ABSTRACT: Fossil fuel internal combustion engines generate and release a huge amount of nitrogen dioxide, leading to respiratory and allergic diseases such as asthma, pneumonia, and possibly tuberculosis. Here we develop an alveolus-inspired membrane sensor (AIMS) for self-powered wearable nitrogen dioxide detection and personal physiological assessment. The bionic AIMS exhibits an excellent sensitivity up to 452.44%, a good linearity of 0.976, and superior selectivity under a NO2 concentration of 50 ppm. Furthermore, the AIMS can also be employed to diagnose human breath behaviors for breath analysis. The fundamental sensing mechanism is established using a combination of thermodynamic analysis, finite-element analysis, and phase-field simulations. It is found that the depolarization field inside the sensitive materials plays a crucial role in the self-powered gas-sensing performance. This work not only provides an efficient, low-cost, portable, and environmentally friendly means for active environmental assessment and personal biomonitoring but also provides a deep understanding of the gas-sensing mechanisms.

KEYWORDS: wearable biosensors, personalized healthcare, alveolus-inspired, nitrogen dioxide, phase-field simulation

Nitrogen dioxide (NO2) is a ubiquitous hazardous gas species that causes serious environmental harm including ozone formation, acid rain, and water pollution. Exhaust gas from fossil fuel engines contains a large amount of nitrogen dioxide and its derivatives, imposing huge threats to air quality and public health. The chronic exposure of people to NO2 at concentrations above 40–100 μg/m3 may cause pulmonary edema and respiratory diseases. According to clinical statistics, continuous exposure to NO2 within the environment is associated with increased risks of cardiovascular disease, incident chronic kidney disease, or cancer, where a 10 μg/m3 change in NO2 generates a relative mortality risk of 1.012. In the United States, approximately 6.3% of the adult population diagnosed with chronic obstructive pulmonary diseases (COPD) is ascribed to exposure to NO2. Therefore, wearable on-body sensors for continuous and convenient ambient NO2 detection are highly desired.

Current NO2-sensing technologies are based primarily on metal oxide semiconductors, such as SnO2, TiO2, ZnO, and WO3. A wide adoption of these technologies could be challenged by the requirement of a high-temperature substrate and light irradiation to enhance the bulk carrier density for chemical reactions. Furthermore, these sensors require a power supply and are hard to be made into a wearable form, with limited portability and mobility for continuous toxic gas detection and personal physiological analysis. A superior solution could be developing a wearable sensor that simultaneously detects chemicals in the inhalation and measures the breath rate.

Alveoli accomplish the gas exchange between the human body and its ambient environment through sustainably stretching and shrinking during the inhalation–exhalation.
process. The main objective of this work is to develop an alveolus-inspired membrane sensor (AIMS) for self-powered personalized health care, which holds a dual functionality of NO₂, room-temperature detection and breath behavior continuous monitoring. By using the coupling effect between contact electrification and electrostatic induction between two membranes with different electron affinities, the developed AIMS could convert the mechanical inflation and deflation of gases into electrical signals. The AIMS exhibits excellent sensing performance with a high sensitivity (452.44%) and linearity (0.976). In addition, the response of the bionic AIMS toward NO₂ is over 20 times higher than those from other gases such as CO, H₂S, SO₂, NH₃, and CO₂ at a fixed gas concentration of 50 ppm, demonstrating an excellent selectivity. The established sensing mechanism was verified theoretically by using thermodynamic analysis, finite element calculation, and phase-field simulations. This work provides a facile, low-cost, and wearable approach for active breath gas sensing and real-time physiological assessment.

RESULTS AND DISCUSSION

Figure 1a shows the generation and release of nitrogen dioxide from internal combustion engines via burning fossil fuels. To perform the wearable nitrogen dioxide detection and personal breath behavior monitoring, an AIMS was developed, as shown in Figure 1b. It was vertically laminated with a latex film, sensing material, copper electrode, and a plastic air conduit serving as the gas-conducting channel. Here, the latex film is selected as the contacting layer for its good stretchability and strong electron affinity. The fabrication flowchart for the sensor is illustrated in Figure S1 and discussed in detail in the Experimental Methods. Figure 1c is a photograph of the as-fabricated AIMS, where gas inflation holds up the latex membrane to form a tent, while deflation will shrink the tent. During this process, the latex goes through a cycle of contact and separation with the bottom sensing film, pumping the electrons to flow back and forth between the copper electrode and the ground.

The working principle of the as-prepared AIMS is elucidated in Figure 1d. In the initial status, no test gas was injected into the sensor, and the latex and sensing film are in intimate contact with each other. Due to their difference in triboelectric series, the latex layer attracts electrons from the sensing film, leaving a net amount of negative triboelectric charges on the latex film and an equal amount of positive charges on the sensing film, as demonstrated in Figure 1d-I. Once the target gas was injected and held up the latex membrane, an electric field was established between the positively charged sensing layer and the negatively charged latex film, resulting in a higher electric potential on the sensing layer. To balance the potential difference, the free electrons flow from the ground to the copper electrode, as shown in Figure 1d-II. With the increasing amount of inflation gas, the electric potential difference keeps increasing until the gap between the latex and sensing layers reaches a maximum, and no induction current could be observed (Figure 1d-III). Subsequently, the elastic restoring force of the latex membrane drives the test gas to be ejected from the chamber and shortens the distance between the latex film and the sensing film. As a result, the damping potential difference impels the induction charge to flow from the copper electrode to the ground (Figure 1d-IV).

To obtain a more quantitative understanding of the proposed electrical signal generation process of the AIMS, the electric potential distribution in the whole device is investigated through finite element analysis. As revealed in Figure 1e, due to the reduced screening effect of the positively charged latex film arising from the separation, the potential difference between the latex and sensitive layer increases with the enlarging of the gap in between. The simulated open-circuit voltage and electric field are shown to be proportional...
to the gap distance between the latex layer and sensitive layer (Figures S2 and S3, Supporting Information), which demonstrates the feasibility of the AIMS for detecting the gas flow volume.

To ensure high sensitivity and potential durability for operation under extreme conditions, tungsten trioxide (WO$_3$) composite films were utilized as the gas-sensing material. The scanning electron microscope image of WO$_3$ treated by 0.02 g of sodium hydroxide (NaOH) is shown in Figure 2a (Figure S4 and Figure S5, Supporting Information). It can be clearly seen that with further increasing the amount of NaOH, the morphology of the composite changes from granules to a curved surface structure. This can be attributed to the chemical reaction between sodium hydroxide and tungsten trioxide when the concentration of sodium hydroxide reaches a threshold amount. To investigate the adsorption and desorption behaviors of the gas-sensing materials, a Brunauer–Emmett–Teller (BET) test was measured and is depicted in Figure S6. A specific surface area of 51.73 m$^2$·g$^{-1}$ was observed for the NaOH-treated WO$_3$ sample. The good adsorption properties are ascribed to the hierarchical structure arising from the alkali treatment, which is conducive to the adsorption of the gas molecules and gas detection.

Figure 2. Chemical synthesis of sensing materials and characterizations. (a) SEM image of 0.02 g NaOH treated WO$_3$. The scale bar is 100 nm. (b) XRD patterns of a 0.02 g NaOH treated WO$_3$ sample. (c) Output voltage under repeated dry air inflation and deflation. (d) Output voltage versus various injected air volumes. (e) Thermal stability measurement. (f) Dependence of the output voltage on humidity.

Figure 3. Sensing performance of the alveolus-inspired membrane sensor. (a) Dynamic response of AIMS with 0.02 g NaOH treated WO$_3$ under different NO$_2$ concentrations. (b) Sensitivity for the sample with 0.02 g NaOH treated WO$_3$. (c) Dynamic response profile of an as-prepared AIMS under 80 ppm of NO$_2$. (d) Long-term stability of the AIMS. (e) Respiratory patterns detected by AIMS with 0.02 g NaOH treated WO$_3$. (f) Selectivity of AIMS with 0.02 g NaOH treated WO$_3$ for NO$_2$ sensing.
To investigate the gas-sensing properties of the AIMS, we built a measurement system as sketched in Figure S9. Based on a four-way gas valve connecting an air inlet, an air outlet, a syringe, and the sensor, the gas input, gas output, injection, and ejection can be precisely controlled by tuning a linear motor with adjustable frequencies, velocities, and amplitudes. For instance, the injected volume of the testing gas from a syringe into the connected sensor can be accurately modulated by setting the amplitude of the linear motor (Figure S10).

Figure 2c shows the dynamic output voltage profile of the as-fabricated AIMS under a fixed 5 mL injection volume of dry air. The output voltage displays an alternating behavior with a stable amplitude. The output voltage rises during inflation and falls during deflation, consistent with the finite element analysis. To investigate the influence of the injected gas volume on the sensing performance, a linear motor with a tunable amplitude was connected with a syringe to achieve a precise control of the gas injection volume. As shown in Figure 2d, the output voltage of the AIMS is approximately proportional to the injected gas volume with a linearity of 0.976 (inset of Figure 2d), which demonstrates the potential and feasibility of AIMS for the real-time detection of gas inflation volume.

To verify the robustness and stability of the AIMS under environmental influences, the impacts of temperature and humidity on the output behavior were measured and plotted in Figure 2e and f (Figure S11, Supporting Information), respectively. The open-circuit voltage remains almost the same within the temperature range from 20 to 34 °C, indicating that the temperature has a negligible influence on the output performance of AIMS. For humidity, the open-circuit voltage fluctuates slightly with humidity values of 11.3%
RH, 32.8% RH, 57.5% RH, and 75.3% RH, which is attributed to the dissolution of adsorbed water molecules into the sensing material. The absorption of water molecules changes the permittivity of the contacting layer during the electricity generation, thereby affecting the output performance. Therefore, to ensure accuracy, all the following measurements were conducted using a dry diluent gas and dry target gases.

To explore the gas-sensing capability of the as-fabricated AIMS, the output voltage at NO2 gas concentrations from 0 to 80 ppm was investigated. Compared with 0.01 and 0.1 g alkali treatments (Figure S12 and Figure S13), the device with 0.02 g NaOH treatment revealed a much better sensitivity and linearity, as shown in Figure 3a, where a response of 340.24% was achieved when being exposed to 80 ppm of NO2. In addition, as presented in Figure 3b, a linearity of 0.992 is observed for the AIMS with 0.02 g NaOH treatment, demonstrating its capability of actively detecting nitrogen dioxide in a wide concentration range. Figure 3c illustrates the dynamic response profile of an as-fabricated AIMS under 80 ppm of NO2, where the response and recovery times are 273 s and 330 s, respectively. It is noted that both the response and recovery curves vary quickly at first and then gradually become saturated, which shows a similar changing tendency as that of the resistance-based gas sensor. To further testify the durability of the AIMS, the responses of a NaOH-treated WO3 film-based sensor to various NO2 concentrations were tested weekly for one month. As presented in Figure 3d, a negligible response reduction of less than 5% is observed at each concentration level, indicating a good long-term stability of the prepared AIMS for practical usage.

To verify the ability of the AIMS in measuring human respiratory characteristics, three types of breathing patterns, including normal, rapid, and deep breathing, were recorded in real time and plotted in Figure 3e. It is found that the intervals between the signal peaks and amplitudes in the generated electrical signals vary with different breathing behaviors. A deep breath has the longest interval and the largest amplitude, while a rapid breath shows the shortest interval and the smallest amplitude. The reason is that the intervals and amplitudes are proportional to the period and respiratory characteristics, respectively. Consequently, it enables the practicability of AIMSs in distinguishing diverse breathing patterns without any power supply. Figure 3f demonstrates the selectivity of the AIMS for NO2 sensing in comparison with other gases including carbon monoxide, carbon dioxide, hydrogen sulfide, sulfur dioxide, and ammonia at a fixed concentration of 50 ppm (Figure S14, Supporting Information). It clearly shows that the response of the AIMS toward NO2 is at least 20 times higher than other gases, implying a good selectivity of NO2 sensing.

In order to achieve a fundamental understanding of the sensing mechanism of the self-powered triboelectric gas sensor, we performed a theoretical analysis based on thermodynamic equilibrium and dielectric physics. As shown in Figure 4a, under dry air, oxygen molecules (O2(gas)) would be adsorbed onto the surface of the sensing layer by capturing free electrons from the conduction band of the sensing layer to form species O2(ads),

$$\text{O}_2(\text{gas}) + e^- \rightarrow \text{O}_2(\text{ads}) \quad (1)$$

Due to the stronger electron affinity of NO2 (2.27 eV) than that of O2 (0.44 eV), NO2 molecules upon injection (Figure 4b) would extract electrons from adsorbed oxygen ion (O2(ads)) on the sensing layer or directly withdraw electrons from the conduction band. These processes can be summarized in the following reaction:

$$\text{NO}_2(\text{gas}) + \text{O}_2(\text{ads}) \rightarrow \text{NO}_2(\text{ads}) + \text{O}_2(\text{gas}) \quad (2)$$

Combining these two reaction processes in eq 1 and eq 2, a comprehensive reaction is given by

$$\text{NO}_2(\text{gas}) + e^- \rightarrow \text{NO}_2(\text{ads}) \quad (3)$$

The reaction equilibrium constant K for the reaction in eq 3 can be written as

$$K = \frac{a_{\text{NO}_2}^a}{a_e^a a_{\text{NO}_2}^s} = \frac{1}{a_e^a a_{\text{NO}_2}^s} = \frac{1}{c_e c_{\text{NO}_2}} \quad (4)$$

where $a_{\text{NO}_2}^a$, $a_e^a$, and $a_{\text{NO}_2}^s$ are the activities of $\text{NO}_2^-$, $e^-$, and NO2 species, respectively. Since the adsorbed (NO2(ads)) molecules are immobile assuming an activity of 1, the reaction equilibrium constant K can be written as

$$K = \frac{a_{\text{NO}_2}^a}{a_e^a a_{\text{NO}_2}^s} = \frac{1}{a_e^a a_{\text{NO}_2}^s} = \frac{1}{c_e c_{\text{NO}_2}} \quad (5)$$

where $c_e$ is the concentration of electrons in the sensing material, $c_{\text{NO}_2}$ is the concentration of NO2 gas, and K is the reaction equilibrium constant dependent on temperature. Therefore, the concentration of free electrons in the sensing material can be expressed as

$$c_e = \frac{1}{K c_{\text{NO}_2}} \quad (6)$$

It is consistent with the fact that the free electron concentration $c_e$ decreases with increasing ammonia concentration $c_{\text{NH}_3}$. The relationship between the polarizability and free electron concentration of the sensing material can be written as

$$\chi = \chi_t + \alpha c_e \quad (7)$$

where $\chi$ is the total polarizability, $\chi_t$ is the static polarizability, and $\alpha$ is a constant. As a result, the permittivity of sensing material can be obtained as

$$\varepsilon_i = \varepsilon_t + 1 = \varepsilon_t + 1 + \alpha c_e = \varepsilon_t + \alpha c_e \quad (8)$$

where $\varepsilon_i$ is the relative permittivity and $\varepsilon_t$ is the static permittivity.

Substituting eq 6 into eq 8, we can obtain the relationship between the relative permittivity and gas concentration, as follows:

$$\varepsilon_i = \varepsilon_t + \frac{\alpha}{K c_{\text{NO}_2}} \quad (9)$$

The open-circuit output voltage $V_{oc}$ for the single-electrode TENG with a large distance (g) between the primary electrode and reference electrode (ground in this work) is given by

$$V_{oc} = \frac{\sigma S}{2C_a} \quad (10)$$

where $\sigma$ is the triboelectric charge density on the surface of the dielectric layer, $S$ is the area of the device, and $C_a$ is the capacitance between the dielectric layer and the primary electrode. In this case, the capacitance $C_a$ can be regarded as a
series connection of the air layer and the sensitive layer between the dielectric film and the primary electrode as below:

$$\frac{1}{C_a} = \frac{1}{C_{\text{air}}} + \frac{1}{C_{\text{dielectric}}} = \frac{x}{\varepsilon_0 S} + \frac{d}{\varepsilon_{d} \varepsilon_r S}$$ \hspace{1cm} (11)

Consequently, the open-circuit voltage can be expressed as

$$V_{oc} = \frac{\sigma}{2} \left( \frac{x}{\varepsilon_0} + \frac{d}{\varepsilon_{d} \varepsilon_r} \right)$$ \hspace{1cm} (12)

Substituting eq 9 into eq 12, we can obtain the relationship between the output voltage and testing gas concentration as shown below:

$$V_{oc} = \frac{\sigma}{2 \varepsilon_0} \left( \frac{x}{\varepsilon_0} + \frac{d}{\varepsilon_{d} \varepsilon_r \varepsilon_{\text{NO}_2}} \right)$$ \hspace{1cm} (13)

And the response of the sensor can be expressed as

$$R = \frac{V_{g} - V_0}{V_0} = \frac{d}{x} \frac{1}{\varepsilon_{d} \varepsilon_r \varepsilon_{\text{NO}_2}}$$ \hspace{1cm} (14)

Since the triboelectric charge density $\sigma$, maximum gap $x$, film thickness $d$, temperature $T$, and reaction equilibrium constant $K$ remain the same during the gas-sensing process, the change in the open-circuit voltage depends only on the varying permittivity arising from the chemical adsorption of the target gas. It can be clearly seen that the increase of gas concentration leads to the enhancement of $V_{oc}$ which is consistent with the experimental results.

The sensitivity $S$ of the fabricated sensor is defined by

$$S = \frac{\Delta R}{\Delta C} = \frac{\partial R/\partial C_{\text{NO}_2}}{\partial C_{\text{NO}_2}} = \frac{\sigma d}{Kx} \left( \frac{\varepsilon_{d} \varepsilon_{\text{NO}_2}}{x} + \frac{\alpha}{K} \right)^{-2}$$ \hspace{1cm} (15)

From eq 15 we can see that a smaller gap between two contacting surfaces and a thicker sensing film is required for a higher sensitivity. By plugging the measured charge density $\sigma = 90$ nC/m$^2$ and parameters $d = 1$ mm and $x = 15$ mm into eq 13, the calculated output voltage agrees well with experimental data for NO$_2$ gas concentrations from 0 to 80 ppm (Figure 4c), validating the above thermodynamic analysis. To further verify the proposed theoretical modeling, finite element simulations were carried out to quantitatively investigate the influence of permittivity on the electric potential distribution and the output performance of the AIMS. According to the calculated results, the increase in permittivity obviously decreases the open-circuit voltage (Figure 4d) as well as the electric field inside the sensing layer (Figure 4e). As shown in Figure 4f (Figure S15, Supporting Information), with increasing permittivity, the electric potential varies near the sensing film but remains almost uniform in other parts of the device (Figure S16 and Figure S17, Supporting Information). The enhancement in permittivity lowers the potential inside the sensing film, leading to a more gradual potential variation approaching that of the surrounding area. This is because that the permittivity change arising from the gas adsorption mainly occurs in the local area of the sensing film via charge transfer, and the combination of trapped charges and the triboelectric charge dominates the electric field distribution.

A more intuitive and microscopic understanding of the gas-sensing mechanism can be obtained by examining the depolarization behavior as shown in Figure 4g–j. Upon exposure to nitrogen, there is no charge transfer taking place before the contact of two contacting layers because no triboelectrification or gas adsorption occurs. In this case, no electric field was established and the separation of two contacting layers cannot produce an open-circuit voltage ($V_{oc}$), as shown in Figure 4g. Once a contact electrification is established in a nitrogen atmosphere, the opposite triboelectric charges on the two contacting surfaces result in an electric field inside the sensing film, leading to the rearrangement of the free charges in the film (Figure 4h) and consequently the formation of a depolarization field $E_d$ (white arrow) opposing the electric field $E_{ui}$ arising from the triboelectric charges. The total electric field $E_{total}$ can thus be written as

$$E_{total} = E_{ui} + E_d$$ \hspace{1cm} (16)

Therefore, the depolarization field contributes to the decrease of the total electric field (blue arrow). In this case, under the air atmosphere (Figure 4i), adsorbed oxygen molecules capture electrons from the sensing film and thus decrease the bulk free charge density. As a consequence, fewer charges are available to establish the depolarization field inside the film, leading to a weaker depolarization field. When AIMS is exposed to a NO$_2$ atmosphere, the adsorbed NO$_2$ molecules would further withdraw the electrons from the sensing film and thus further decrease the depolarization field (Figure 4j). Therefore, with increasing NO$_2$ concentration, the depolarization field continues to decrease while the total electric field continues to increase. Since the potential difference equals the integral of electric field over the distance, the reduction in the depolarization field gives rise to the enhancement of the output voltage. In other words, extracting electrons from the sensing materials through chemical adsorption would reduce the ability of the sensing film to form a depolarization field and hence improve the electric output voltage.

We also performed phase-field simulation to numerically illustrate the influence of permittivity change on the total electric field and the induced polarization in the sensing film. It is found that the polarization increases with increasing relative dielectric constant, while the electric field follows an opposite trend, as revealed in Figure 4k (Figure S18 and Figure S19, Supporting Information). Given that the depolarization field is proportional to the polarization once the device is fixed, the increase in permittivity facilitates the depolarization of the sensitive layer, which is in agreement with the aforementioned theoretical analysis and experimental data.

**CONCLUSIONS**

We developed a wearable alveolus-inspired active membrane sensor for effective nitrogen dioxide detection and personal respiratory behavior monitoring. Alkali-treated tungsten trioxide is chosen to detect the level of nitrogen dioxide, where a response of 340.24% and linearity of 0.976 are achieved when it is exposed to 80 ppm of NO$_2$. Furthermore, the device exhibits excellent selectivity and thermal and humidity stability. The sensing mechanism is theoretically unraveled by using thermodynamic analysis, finite element calculation, and phase-field simulation. It is found that the depolarization field arising from the bulk free electrons inside the sensing layer plays a dominant role in affecting the output performance: the adsorbed gas molecules capture electrons from the sensing layer and thus reduce the depolarization field inside the sensing layer, leading to an enhancement of the
electric output. This work provides a unique approach for self-powered toxic gas detection and breath analysis. Giving a collection of compelling features such as low cost, light weight, high sensitivity, selectivity, and stability, the wearable AIMS could be widely adopted for environmental monitoring and personal health assessment.

EXPERIMENTAL METHODS

Preparation of Sensing Materials. Sodium hydroxide in 0.01, 0.02, and 0.10 g amounts was respectively dissolved in separate 50 mL of deionized water with each subjected to 1 h of sonication to allow the solution to mix well. Then, 0.232 g of tungsten trioxide was dispersed into each prepared sodium hydroxide solution with ultrasonication for 3 h. Meanwhile, 0.232 g of tungsten trioxide was dispersed in deionized water and sonicated for 3 h as a control. The prepared suspensions were then spray-deposited on a copper-coated acrylic sheet as a sensing film. Finally, the fabricated devices were heated in a vacuum drying oven at 60 °C for 12 h.

Fabrication of AIMS. A layer of acrylic with the dimensions of 40 mm × 40 mm × 1 mm was tailored by laser etching. A layer of latex with dimensions of 40 mm × 40 mm × 0.25 mm and the tailored acrylic sheet were cleaned by ethanol and deionized water. Then a copper electrode with a thickness of 200 nm was coated on one side of the tailored acrylic sheet by thermal evaporation, followed by spray deposition of prepared suspensions as the gas-sensing material. Subsequently, the WO3/copper-coated acrylic sheet was etched by a laser machine to create a central hole with a diameter of 4.0 mm. Then, the latex layer was attached to a WO3/copper-coated acrylic sheet to form the gas test chamber. Epoxy resin was used to seal the edges between the latex film and the acrylic sheet to ensure gas tightness. A plastic tube was integrated with the prepared sensor as the inlet and outlet of the target gas into the sensor.

Gas Distribution System. The testing system of the sensor is based on a customized static gas distribution system consisting of a four-channel valve connected with the sensor, the air inlet, the air outlet, and syringe. A linear motor was integrated with the syringe to mechanically and accurately control the extraction, emission, injection, and ejection of the target gas. Different concentrations of target gas were modulated by a mass flow controller (Wuxi Aituoli Electronic Technology Co., Ltd., MFC 300) with a constant flow rate of 200 sccm, which was connected to the inlet of the testing system. The test concentration of NO2 was in a wide range from 0 to 100 ppm with dry air as the diluent gas. The injection and ejection volumes of the testing gas can be accurately controlled by setting the amplitude of the linear motor. Prior to the testing process, the whole gas path must be cleaned by dry air for at least 3 h to remove the residual gas molecules adhered on the tubes.

Characterization and Measurement. The morphologies of samples were characterized by a field emission scanning electron microscope (FESEM) (S-4800, Japan, Hitachi) operated at 5 kV. An X-ray diffractometer (D8 Advance, Bruker-AXS, Germany) equipped with Cu Kα radiation (λ = 1.5418 Å and 2θ = 20—80°) was used to analyze the crystal structure of the samples at room temperature. The N2 adsorption—desorption isotherms were obtained via a Micrometrics ASAP 2020 M system, and the surface area was calculated by using the BET method. The output voltage and current across the testing sensor were measured by a Keithley 6514 electrometer system, and the data were recorded in real time by a personal computer with Labview software. The response is defined as R = (Vf − Vi)/Vi × 100% (Vi is the initial output voltage in air, while Vf is the output voltage in the target gas). The response and recovery times are defined as the time when the sensor attains 90% of total voltage change in response to gas adsorption and desorption. The RH levels of 11.3%, 32.8%, 57.5%, and 75.3% were achieved by saturated solutions of LiCl, MgCl₂, NaBr, and NaCl, respectively. The target gases were first injected into the bottle of saturated salt solutions and then inflated into the AIMS to ensure a certain relative humidity level.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsnano.0c01804.

AUTHOR INFORMATION

Corresponding Authors

Yuanjie Su — State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China; School of Materials Science and Engineering, Pennsylvania State University, State College, Pennsylvania 16802, United States; orcid.org/0000-0002-6851-4476; Email: yjsu@uestc.edu.cn

Jianjun Wang — School of Materials Science and Engineering, Pennsylvania State University, State College, Pennsylvania 16802, United States; Email: jzw12@psu.edu

Long-Qing Chen — School of Materials Science and Engineering, Pennsylvania State University, State College, Pennsylvania 16802, United States; Email: lqc3@psu.edu

Jun Chen — Department of Bioengineering, University of California, Los Angeles, Los Angeles, California 90095, United States; Email: jun.chen@ucla.edu

Authors

Bo Wang — School of Materials Science and Engineering, Pennsylvania State University, State College, Pennsylvania 16802, United States

Tiannan Yang — School of Materials Science and Engineering, Pennsylvania State University, State College, Pennsylvania 16802, United States

Boxi Yang — State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China

Guangzhong Xie — State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China

Yihao Zhou — Department of Bioengineering, University of California, Los Angeles, Los Angeles, California 90095, United States

Songlin Zhang — Department of Bioengineering, University of California, Los Angeles, Los Angeles, California 90095, United States

Huiling Tai — State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China; orcid.org/0000-0001-5966-3843

Zhixiang Cai — Department of Bioengineering, University of California, Los Angeles, Los Angeles, California 90095, United States

Guorui Chen — Department of Bioengineering, University of California, Los Angeles, Los Angeles, California 90095, United States

Yadong Jiang — State Key Laboratory of Electronic Thin Films and Integrated Devices, School of Optoelectronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610054, China

Complete contact information is available at:
Author Contributions

Y. Su and J. Wang contributed equally to the work. J.C., Y.S., and L.Q.C. planned the study and guided the whole project. Y.S. and J.C. organized the data and drew the figures. Y.S., J.C., L.Q.C, and J.W. performed the data analysis and wrote the manuscript. B.Y. performed the gas-sensing experimental measurements. J.W., B.W., and T.Y. assisted Y.S. in the thermodynamic analysis, finite element calculation, and phase-field simulation. All authors contributed to design this work and comment on the manuscript. J.C. submitted the manuscript and was the lead contact.

Notes

The authors declare no competing financial interest.

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