, constructing a nanostructure with a large effective reaction area (i.e., specific surface, crystal defects, etc.) and well-optimized carrier concentration is highly desirable to improve the sensing characteristics at low temperature (Shalev, 2017).

Recently, heterostructures consisting of two different semiconducting nanomaterials, such as 2D semiconducting TMDs and metal oxide semiconductors, have been investigated as promising active sensing materials for chemiresistive gas sensors (Kumar et al., 2020; Paolucci et al., 2020; Zhao et al., 2018). Owing to their different electronic band structures, the effective charge concentration can be modulated by the charge transfer between the two atomic layers (Gu et al., 2017; Hao et al., 2018). This contributes to the enhancement of the chemisorption of oxygen, which is one of the major factors that determine the sensing response at low operating temperatures. In addition, reactive sites are increased via the large specific surface area obtained by the formation of the heterostructure, which facilitates the chemical interaction between the gas molecules and the sensing materials. This leads to improved response time and reversible...
behavior of the sensor at room temperature (Han et al., 2018; Lee et al., 2018; Li et al., 2017; Wang et al., 2021).

In this work, we investigated the gas sensing characteristics of a 1D–2D hybrid network structure with SnO$_2$ nanowires and SnSe$_2$ layers. The surface of the pristine SnO$_2$ nanowires was shallowly converted into ultrathin SnSe$_2$ by chemical vapor deposition (CVD). The hybridized nanowire networks showed increased chemisorption of oxygen ions after selenization, which led to electron transfer from SnO$_2$ to the SnSe$_2$ layer. The formation of the ultrathin SnSe$_2$ also provided carrier accumulation on the surface of the nanowires network, which resulted in stable NO$_2$ sensing performance at room temperature. As a result, oxygen molecules adsorption is facilitated by large electron density of SnSe$_2$ surface which is accumulated from SnO$_2$ to SnSe$_2$.

The influence of the gate voltage on the detection of NO$_2$ gas is demonstrated using a highly doped Si as a back gate. The adsorption energy was reduced by applied gate bias, which facilitated the chemical reaction between the surface of the sensing material and gas molecules. As a result, enhanced response performance with 50 ppm of NO$_2$ could be achieved at room temperature.

RESULTS AND DISCUSSION

Creation of 1D–2D hybrid nanowires network via chemical vapor deposition

Pristine SnO$_2$ nanowires were prepared by a vapor-liquid-solid (VLS) method and selenized using a direct selenization process based on CVD (Figure 1A). First, Au (3 nm)/Pt (300 nm)/Ti (50 nm) interdigitated electrodes with 20-μm width and spacing were prepared, and then, SnO$_2$ nanowires were selectively grown via the VLS growth method at 900°C for 30 min. The resulting ultrathin SnSe$_2$ was synthesized on the surface of the SnO$_2$ nanowires network at 550°C for 30 min using Se powder as the Se precursor (see STAR Methods for details).

Field emission scanning electron microscopy (FESEM) and field emission transmission electron microscopy (FETEM) were conducted to confirm the morphology and microstructure of SnO$_2$ nanowires after the surface selenization process. The Au layer was used for the selective growth of SnO$_2$ nanowires, so the SnO$_2$ nanowires were grown on only the interdigitated electrodes and formed a network structure. As shown in Figure 1B, this networked structure of SnO$_2$ nanowires is maintained after the CVD-based selenization process.

Figures 1C and 1D present low- and high-magnification FESEM images of the 1D SnO$_2$–2D SnSe$_2$ hybrid nanowire network. It is clear that highly dense nanowires are randomly oriented with 40- to 50-nm diameter. Figure 1E shows an FETEM image of the 1D SnO$_2$–2D SnSe$_2$ hybrid nanowire network. An ultrathin SnSe$_2$ layer with thickness of a few nanometers was formed uniformly on the surface of as-grown SnO$_2$ nanowires (Figure S1). The scanning TEM (STEM) image and corresponding energy-dispersive X-ray spectroscopy (EDS) mapping images of the SnO$_2$ nanowires network with the SnSe$_2$ layer show the coexistence of Sn, O, and Se over the whole nanowires network, as well as the distribution of Se throughout the surface of the SnO$_2$ nanowires (Figure 1F) (Zhou et al., 2015).

Structural and chemical characterizations of the 1D SnO$_2$–2D SnSe$_2$ hybrid nanowires network

X-ray diffraction (XRD) was conducted to investigate the crystal structure of the 1D–2D hybrid nanowires. Figure 2A shows the XRD spectra of as-grown SnO$_2$ nanowires before and after the CVD-based surface selenization. The XRD pattern of the pristine SnO$_2$ nanowires shows multiple peaks located at 26.4°, 33.7°, 51.8°, and 54.8°, which correspond to the (110), (101), (211), and (200) planes of SnO$_2$, respectively (JCPDS 41-1445). After the surface selenization, diffraction peaks of SnSe$_2$ start to appear with the peaks observed in the pristine SnO$_2$ nanowires. The peaks at around 29.6°, 30.6°, 43.5°, and 47.5° are assigned to the (002), (011), (003), and (110) planes of SnSe$_2$, respectively. This indicates that the ultrathin SnSe$_2$ was successfully synthesized on the surface of SnO$_2$ nanowire networks.

As shown in Figure 2B, Raman spectroscopy was conducted to confirm the atomic bonding structure of the 1D SnO$_2$–2D SnSe$_2$ hybrid nanowires. The Raman spectrum of the pristine SnO$_2$ nanowires shows three characteristic peaks at around 474, 633, and 776 cm$^{-1}$. These are respectively related to the $E_g$, $A_{1g}$, and $B_{2g}$ modes of the SnO$_2$ nanowires, which have rutile tetragonal structure (Chen et al., 2017; Costa et al.,...
Compared to the pristine SnO$_2$ nanowires, two prominent Raman vibrational modes of SnSe$_2$ are exhibited at 116.6 and 184.7 cm$^{-1}$ after the selenization. The Raman peaks are ascribed to the in-plane A$_{1g}$ mode and the out-of-plane E$_g$ mode, respectively (Shao et al., 2018). The weak intensity of the E$_g$ mode is attributed to the few scattering centers in the few-layered SnSe$_2$ (An et al., 2020). The frequencies of these two characteristic Raman peaks depend on the number of layers of SnSe$_2$ (Gonzalez and Oleynik, 2016; Zhang et al., 2018). Thus, the crystalline SnSe$_2$ is well formed on the surface of SnO$_2$ nanowires with fewer than 5 layers, which agrees with the FETEM (Figure 1E) and XRD results (Figure 2A).

The in-plane A$_{1g}$ vibrational mode of SnO$_2$ also shows relatively weak peak intensity, suggesting the presence of SnO$_2$ nanowires below the selenized surface. However, there is a red shift of the A$_{1g}$ mode from 633 to 631 cm$^{-1}$, implying that there is incorporation of oxygen into the crystal lattice (Li et al., 2020). This can...
change the interaction of the planar lattice, thus affecting the in-plane vibrational mode. Moreover, a weak Raman peak is observed around 107 cm\(^{-1}\), which corresponds to the B\(_{3g}\) mode of SnSe (Jiang et al., 2017). This indicates the presence of a partially selenized region in the as-prepared nanowires.

As shown in Figures 2C–2E, the valence state of each element on the surface of the selenized SnO\(_2\) nanowires was also investigated by X-ray photoelectron spectroscopy (XPS). The high-resolution Sn 3d spectrum in Figure 2C exhibits two sets of core levels of Sn, which correspond to Sn-O bonding in SnO\(_2\) (Sn 3d\(_{5/2}\): 487.19 eV, Sn 3d\(_{3/2}\): 495.6 eV) and Sn-Se bonding in SnSe\(_2\) (Sn 3d\(_{5/2}\): 485.63 eV, Sn 3d\(_{3/2}\): 494.16 eV) (Rai et al., 2019; Wang et al., 2021). The weak intensity of the peaks of Sn-Se bonding indicates the presence of the ultrathin SnSe\(_2\) layer on the surface of SnO\(_2\) nanowires.

In the XPS spectrum of O 1s (Figure 2D), two peaks at 531.10 and 532.04 eV are associated with O-Sn bonding in SnO\(_2\) and chemisorbed oxygen ions, respectively. As shown in Figure S2, the concentration of chemisorbed oxygen ions is increased after the selenization process. This clearly indicates that the CVD-based surface selenization method can result in the increase of the oxygen chemisorbed on the surface of SnO\(_2\) nanowires.

The XPS spectrum of Se 3d in Figure 2E can be deconvoluted into two peaks, which are assigned to Se 3d\(_{5/2}\) (53.57 eV) and Se 3d\(_{3/2}\) (54.72 eV) (Lu et al., 2021). These XPS results are consistent with the EDS data in Figure 1F, implying the coexistence of Sn, O, and Se in as-grown samples. Based on these results, it can be concluded that the CVD process successfully selenized the surface of the rutile SnO\(_2\) nanowires with ultrathin SnSe\(_2\), which had good crystallinity. The formation of a 2D SnSe\(_2\) layer on the surface of 1D SnO\(_2\) nanowires increases the interaction with the atmosphere, which can be expected to enhance the gas sensing performance.
Gas sensing characteristics of the 1D SnO$_2$–2D SnSe$_2$ heterostructure-based gas sensor for NO$_2$ gas

A schematic drawing of the 1D SnO$_2$–2D SnSe$_2$ hybrid nanowire network-based gas sensor is shown in Figure 3A. To investigate the capabilities of the ultrathin 2D SnSe$_2$ layers on 1D SnO$_2$ nanowires, the dynamic resistance responses of the SnO$_2$ nanowires were measured before and after the surface selenization at different NO$_2$ concentrations with different temperatures. The gas responses were calculated by $S = R_g/R_a$ in oxidizing gas and $R_a/R_g$ in reducing gas, where $R_a$ and $R_g$ are the resistances of the sensor in air and in the presence of the target gas, respectively.

The transient resistance curves of the 1D–2D heterostructure (left) and pristine SnO$_2$ nanowires network (right) in Figure 3B show the resistance in response to the analyte gas (NO$_2$). NO$_2$ gas molecules act as electron acceptors that pick the electrons out of the surface of sensing materials (Cheng et al., 2016; Lee et al., 2018). When the gas molecules are adsorbed onto the surface of the 1D–2D heterostructure and the pristine SnO$_2$ nanowires network, the electrons in the conduction band are extracted, decreasing the concentration of carriers, and broadening the depletion layer (Feng et al., 2014). This contributes to the formation of a depletion layer through the surface of the nanowires, which increases the resistance of the sensor. The bare SnO$_2$ and 1D SnO$_2$–2D SnSe$_2$ nanowire networks have n-type semiconducting behavior (Sun et al., 2012).

The 1D SnO$_2$–2D SnSe$_2$ nanowire heterostructures clearly exhibited a very good response at room temperature, while there was no response to NO$_2$ gas in the gas sensor based on a pristine SnO$_2$ nanowires network (Figures 3B and S3). The formation of the hybrid of 1D SnO$_2$ and 2D SnSe$_2$ nanowires network improved the sensing characteristics at low temperature compared with the bare SnO$_2$ nanowires. The resistance variation of the 1D SnO$_2$ and 2D SnSe$_2$ nanowires network gas sensor reaches its maximum at room temperature. As the temperature increases with increments of 50°C from room temperature to 150°C, the resistance variation of the sensor with the 1D–2D hybrid structure decreases by 2, 1.5, 1, and 0.5 kΩ, respectively. The recovery of the resistance to its initial value in air was also observed from room temperature to 150°C, implying good reversible behavior of the 1D SnO$_2$–2D SnSe$_2$ heterostructure-based gas sensor.
Figure 3C shows the dependence of the sensitivity on the operating temperature at three different concentrations (10, 30, and 50 ppm). The sensitivities are proportional to the gas concentration, which is attributed to its dependence on the amount of gas molecules that can react with the sensing material. The maximum value of the gas response was 1.129 at 50 ppm of NO₂ and room temperature. The gas response decreased when the working temperature increased from room temperature to 200°C.

The enhancement of the sensing characteristics at room temperature was ascribed to the accumulation of electrons that are transferred from the as-prepared SnO₂ nanowires on the surface of the SnSe₂ layer. When the ultrathin SnSe₂ is formed on the surface of SnO₂ nanowire networks, electrons are transferred from SnO₂ to SnSe₂ due to the higher bandgap (E₉) and Fermi level (E_F) of the pure SnO₂ than those of SnSe₂ (Matysiak et al., 2020; Vemula et al., 2021; Zhou et al., 2015). This creates an interface depletion layer at the SnO₂ and an accumulation layer at the SnSe₂, as illustrated in Figure S4.

Oxygen molecules are attracted by the accumulated electrons on the SnSe₂ layer, which corresponds to the increase in the chemisorption of oxygen ions, which is consistent with Figure 2D. The increased concentration of the chemisorbed oxygen ions causes the reactions between the NO₂ molecules and adsorbed oxygen ions to multiply, which leads to an improved gas response compared to the gas sensor based on the pristine SnO₂ nanowires. Moreover, the analyte gas can react with defects, resulting in an increase of sensitivity (Thang et al., 2020).

The gas response reaches its maximum at a specific temperature with a mechanism between the available reactive sites at high temperature and slow kinetics at low temperature (Kolmakov et al., 2005; Wang et al., 2010). The speed of chemical reactions is determined by the activation of adsorbed oxygen molecule and lattice ionic oxygen to form active O²⁻, O⁻, and mobile O²⁻ species. This phenomenon continues up to a certain operating temperature. And above that, it is difficult to adsorb the exothermic gas molecule by thermal energy, and the gas molecules are easily desorbed, reducing the gas response (Sun et al., 2012; Ping et al., 2017). The number of reactive sites available for the reaction with gas molecules decreases with increasing operating temperature and at higher temperature, the NO₂ gas molecules are easily desorbed and accelerated on surface, which leads to a low response compared with the one at room temperature (Figure 3C) (Ping et al., 2017). Therefore, the ultrathin SnSe₂ layers on SnO₂ nanowire networks dramatically enhanced the gas sensing performance at room temperature.

The selectivity of the 1D SnO₂–2D SnSe₂ heterostructure-based gas sensor was investigated by measuring the sensing behavior at room temperature in various gases (nitrogen dioxide (NO₂), acetone (C₃H₆O), benzene (C₆H₆), and toluene (C₇H₈)). As shown in Figures 3D and S5, the measure of selective detection to NO₂ gas, S_NO₂/S_gas (S_NO₂, response to NO₂ gas, S_gas, response to corresponding gas) values can be calculated. The S_NO₂/S_gas values for the 2D SnSe₂-based gas sensor to C₃H₆O, C₆H₆, and C₇H₈ gases were 1.129, 1.126, and 1.129 in 50 ppm gas concentration, respectively. These results indicate that S_NO₂/S_gas values are approximately identical to the response to NO₂ gas, indicating that the 2D SnSe₂-based gas sensor has selectivity for NO₂ gas (McAlpine et al., 2007; Shehada et al., 2015).

Enhancement of gas sensing performance of the 1D SnO₂-nanowire–2D SnSe₂ heterostructure-based gas sensor for NO₂ gas by introducing back-gate bias

The typical gas molecule adsorption systems of the surface of the sensing material depend on the energy gap between the Fermi level of metal oxide and the valence band of the gas molecule (Feng et al., 2014; Zhang et al., 2017). When the target gas molecules are attached to the surface of the metal oxide film, carriers on the sensing material surface move into gas molecules by the quantum tunneling. It is because the conduction band of the gas molecule is closer to the Fermi level of the metal oxide than the valence band of the gas molecule. Thus, the energy gap acts as an energy barrier for gas absorption and electron transfer. That means controlling the gate bias causes the Fermi level of the metal oxide to be much closer to the conduction band, lowering the energy barrier and improving gas sensing performance as much as shown in Figures S4C and S4D (Henning et al., 2015; Khan et al., 2021). Highly doped Si with 300-nm-thick SiO₂ was adopted as a back gate to elucidate the effect of back-gate bias on the sensing characteristics at room temperature, as shown in Figure 3A. The transient resistance to different NO₂ concentrations was measured at room temperature while applying gate bias (i.e., V_g = 0.5, 1.5, and 2.5 V). Compared to the response without gate voltage, the gas sensor shows a very good response (more than 50% higher), even at the lowest NO₂ concentration.
Moreover, as shown in Figure 4B, the response and recovery behavior were also improved with the gate voltage (1.5 V). With a gate voltage of 1.5 V, the recovery time improved from 373 s to 346 s, and the response time was decreased from 375 s to 110 s. This indicates that the energy barrier for the adsorption on the reactive sites would be decreased by the back-gate voltage, which leads to the enhanced reaction between the NO₂ gas molecules and the nanowire surface at room temperature (Hellmich et al., 1997; Vemula et al., 2021). However, the recovery time was still slow, so further research is needed to improve it.

Figure 4C presents the response to different NO₂ gas concentrations as a function of back-gate bias at room temperature. The best gas response achieved at room temperature was 2.2 \((R_a/R_g)\) with exposure to 50 ppm of NO₂ gas at \(V_g = 1.5 \text{ V}\). This result was almost two times higher than the gas response of 1.13 \((R_a/R_g)\) without applying the gate bias. An increase of the response was also observed with increasing gas concentration, which is attributed to the increased amount of reactive gas molecules. The back-gate voltage contributes to the electron flow by controlling the energy barrier for the adsorption of analyte gas molecules on the surface of 1D–2D hybrid nanowires (Hellmich et al., 1997; Sun et al., 2012; Vemula et al., 2021). As a result, the sensing performance was improved by applying the back-gate voltage.

Conclusions

In summary, a gas sensor was fabricated based on a 1D – 2D hybrid nanowire network that consisted of SnSe₂ layers and SnO₂ nanowire, which was obtained using the VLS method and CVD. The sensor had noticeably good gas sensing characteristics at room temperature for NO₂ gas compared to one fabricated with a pristine SnO₂ nanowire network. The sensing characteristics at room temperature were increased by the accumulation of electrons transferred from the SnO₂ nanowires to the surface of the SnSe₂ layer.

When back-gate bias \((V_g = 1.5 \text{ V})\) was applied to the gas sensor, it showed better sensing performance, including the response time and sensitivity. The enhancement of sensing performance resulted from the energy barrier for the NO₂ gas adsorption on the reactive sites, which was decreased by the back-gate voltage. Considering the sensitivity, response time, and recovery time, the proposed sensor has better performance than a previous NO₂ gas sensor that works at room temperature. Thus, the results could offer insight into the enhancement of sensing performance for gas sensors operating at low temperature, nanostructure design, and diverse applications for future sensing platforms, such as handheld diagnostic tools and smart sensing devices.

Limitations of the study

This study focuses on gas sensing performance of 1D–2D hybrid of SnSe₂ layers and SnO₂ nanowire networks at room temperature. Sensing performance is improved compared to previous room temperature work sensors, and the next step is to perform as well as high-temperature operating sensors.
STAR METHODS

Detailed methods are provided in the online version of this paper and include the following:

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Supplemental information can be found online at https://doi.org/10.1016/j.isci.2021.103660.

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AUTHOR CONTRIBUTIONS

J. Seo, S. H. Nam, and M. Lee are contributed equally to this work. M. G. Hahm, S. S. Kim, and U. J. Kim conceived and supervised the project. J. Seo, S. H. Nam, M. Lee, and J. Kim prepared and characterized the samples. J. Seo, S. G. Kim, and C. Park performed gas sensor measurements. J. Seo, S. H. Nam, D. Seo, and Y. L. Kim wrote the paper. All authors discussed the results and commented on the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR METHODS

KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| Chemicals, peptides, and recombinant proteins | Sigma Aldrich | CAS: 7440-31-5 |
| Sn powder | Sigma Aldrich | CAS: 7782-49-2 |
| Se powder | Sigma Aldrich |  |
| Au pellet | RNDKOREA | http://www.rndkorea.co.kr/ |
| Pt pellet | RNDKOREA | http://www.rndkorea.co.kr/ |
| Ti pellet | RNDKOREA | http://www.rndkorea.co.kr/ |

Software and algorithms

| Source | ID | URL |
|--------|----|-----|
| Origin 2018 |  | www.originlab.com |
| Adobe illustrator CC 2020 |  | www.adobe.com |
| Adobe photoshop CC 2020 |  | www.adobe.com |
| Cinema 4D 2019 |  | www.mawon.net |
| Optical microscopy Olympus |  | BX53M |
| Raman spectroscopy HORIBA Jobin Yvon |  | LabRAM Revolution |
| X-ray diffraction PANalytical B.V. |  | Pro MRD |
| X-ray photoelectron spectroscopy Thermo Fisher Scientific |  | K-Alpha |
| Field emission scanning electron microscopes Hitachi |  | S-4300SE |

RESOURCE AVAILABILITY

Lead contact

Further information requests should be directed to the lead contact, Myung Gwan Hahm (mghahm@inha.ac.kr).

Materials availability

This study did not generate new unique reagents. All the materials and methods used for the generation of data and analysis are mentioned in the manuscript.

Data and code availability

This Data used in this paper will be shared by the lead contact upon request. This paper does not report original code. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Our study does not use experimental models typical in the life sciences.

METHOD DETAILS

Synthesis of SnO₂ nanowires

Networked SnO₂ nanowires were grown using a vapor-liquid-solid (VLS) method. For the growth of the nanowires, a photolithography method was used first, and a trilayered-interdigitated electrode (50-nm-thick Ti, 200-nm-thick Pt and 3-nm-thick Au) was sequentially deposited on the SiO₂-grown Si (300 nm) substrates through sputtering. Next, the substrates were put into a horizontal quartz tube furnace on top of an Al₂O₃ crucible with high-purity (99.9%) metallic Sn powder as a source. The furnace was heated to 900°C for 30 min in Ar (300 sccm) and O₂ (10 sccm) gas flows, and the SnO₂ nanowires were selectively grown on the substrates.
Preparation of 1D SnO$_2$ – 2D SnSe$_2$ hybrid nanowire network

Ultrathin SnSe$_2$ was synthesized on the surface of the as-prepared SnO$_2$ nanowire network by CVD. A quartz tube was evacuated by a mechanical pump and flushed with 5% H$_2$-balanced Ar gas. The reaction was carried out at 550°C for 30 min using Se powder as the Se precursor.

Material characterization

XRD (Pro MRD) was conducted to confirm the crystal structure of the 1D SnO$_2$ – 2D SnSe$_2$ hybrid nanowire network. The Raman spectra of the pristine SnO$_2$ nanowires before and after the selenization process were obtained by Raman spectroscopy (LabRAM Revolution, HORIBA Jobin Yvon) with a 532-nm green laser. The valence state of each element of the as-prepared 1D SnO$_2$ – 2D SnSe$_2$ heterostructure was confirmed by XPS (K-Alpha, Thermo Scientific). The microstructure of the 1D SnO$_2$ – 2D SnSe$_2$ hybrid nanowire network was characterized by FESEM (S-4300SE, Hitachi) and FETEM (JEM-2100F, JEOL).

Gas sensing studies

For measuring the sensing performance, the gas sensor was electrically connected to an electrical measuring system that was interfaced with a computer. The sensors were placed in a horizontal tube furnace, and the temperature was measured in the range of 25–200°C. The desired concentration of the target gas was controlled in the gas chamber through mass flow controllers. To reduce any possible variation in the sensing properties, the total flow rate was fixed at 500 sccm. The resistances of the sensors were measured in air ($R_a$) and in the presence of the target gas ($R_g$), and the sensor response was defined as $S = R_g/R_a$ in oxidation gas and $R_g/R_a$ in reducing gas. The response and recovery times were estimated as the time required to reach 90% of the saturated resistance after the NO$_2$ gas injection and removal, respectively.

QUANTIFICATION AND STATISTICAL ANALYSIS

Our study does not include statistical analysis or quantification.

ADDITIONAL RESOURCES

Our study has not generated or contributed to a new website/forum or if it is not part of a clinical trial.