

Highly Deformable Fabric Gas Sensors Integrating Multidimensional Functional Nanostructures

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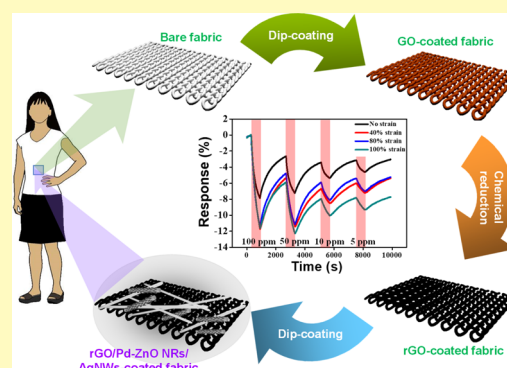
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ABSTRACT: Highly strain-endurable gas sensors were implemented on fabric, which was taken from a real T-shirt, employing a sequential coating method. Multidimensional, functional nanostructures such as reduced graphene oxide, ZnO nanorods, palladium nanoparticles, and silver nanowires were integrated for their realization. It was revealed that the fabric gas sensors could detect both oxidizing and reducing gases at room temperature with differing signs and magnitudes of responses. Noticeably, the fabric gas sensors could normally work even under large strains up to 100%, which represents the highest strain tolerance in the gas sensor field. Furthermore, the fabric gas sensors turned out to bear harsh bending and twisting stresses. It was also demonstrated that the sequential coating method is an effective and facile way to control the size of the fabric gas sensor.

KEYWORDS: fabric gas sensors, strain endurance, multidimensional nanostructures, palladium-decorated ZnO nanorods, multiple gases



People face ever-increasing threat of being exposed to a wide variety of dangerous gases in daily lives. The primary sources of the gas hazard come from the private and public sectors.¹ In this regard, people living in urban areas are more endangered because much more toxic gases are generated in the city by combustion of traditional fossil fuels.² Typical toxic gases generated from the combustion process include nitrogen dioxide (NO₂), ammonia (NH₃), and carbon monoxide (CO), all of which can cause diseases of important body organs such as the lung and liver or damage the immune system.³ Fuel cells that use hydrogen gas (H₂) are gradually spreading in diverse applications as an alternative power generator.⁴ Despite its environment friendliness, however, the hydrogen gas is very diffusive and highly explosive above a critical concentration (>4%) in air.⁵ For this reason, early and reliable detection of H₂ should be warranted for further spread of the technology.

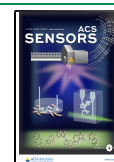
What makes the situation more difficult is that all the gases mentioned above are ubiquitous and their concentrations are strongly location-dependent. Under this circumstance, the best way to ensure gas safety may be implementing a wearable or patchable gas sensor,^{3,6–9} which can monitor dangerous gases in real time. To this aim, there has been an attempt to integrate a gas sensor into a smart phone.¹⁰ However, this approach might not be the ultimate solution because the smart phone placed in any enclosed space fails to detect toxic gases. Gas sensors that can be fabricated or patched on clothes would be ideal because of their real-time exposure to the environment. Recently, several research groups have endeavored to fabricate gas sensors on fabrics^{6–8,11–13} employing methods such as dip-

coating, drop-casting, and electroless plating. Carbon nanostructures such as graphene, reduced graphene oxide (rGO), and carbon nanotubes (CNTs) were used as major gas detectors owing to their good wettability on fabrics and sensibility to multiple gases.^{14,15} The prior proof-of-concept studies have demonstrated that gas sensors could be implemented on fabrics and they could detect toxic gases even at room temperature (RT).^{6,7,9,11,16} However, these foregoing studies lacked the deformability enough for wearable or patchable gas sensors. Most fabrics for clothes are interwoven with multiple fibers, including both natural fiber (cotton) and synthetic fibers (polyester and polyurethane).¹⁷ Because of the good elasticity and large stretchability of the synthetic components, the fabrics show good elastic deformability,¹⁷ which is critical because the clothes experience large strains during human motions. Thus, the practical wearable sensors should also well-function under large strains. This task is difficult to meet because the conventional 2D nanostructures such as rGO are easily torn under moderate strains (<20%) and the sensor resistance rapidly rises to the level at which the sensor loses its functionality. For this reason, there has never

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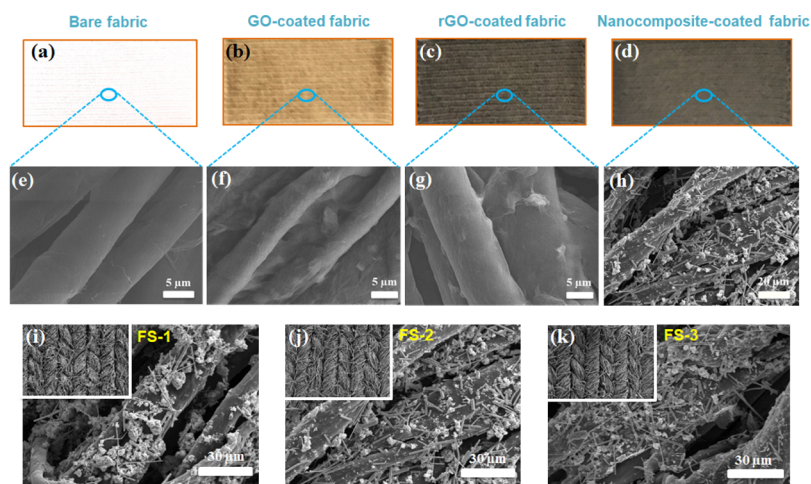


Figure 1. Photographs of (a) bare fabric, (b) GO-coated fabric, (c) rGO-coated fabric, and (d) nanocomposite-coated fabric. SEM images of (e) bare fabric, (f) GO-coated fabric, (g) rGO-coated fabric, and (h) nanocomposite-coated fabric for selected areas. SEM images of (i) FS-1, (j) FS-2, and (k) FS-3.

been a report on fabric-based gas sensors that could detect multiple gases under large strains.

In this work, we fabricated stretchable gas sensors on a fabric, employing a facile, sequential coating method. Multi-dimensional nanostructures such as rGO, zinc oxide nanorods (ZnO NRs), palladium nanoparticles (PdNPs), and silver nanowires (AgNWs) were combined to efficiently detect multiple gases. Notably, the stretchable fabric gas sensors responded to four types of gases at RT and even under large strains up to 100%.

EXPERIMENTAL SECTION

Materials and Reagents. Ethylene glycol ($\text{C}_2\text{H}_6\text{O}_2$, EG), silver nitrate (AgNO_3), polyvinylpyrrolidone (PVP, $M_w \sim 1,300,000$), copper(II) chloride dehydrate ($\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$), potassium permanganate (KMnO_4), hydrazine monohydrate ($\text{N}_2\text{H}_4 \cdot \text{H}_2\text{O}$), sodium tetrachloropalladate(II) (Na_2PdCl_4), zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), and hexamethylenetetramine (HMTA, $\text{C}_6\text{H}_{12}\text{N}_4$) were all purchased from Sigma-Aldrich. Sulfuric acid 98% (H_2SO_4), phosphoric acid 85% (H_3PO_4), hydrogen peroxide 30% (H_2O_2), hydrochloric acid 20% (HCl), acetone ($(\text{CH}_3)_2\text{CO}$), and ethyl alcohol ($\text{C}_2\text{H}_5\text{OH}$) were purchased from Daejung Chem. Graphite powders were purchased from Imerys Graphite and Carbon.

Synthesis of GO and AgNWs. GO was prepared by the modified Hummer's method.^{18,19} For this, 3.0 g of graphite flakes was first added to 400 mL of concentrated $\text{H}_2\text{SO}_4/\text{H}_3\text{PO}_4$ (9:1) solution under stirring. At the next step, 18.0 g of KMnO_4 powder was slowly added to this suspension. Because of the exothermic nature of this process, the temperature of the reaction mixture increased to 35–40 °C. After that, the reaction solution was kept for 12 h at 50 °C with stirring and then cooled down to 0–5 °C using ice. During this process, 30% H_2O_2 was added until the reaction mixture was discolored to bright yellow. Next, the mixture solution underwent repeated centrifugation and washing, using deionized (DI) water and HCl solution. The output of this process was washed again with ethanol until the pH reached ~ 7 . Finally, the precipitate was dried in a vacuum oven at RT. AgNWs were synthesized using a conventional polyol method. The synthesis procedures were described elsewhere in detail.^{19,20}

Synthesis of PdNP-Decorated ZnO NRs (Pd–ZnO NRs). ZnO NRs were synthesized employing the same method as previously reported.²¹ To form PdNPs on the surface of ZnO NRs, we modified the method reported in the previous literature.²² At first, 50 mg of ZnO NRs was dispersed in 10 mL of EG by sonicating the colloid for 10 min and then heated to 160 °C under constant stirring. At the

same time, two reactant solutions of PVP and Na_2PdCl_4 were prepared by adding 0.0432 g of Na_2PdCl_4 and 0.0832 g of PVP into 4 and 8 mL of EG, respectively. At the next step, the Na_2PdCl_4 solution (4 mL) and PVP solution (8 mL) were injected into the ZnO NR colloidal solution over a span of 30 min, and the reaction continued for another 5 min. Finally, the product was washed with ethanol and DI water and dried at 70 °C.

Fabrication of Stretchable Gas Sensors on Fabric. The fabric samples used in this work were severed from a real T-shirt (see Figure S1), which consisted of 94% cotton and 6% spandex. To implement stretchable gas sensors on the fabric, we developed a sequential dip-coating method, as schematically presented in Figure S2. A fabric of size in $2 \text{ cm} \times 1 \text{ cm}$ was rinsed several times with DI water and ethanol to remove organic and inorganic dirt on the surface. At the first step, the fabric was immersed in 5 mg/mL GO solution for 15 min and then taken out of the solution. It was subsequently dried for 10 min at 80 °C. This immersion and drying cycle was repeated three times to completely coat the fabric surface with GO. At the next step, the chemical reduction method using hydrazine was used to reduce GO to rGO.²³ For this, the GO-coated fabric was placed on top of a vial containing 3 mL of hydrazine solution and it was placed inside a beaker, which was tightly sealed afterward using aluminum foil. Upon heating the whole thing for 8 h in a convection oven at 80 °C, the color of the fabric changed to black, indicating the reduction of GO to rGO. The last step was to coat the mixture of Pd–ZnO NRs and AgNWs on the rGO-coated fabric. Three different mixture solutions were prepared to see the effect of AgNWs, for which 5, 10, and 15 mg of AgNWs were mixed with a fixed amount (15 mg) of Pd–ZnO NRs in 5 mL of DI water and sonicated for 1 h. The rGO-coated fabric was dipped into the respective Pd–ZnO NRs/AgNWs mixture solutions for 5 min and dried for 15 min at 80 °C. The fabric gas sensors obtained through these steps were named FS-1 (ratio = 3:1), FS-2 (ratio = 3:2), and FS-3 (ratio = 1:1), depending on the weight ratio between Pd–ZnO NRs and AgNWs in the mixture solution.

Material Characterization and Gas-Sensing Test. The stepwise surface morphology change was analyzed using field emission scanning electron microscopy (FE-SEM, JEOL JSM-7500F) mounted with an energy-dispersive X-ray spectrometry (EDX) instrument. The crystalline characteristics of samples were examined by X-ray diffraction (XRD, D8 ADVANCE, Bruker) with copper $K\alpha$ radiation. The degree of reduction of GO to rGO was analyzed by X-ray photoelectron spectroscopy (XPS, K-Alpha, Thermo Electron). The sheet resistances of regular-sized and large-sized samples were measured using the standard four-point probe method (CMT-100). Furthermore, the stretchability of the nanocomposite-coated fabric was diagnosed utilizing a custom-made stretching machine with a stretching rate of 2 cm/min.

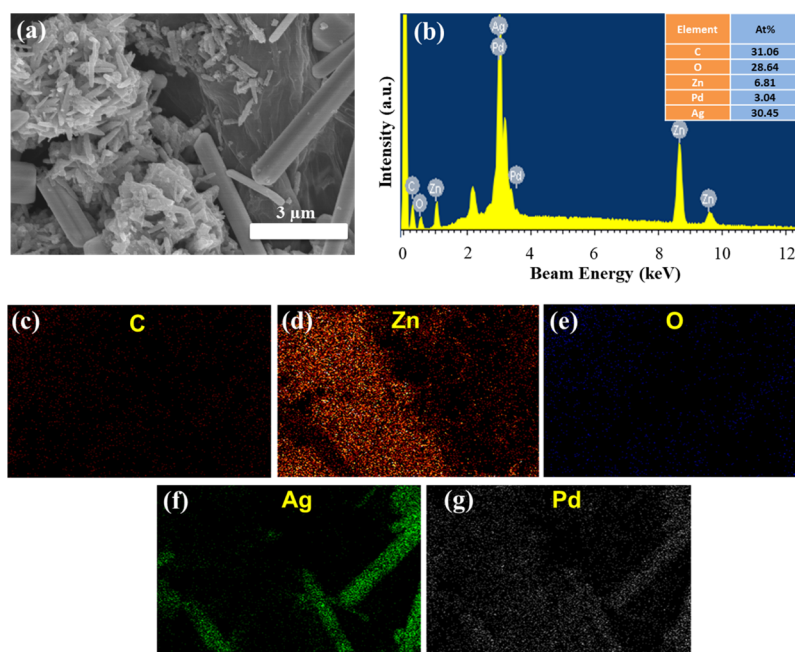


Figure 2. (a) SEM image and (b) EDX spectrum of a nanocomposite-coated fabric (FS-2). EDX element maps of (c) C, (d) Zn, (e) O, (f) Ag, and (g) Pd of the selected area.

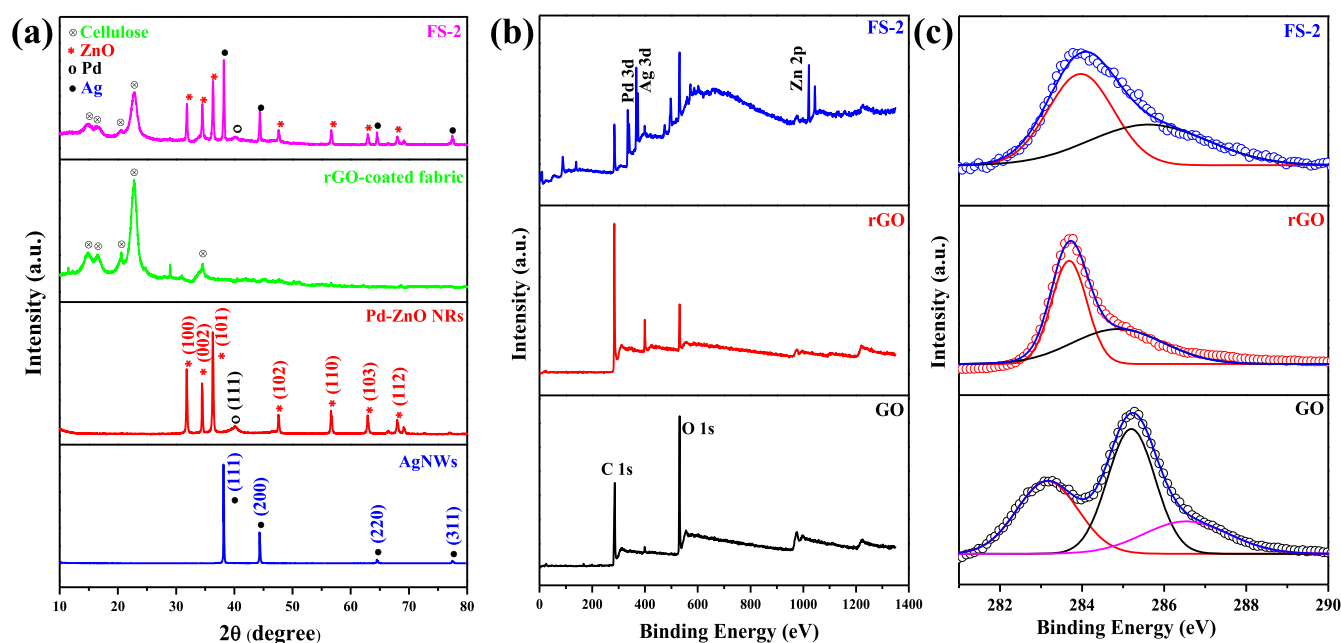


Figure 3. (a) XRD patterns of AgNWs, Pd-ZnO NRs, rGO-coated fabric, and nanocomposite-coated fabric (FS-2). (b) Overall XPS spectra of GO-coated fabric, rGO-coated fabric, and FS-2 sample. (c) XPS spectra focused on the C 1s peaks of the respective samples.

The gas-sensing performance of the nanocomposite-coated fabric gas sensors was mainly evaluated using a specially designed gas-sensing system, which can monitor the gas response under variable strains. The gas chamber is equipped with multiple gas sources and a gas-mixing system (see Figure S3 for reference). The target gases such as NO₂, H₂, NH₃, and CO were diluted by mixing with synthetic air, and the air-carried target gases with specific concentrations were fed into the chamber at the fixed flow rate of 500 sccm. The variation of sensor resistance was measured at RT and recorded in a computer through a data acquisition system. The response of a gas sensor was defined as

$$\text{Response (\%)} = \frac{R_{\text{gas}} - R_{\text{air}}}{R_{\text{air}}} \times 100 \quad (1)$$

where R_{air} and R_{gas} are the electrical resistances of the sensor in air and a target gas, respectively. In addition, the temperature dependence and humidity dependence of sensor performance were also examined, using another gas-sensing system.

RESULTS AND DISCUSSION

Appearance Change and Nanostructure Distribution.

Figure 1a–d show the stepwise color changes of a fabric sample, corresponding to the respective process steps. The

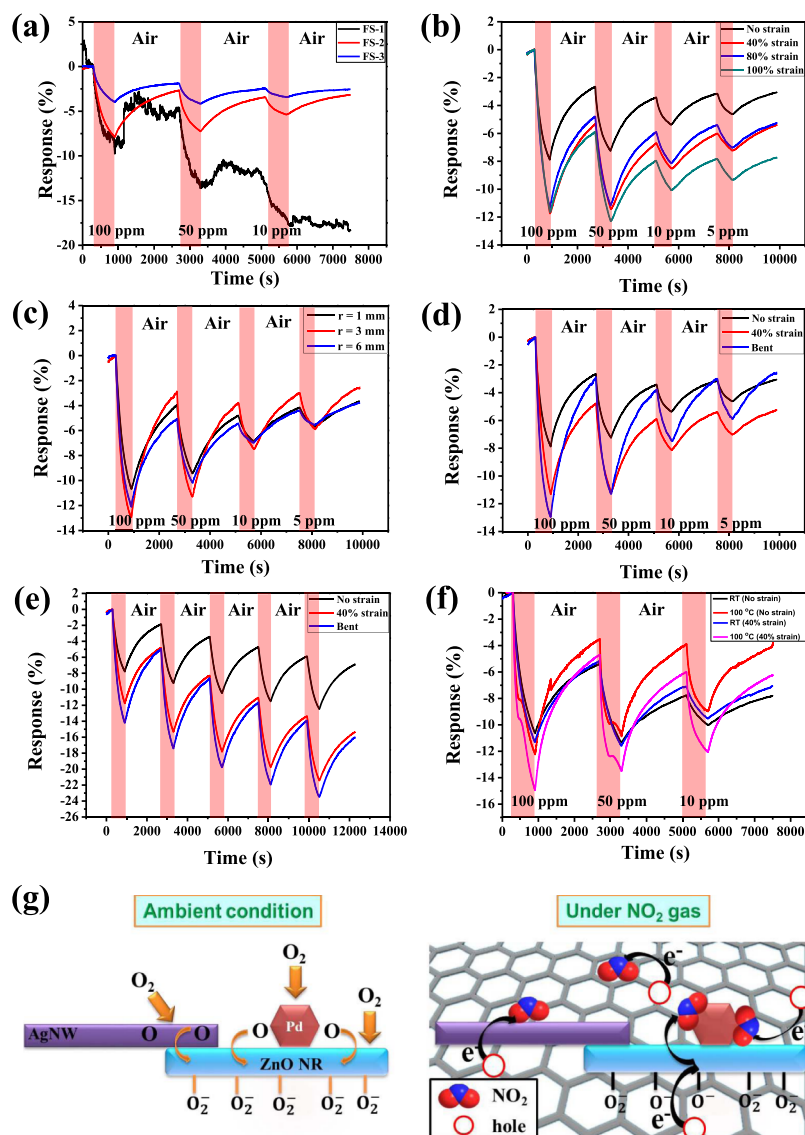


Figure 4. (a) NO₂ responses of FS-1, FS-2, and FS-3 at an unstrained state. NO₂ responses of FS-2 (b) under different tensile strains (0–100%), (c) different bending radii (1–6 mm), and (d) different strain states (no strain, 40% tensile strain, and bending strain). (e) Cyclic responses of FS-2 to 100 ppm of NO₂ under no strain, 40% tensile strain, and bending strain. (f) NO₂ responses of FS-2 at different temperatures with or without tensile strain. (g) Schematic picture for illustrating the NO₂-sensing mechanism of the fabric gas sensor.

white color of the original fabric changes to light brown upon coating with GO and, in turn, to black after the reduction of GO to rGO, and the black color remains almost unchanged after further coating with Pd–ZnO NRs/AgNWs. Narrowing the focus down to a deep micrometer scale, it is found from Figure 1e that the bare fabric is composed of a bundle of many smooth and uniform strands with a thickness of 7–10 μm . The GO flakes completely wrap around the strands (Figure 1f), and the high strand-wrapping quality is retained even after GO-to-rGO reduction (Figure 1g). This complete covering with GO or rGO protects the textile strands from any chemical damage when the fabric is exposed to toxic gases. At the last step, AgNWs and Pd–ZnO NRs are overcoated on the surface of the rGO layer (Figure 1h). They are randomly distributed overall, although some local agglomerates are found. The AgNW density increases in the order FS-1, FS-2, and FS-3 (Figure 2i–k), as expected from the increasing AgNW colloidal concentrations for the synthesis of these samples. For FS-1, the Pd–ZnO NRs are apparently agglomerated and

the AgNWs are insufficient for complete networking, while the AgNW density for FS-3 is in surplus. In this aspect, FS-2 may be the optimal sample. For comparison, the individual nanostructures used in the composite fabrication are shown in Figure S4.

Figure 2 exhibits a SEM image and EDX element maps for a selected area of the FS-2 sample. For this area, any textile strand is not found because it may be located underneath the rGO sheets. Pd–ZnO NRs are widely distributed over the rGO sheets. Randomly oriented AgNWs form a network over the rGO layer and their tips are interdigitated with high-density Pd–ZnO NRs. In particular, the content of PdNPs is estimated at 3 at. % for this selected area. It is inferred that a significant amount of oxygen comes from the underlying fabric (Figure 2e).

Crystal Quality and Reduction State. Figure 3a shows XRD patterns of a FS-2 sample and an rGO-coated fabric sample, in comparison with those of pure AgNWs and Pd–ZnO NRs. The FS-2 sample reveals sharp characteristic peaks

Table 1. Comparison of NO₂-Sensing Performance of Several Flexible or Stretchable Gas Sensors at Different Strain States

materials ^a	NO ₂ conc. (ppm)	operating temperature (°C)	response (%)			refs
			bending (radius/angle)	stretching (tensile strain)	twisting (twist angle)	
Pd-ZnONRs/AgNWs/rGO fabric	100	RT	11 (1 mm)	12 (100%)	11 (360°)	this work
Co ₃ O ₄ /MWCNT hybrid fiber	50	RT	3.25 (120°)	no	no	38
Al-ZnO/AgNWs/PDMS	10	RT	no	32.3 (30%)	no	32
CNTs/graphene hybrid/PI	5	RT	14 (15 mm)	no	no	39
rGO/AgNWs/PU sponges	50	RT	10 (3 mm)	15 (60%)	no	19
Zn _(0.5) Fe _(0.5) O ₄	30	90	125 (60°)	no	no	40
Al/Graphene/PI	1.2	150	6.2 (1.9 mm)	no	no	41
2D RuO ₂ NSs-AgNWs/PI	20	80.3	1.124 (30°)	no	no	42
all graphene/PI	5	RT	10 (1 mm)	no	no	43
Fe ₂ O ₃ /PANI/PSS/PET	20	RT	5 (180°)	no	no	44

^aPDMS: polydimethylsiloxane, PI: polyimide, PU: polyurethane, PET: polyethylene terephthalate.

at the same peak positions as those of its constituting nanostructures (rGO, AgNWs, ZnO NRs, and PdNPs), indicating the high crystal quality of all the structural components. AgNWs and ZnO NRs are analyzed to have a face-centered cubic (fcc) structure (JCPDS card no. 04-0783)²⁴ and hexagonal wurtzite structure (JCPDS card no. 36-1451),²⁵ respectively. A small peak appearing at $2\theta = 40.0^\circ$ for Pd-ZnO NRs is indexed to the (111) plane of fcc Pd (JCPDS card no. 05-0681).²⁶ In the case of rGO-coated fabric, five characteristic peaks at $2\theta = 14.8, 16.4, 20.5, 22.7,$ and 34.6° correspond to the typical XRD pattern of cellulose, which is the main component of the fabric.²⁷

Figure 3b displays the overall XPS spectra of GO-coated fabric, rGO-coated fabric, and nanocomposite-coated fabric (FS-2). It is clear that both GO-coated and rGO-coated fabrics show characteristic C 1s and O 1s peaks at 285.1 and 528.5 eV, respectively, confirming the uniform decoration of GO and rGO on the fabric. The O 1s peak intensity of rGO-coated fabric is greatly shrunk from that of GO-coated fabric, whereas the C 1s peak behaves in the opposite way. This is indicative of the substantial reduction of GO to rGO. The atomic ratios of C to O for GO-coated and rGO-coated fabrics were estimated at 2.06 and 7.24, which means that the O content of rGO is just 12.1 at. %. Ag 3d, Pd 3d, and Zn 2p peaks also appear for the FS-2 sample, suggesting the decoration of Pd-ZnO NRs and AgNWs over the rGO layer. Figure 3c presents XPS spectra of the three samples focused on the C 1s peak, which has three distinctive origins. The peaks centered at 286.7 and 285.5 eV originate from the C–O bonding and the C–OH bonding, respectively.²³ Another peak with its center at 284 ± 0.3 eV arises from the C=C bonding.^{28,29} It is found that the intensities of both the C–O peak and the C–OH peak for rGO-coated fabric and the FS-2 sample are substantially decreased from those of the GO-coated fabric. On the contrary, the C=C bonding peak becomes stronger for both samples. These findings corroborate that GO can be effectively reduced to rGO in the hydrazine fume environment.

Response to NO₂ Gas under Diverse Strains. The gas-sensing performance of the nanocomposite-coated fabric gas sensors was tested normally at RT. Figure 4a shows the NO₂ response behaviors of three types of sensors (FS-1, FS-2, and FS-3) at an unstrained state. Apparently, all the fabric gas sensors exhibit negative responses (resistance drops) at the presence of NO₂ gas. However, FS-1 shows noisy response and poor recovery, which is attributed to incomplete AgNW

network formation. On the other hand, both FS-2 and FS-3 exhibit clear response signals. Nonetheless, the response of FS-2 is bigger than that of FS-3. The effect of relative weight fraction of AgNWs is also reflected on the sensor resistances (Figure S5). From this set of experiments, FS-2 was chosen as a standard fabric gas sensor for further studies. Figure 4b displays the NO₂-sensing performance of FS-2 under varying tensile strains. Because the rupturing strain of the FS-2 was estimated at $\sim 120\%$ (Figure S6), the applied strain was modulated in the range of 0–100%. Surprisingly, the sensor normally works even under large strains up to 100%, which is the highest endurable strain ever reported in the gas sensor field. The response signal gradually decreases with decreasing NO₂ concentration and it sustains below 5 ppm. Moreover, the magnitude of response changes little with increasing the strain, even though the sensor resistance increases approximately three-fold under a 100% strain (Figure S7). The response of the sensor to 100 ppm of NO₂ is estimated at $\sim 8\%$ under zero strain and $\sim 12\%$ under strains of 40–100%.

The normal operation of FS-2 is also observed at bent states, as shown in Figure 4c,d. To make the bent states, the sample is wrapped around cylindrical rods with different radii of 1, 3, and 6 mm (see Figure S8). It is found that clear, sharp, and concentration-dependent response signals come from the bent states. There is no deterioration in the response, demonstrating the sensor's good adaptability to bending strains. Furthermore, FS-2 turned out to endure a 360° twisting strain and detect NO₂ normally (Figure S9). The cyclic response behaviors of the sensor at different strain states are presented in Figure 4e. It is clearly seen that the response signals are quite reproducible at all the strain states, although the drift of baselines is also observed. The drift phenomenon often appears in gas sensors made of semiconductors and is known to have multiple sources such as structural or morphological variation of components, diffusion of oxygen vacancies, and insufficient energy supply. Potential solutions to relieve the drift may include electrical baseline manipulation, frequency-dependent signal filtering, and heating the gas sensor. In addition, the effects of temperature and humidity on FS-2 performance were examined. Figure 4f shows response curves at two temperatures (RT and 100 °C) and two strains (0 and 40%). It is apparent that the fabric gas sensor responds to NO₂ without performance degradation even under harsh conditions of 100 °C and 40% strain. The sensor also shows good response behaviors at a relative humidity of 15% (Figure S10), but the

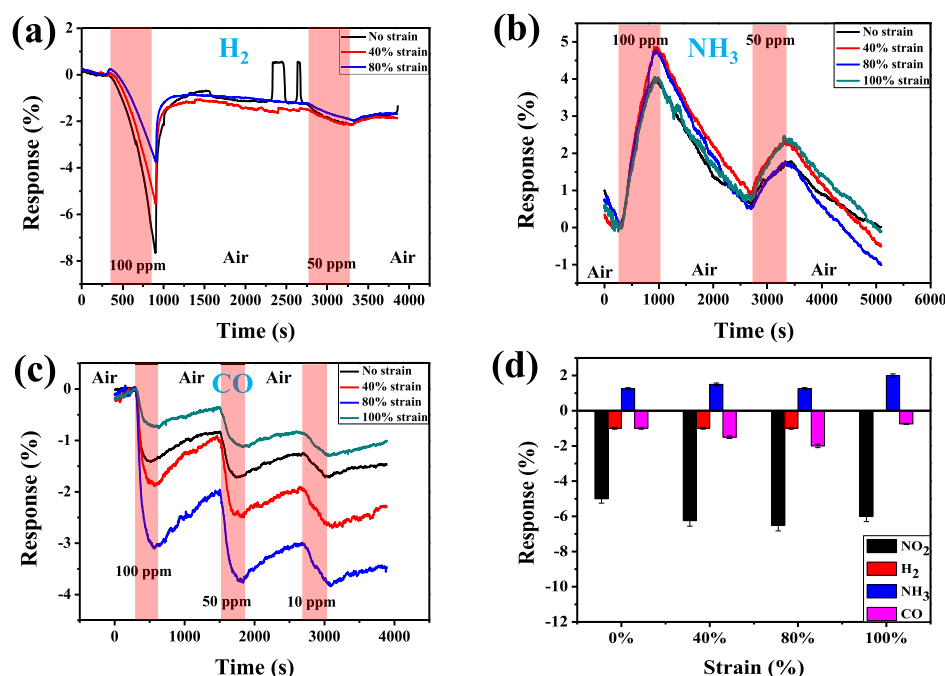
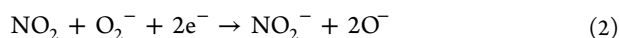


Figure 5. Strain-dependent response behaviors of FS-2 to (a) H₂, (b) NH₃, and (c) CO gases. (d) Comparison of the strain-dependent responses to four types of gases (NO₂, H₂, NH₃, and CO) at a fixed concentration of 50 ppm.

performance becomes worse at higher humidity because of the water-capture effect of cotton. The NO₂-sensing performance of FS-2 at various strain states is summarized and compared with previous reports in Table 1. It is obvious that our fabric gas sensor is superior to prior flexible or stretchable gas sensors in the aspect of strain adaptability. The outstanding strain adaptability is attributed to several structural factors of the sensor such as unique textile structure, high elasticity of each textile strand, local cracking of rGO sheets, and AgNWs-mediated electrical bridging. Figure S11 shows real rotation of textile strands toward a straining direction and schematic nanostructure configuration on the surface under a 100% tensile strain. The surface of rGO is most likely torn under this strain because the longitudinal strain that a rGO-coated strand should bear is estimated at ~58%. AgNWs can play as an electrical bridge connecting broken rGO pieces.

To explain the NO₂-sensing mechanism of the fabric gas sensor, a schematic picture is displayed in Figure 4g.^{19,30–32} Metallic nanostructures such as PdNPs and AgNWs can facilitate O₂ adsorption onto the ZnO NRs and catalytically dissociate adsorbed O₂ into O atoms, which spread over the ZnO NR surface. During this process, O atoms or O₂ molecules deprive electrons of ZnO NRs, resulting in oxygen ions (O[−] or O₂[−]) and surface electron depletion. When the nanocomposite is exposed to NO₂, the NO₂ molecules may be chemisorbed preferably near the PdNPs and AgNWs, and they tend to take electrons from nearby medium. Rather than ZnO NRs, which cannot supply electrons because of the surface depletion, rGO sheets may act as an electron supplier. On the whole, electrons can be effectively transferred from rGO to NO₂ molecules, following the reaction given below.



Strain-Dependent Responses to H₂, NH₃, and CO Gases. Figure 5a presents the response curves of FS-2 to H₂ gas. The fabric gas sensor shows sharp response signals to 100

ppm of H₂ and recognizable signals to 50 ppm under varying strains of 0–80%. At a 100% strain, there was no meaningful response (Figure S12). The sign of response is negative and its magnitude consistently decreases as the applied strain increases: the responses to 100 ppm of H₂ are calculated to be −8.0, −5.5, and −4.0% for zero, 40, and 80% strains. Upon absorbing H₂ molecules, PdNPs dissociate them into the H atom and form PdH above a critical H concentration. As a consequence, their volume expands, leading to a drop in contact resistance between neighboring Pd–ZnO NRs.^{30,33,34} As schematically presented in Figure S13a, this contact resistance drop will finally decrease the sensor resistance. The consistent response decrease with increasing strain may be attributed to the strain-dependent reduction in junction density between Pd–ZnO NRs and AgNWs. Figure 5b shows the response curves to NH₃ gas under various tensile strains. Over the tested strain range (0–100%), the response curves of the fabric gas sensor are almost superposed, further supporting its superb adaptability to the external strains. Unlike NO₂ gas, reducing NH₃ molecules donate electrons to rGO sheets, leading to the lowering of hole concentration of rGO and the consequential increase of the sensor resistance (Figure S13b). This is why the FS-2 shows positive responses on the exposure to NH₃ gas.^{35,36} The strain-dependent response curves to CO gas are displayed in Figure 5c. Negative response signals are observed for all the test concentrations (10–100 ppm) and applied strains (0–100%), although their magnitude is small and recovery is immature. CO gas, which is reducing similar to NH₃, may transfer electrons preferably to ZnO NRs,³⁷ resulting in the increase of electron concentration and the decrease of sensor resistance. Figure 5d summarizes the aforementioned observations. It is obvious that the fabric gas sensor can detect all the target gases even under large strains up to 100%, and the magnitude of response strongly depends on the type of gas.

Decoration of the Nanocomposite on a Large-Area Fabric. A large-sized fabric gas sensor may be necessary to detect dangerous gases more sensitively, and uniform decoration of rGO/Pd–ZnO NRs/AgNWs nanocomposite on a large-area fabric is the key for it. We demonstrated the uniform coating of the nanocomposite on a fabric of size 15 cm × 10 cm by employing the sequential coating method. The stepwise color and resistance changes from initial fabric to the final nanocomposite-coated fabric can be found in Figure S14. Next, the sample was segmented into 150 sectors of 1 cm × 1 cm size, and the sheet resistance was measured on every sector (Figure S15). From the numerical values and graphical distribution of sheet resistances (Figure S16b), it is seen that the sheet resistance is generally uniform, indicating the uniform distribution of the nanocomposite. The average sheet resistance was measured at 20.6 kΩ·sq^{−1}. In addition, the NO₂-sensing signals of fabric gas sensors sampled from different locations, which resemble those of FS-2 at both unstrained and 40%-strained states (Figure S16c,d), further support that the sequential coating method developed in this work can be utilized for scaling up the fabric gas sensor to an arbitrary size on demand.

CONCLUSIONS

In conclusion, highly deformable gas sensors were fabricated by integrating multidimensional nanostructures on fabric, which was severed from a real T-shirt. A variety of nanostructures such as rGO, ZnO NRs, PdNPs, and AgNWs were integrated into the nanocomposite by a sequential coating method. It was found that rGO flakes wrapped well around the textile strands, and Pd–ZnO NRs and AgNWs were uniformly distributed over the rGO layer. The fabric gas sensor with optimized densities of nanostructures showed clear response signals to multiple oxidizing and reducing gases such as NO₂, H₂, NH₃, and CO at RT. Most notably, it was demonstrated that the fabric gas sensor could well-function under large strains up to 100%, which is the highest tolerable strain ever reported on gas sensors. Moreover, the fabric gas sensor could normally work at bent and twisted states. Furthermore, it was manifested that the sequential coating method developed in this work could be applied for the fabrication of a large-sized fabric gas sensor. These results suggest that the fabric gas sensor can be a practical option to realize a highly strain-endurable and wearable gas sensor.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acssensors.0c01083>.

Photographs of a real T-shirt and samples severed from it; schematic fabrication process; gas-sensing setup; SEM images of structural components; sensor resistance depending on the weight fraction of AgNWs; rupturing strain of the fabric gas sensor; resistance plots of NO₂ responses; photographs of bending and twisting tests; humidity test results; strain-adapting mechanism; H₂ response under a 100% strain; mechanisms for sensing H₂ and NH₃ and; photograph, area-segmenting chart, and NO₂ response of a large-sized fabric gas sensor (PDF)

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Notes

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