# Ultrasensitive Detection of Volatile Organic Compounds by a Freestanding Aligned Ag/CdSe-CdS/PMMA Texture with Double-Side UV–Ozone Treatment

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ABSTRACT: Volatile organic compounds (VOCs) are organic chemicals having a high vapor pressure at room temperature. Chronic exposure to VOC vapor can be potentially dangerous to human health. In this study, we build a high-performance freestanding aligned Ag/CdSe-CdS/poly(methyl methacrylate) (PMMA) texture to detect VOC vapors. The insight of this new VOC-sensing material is based on electrospinning techniques, ultraviolet (UV)/ozone treatments, and nano-optics. The incorporation of CdSe-CdS core-shell quantum rods (QR) and silver nanocrystals in the PMMA nanofibers amplifies the polarization response of long rods in VOC detection, thus increasing the sensitivity of VOC-sensing materials. Further, the uniaxial aligned Ag/QR/PMMA sensing material was treated by UV-ozone etching to increase surface absorption. The advanced double-sided UV-ozone etching on the uniaxial aligned Ag/QR/PMMA efficiently enhanced the extinction changes of VOCs. Two categories of solvents, typical VOCs and alcoholic VOCs, were put into practical tests for the Ag/QR/PMMA VOC-sensing materials. The Ag/QR/PMMA reached the detection limit for 100 ppm butanol within 1 min. The freestanding aligned Ag/CdSe–CdS/PMMA texture is a newly designed nanocomposite device for environmental risk monitoring. It can be accepted by the market compared to the other highly sensitive commercial VOC-sensing materials.

KEYWORDS: volatile organic compounds, sensing materials, quantum rods, nanocomposite, electrospinning, surface plasmon resonance

# ■ INTRODUCTION

Daily exposure to volatile organic compounds (VOCs) has serious harmful effects including a wide range of sensory irritations and chronic diseases, such as nervous system impairment, asthma, and cancer.<sup>1-4</sup> On the other hand, severe injuries and deaths can occur in the gas explosion and consequent fire when the VOC concentration reaches above the lowest explosion limit (LEL) in air.<sup>5</sup> Therefore, the ability to

monitor VOCs and to deliver alarm messages in the very early stage becomes important for modern society, especially in chemical factory management. To guard our homeland and eliminate accidental factors, a gas sensor needs to be developed

Received: July 14, 2019 Accepted: August 21, 2019 Published: August 21, 2019 urgently as a precaution tool. High-performance VOC sensors should be highly sensitive, highly reproducible, and able to detect in real time.  $^{6-14}$ 

To obtain a highly sensitive VOC sensor, considerable attention has been directed toward the development of VOCsensitive materials. Various VOC-sensing materials have been developed, such as conjugating polymers<sup>15-17</sup> and organic/ inorganic composites.<sup>18-21</sup> Recently, acoustic and optical VOC sensors have attracted a lot of attention owing to their characteristics of easy fabrication, economic cost, and rapid response.<sup>22,23</sup> It has been noted that the sensitivity enhancement in three-dimensional structural materials is due to their high surface-to-volume ratio and the combination of conjugated polymers with quantum nanomaterials.<sup>22</sup> To fabricate a device with a high surface-to-volume ratio, the electrospun technique is a facile and quick process to make functional nanostructures or submicron-sized structures. The precursor solution is subjected to a high voltage during the electrospinning process. When reaching the critical voltage, the electrostatic repulsion overcomes the surface tension, and a Taylor cone is formed. A liquid jet erupts from the droplet from the surface as nanofibers or submicron fibers.<sup>24–27</sup> By alternating voltage, we can effectively tailor the surface chemistry of fibers. The electrospun fibers are important platforms to study the physicochemical interaction of ordered nanorods. The system provides a fundamental understanding of the engineering design and the manufacture of useful devices.28 <sup>-32</sup> Besides, ultraviolet (UV)/ozone treatment is a highly effective cleaning procedure to remove a variety of contaminants from surfaces.<sup>33-36</sup> It is another method widely applied to modify the surface. During the UV-ozone etching treatment, the reaction between ultraviolet light and O2 forms hydroxyl radical  $(OH^{\bullet})$  and ozone  $(O_3)$  with a strong oxidizing ability. Both OH<sup>•</sup> and O<sub>3</sub> further react with organic compounds on the surface and result in an increased surface area for the increment of surface absorption.<sup>37,38</sup>

The surface electrons of nanoparticles can be excited by the incident optical light to exhibit the phenomenon of surface plasmonic polarization, called surface plasmon resonance (SPR). The SPR was dependent on the periodic metallic nanostructures, particle shapes, and size distributions.<sup>39–44</sup> The nonpropagating excitations of the conduction electrons of metallic nanoparticles coupled to the the electromagnetic field result in effective energy transfer from the dipole into the SPR. Silver nanoparticles (Ag NPs) possess a superior SPR performance in the visible range, resulting in a dramatically enhanced light absorption, thus increasing the sensitivity of the gas sensor.<sup>45,46</sup> Furthermore, the metallic interfaces also play complex roles in the basic interactions of an electromagnetic field with optically active materials. CdSe-CdS quantum rods (QRs) can be incorporated into optical sensors, taking advantage of their tunable sizes, high photochemical stability, high quantum yields, and broad absorption range.<sup>20,47-5</sup> During photoexcitation, CdSe-CdS QRs are capable of directional emission of linearly polarized light. It is noteworthy that the aligned quantum rods can be better indicators of gas sensors because of the polarized light emitted by the anisotropic nanocrystals along their crystal long axis.<sup>20,54</sup> The photoluminescence (PL) of quantum rods incorporated into polymer materials responds reversibly and rapidly to environmental changes. Having CdSe-CdS QRs embedded in the orderedarrangement fibers not only greatly increases the light absorption of the sensing material but also provides light polarization toward light scattering.

Herein, using the electrospinning technique, we successfully prepared a hybrid material consisting of CdSe–CdS QRs, Ag NPs, and poly(methyl methacrylate) (PMMA). CdSe–CdS QRs produced unique optical properties for VOC sensing in a particular rod length and diameter distribution. The freestanding Ag/QR/PMMA texture was deposited onto a metal frame substrate and functionalized as a VOC-sensing material. The correlation between the sensitivity and UV–ozone etching treatment on the freestanding Ag/QR/PMMA texture sensing material was investigated to understand the modulation of VOC sensitivity. The polarized light response from CdSe/CdS QRs with respect to various VOC concentrations was explained in detail for the development of real-time reliable high-performance VOC sensors.

#### EXPERIMENTAL METHODS

Preparation of Freestanding Ag/QR/PMMA Sensing Materials. First, Ag NPs were synthesized according to the description from the Lakshminarayana Polavarapu research team.<sup>55</sup> In 50 mL of chlorobenzene, 0.6 mmol of silver nitrate (AgNO<sub>3</sub>) and 6 mmol of oleylamine were dissolved. The mixture was placed in a four-necked flask and heated directly to 120 °C under continuous nitrogen purge for 1 h. The apparatus was then cooled naturally to room temperature (Figure S1).<sup>56</sup> Semiconductor CdSe/CdS core-shell QRs were synthesized according to the synthetic routes published elsewhere in the literature.<sup>48,57,58</sup> Then, 1.0 wt % CdSe/CdS QR solution, 1.0 wt % Ag NP solution, and 27.0 wt % PMMA were added together as a Ag/ QR/PMMA precursor solution.<sup>20</sup> The Ag/QR/PMMA precursor solution was stirred for 24 h. Then, the Ag/QR/PMMA nanofibers were made using the electrospinning technique from the precursor solution in the previous process. The electrospun fibers are deposited onto the top of the metal frame substrate  $(1.00 \text{ cm} \times 1.25 \text{ cm})$  to form a freestanding Ag/QR/PMMA sensing device. The optimized electrospun parameters in the operation were an applied voltage of 10.0-25.0 kV, a working distance of 10.0 cm, a flow rate of 0.5 mL/h, a solution volume of 1.5 mL, and a receiving plate speed of 500 rpm.

Surface Treatment of Freestanding Ag/QR/PMMA Sensing Materials. To increase the sensitivity, the as-prepared freestanding Ag/QR/PMMA sensing material was subjected to UV-ozone etching for further treatment on the Ag/QR/PMMA surface. Two different 30 min procedures were applied to modify the surface of the sensing material. In the first procedure, the freestanding Ag/QR/PMMA sensing material was etched for 30 min only on one side. In the second procedure, the freestanding Ag/QR/PMMA sensing material was etched for 15 min on one side followed by another 15 min on the other side. It has been suggested that the longer the UV-ozone etching time on one side, the more enriched specific surface that it becomes. Furthermore, the enlarged UV-ozone-etched surface area magnified the enhanced sensing signal. The use of this technique allowed us to increase the specific surface area on the freestanding Ag/QR/PMMA sensing materials.

Optical Measurement (Extinction Spectrum). The VOCs were injected into a quartz glass container of 4.5 cm length, 4.0 cm width, and 4.5 cm height. After the volatile organic solvent was totally volatilized in the container, the freestanding Ag/QR/PMMA sensing material was placed in the middle of the container. Then, measurements for the extinction spectrum were performed immediately. The schematic of the as-prepared sensing material and the procedure for extinction spectra measurement are shown in Figure S2. Several volatile organics of alcohols (1-propanol, 1-butanol), aromatic organic solvents (toluene, chlorobenzene), and esters (ethyl acetate, propyl acetate) were used in the measurements of extinction. The maximum extinction change ( $\Delta E$ ) of the peak is determined as the sensitivity for a particular VOC. Since the freestanding Ag/QR/PMMA sensing material encounters volatile organic gas, the surface of the PMMA fibers rapidly absorbs it. The absorption behavior of the sensing material results in a variety of extinction intensities. Therefore, the extinction change ( $\Delta E$ ) of the peak is defined by the extinction before and after the VOC sensing.



Figure 1. (a) TEM image and its diffraction pattern, (b) UV-vis absorption spectrum and PL spectrum, and (c) particle size distribution of CdSe-CdS QRs. (d) TEM image and its diffraction pattern, (e) UV-vis absorption spectrum, and (f) particle size distribution of Ag NPs.



Figure 2. (a) SEM images of Ag/QR/PMMA nanofibers with cavities on the surface. (b) TEM image of the Ag/QR/PMMA nanofibers with embedded CdSe-CdS QRs and Ag NPs.

The extinction formula is defined as follows

 $\Delta E = E_{\rm t} - E_{\rm t_0}$ 

where  $E_{t_0}$  represents the extinction intensity of the peak before the experiment and  $E_t$  represents the extinction intensity of the peak after the experiment of VOC detection.<sup>7</sup>

# RESULTS AND DISCUSSION

Characterization of CdSe–CdS Quantum Rods and Ag NPs. The microstructure image of CdSe–CdS core–shell QRs is shown in Figure 1a. The CdSe–CdS material appears to have individual rods that are ~20.0 nm in length and ~5.0 nm in diameter. Its size distribution is uniform, resulting in an aspect ratio of ~4.0 as shown in Figure 1c. The spherical CdSe core is most often located closer to one end across the rod length of CdS. This asymmetric core—shell configuration leads to a partial charge separation following photoexcitation and gives a narrow emission band.<sup>59</sup> In the inset of Figure 1a, the diffraction pattern of CdSe—CdS QRs shows two diffraction planes of (1110) and (0002) indicating the CdSe core and CdS shell, respectively. The UV—vis absorption analysis presents a bandgap of 2.56 eV as shown in Figure 1b. The PL spectrum indicates the emission

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peak at 630 nm. Because of the described excellent optical properties, semiconductor CdSe–CdS QRs were added into the sensing material for light harvesting. Ag NPs were used as the dopants to enhance the detection limit of the sensing material from surface plasmon resonances. The transmission electron microscopy (TEM) image showing the sizes of the synthesized Ag NPs is depicted in Figure 1d. Figure 1f shows the particle size distribution of synthetic Ag NPs with an average diameter of 7.1 nm. Figure 1e depicts the absorption spectrum of the synthesized Ag NPs with the absorption peak at around 410 nm. Surface plasmonic Ag NPs and semiconductor CdSe–CdS QRs were added into the PMMA polymer solution as a nanocomposite to enrich the sensitivity of the VOC-sensing material.

Morphology of Ag/QR/PMMA Nanofibers. To regulate the diameter of the PMMA nanofiber material, we carefully adjust the applied voltage of the electrospinning procedure. When the voltage was set at 10 kV, the as-formed fiber was coarse, and the fiber diameter distribution was not uniform as observed under the optical microscope (Figure S3a). At 15 kV, the fibers were slightly thinner, but the fiber diameter distribution was still not uniform (Figure S3b). From Figure S3c, the diameter of the fibers was gradually reduced and the distribution was uniform at 20 kV. Finally, at 25 kV, the diameter of the fibers became thicker and less uniform (Figure S3d). The fiber diameter distribution is shown in Figure S3e. A comprehensive comparison shows the best applied voltage at 20 kV. The fiber diameter distribution is relatively uniform and the fiber diameter is slim for advanced experimental studies. In the scanning electron microscope (SEM) image of Figure 2a, it is observed that the surface of Ag/QR/PMMA nanofibers presents various round cavities. We suggest that the irregular orientation of cavities on electrospun fibers had resulted from the evaporation of chlorobenzene in the electrospinning process. Interestingly, the cavities on electrospun fibers increase the specific surface area for VOC absorption and enhance the sensitivity of VOC-sensing materials. Thus, VOCs can easily swell the Ag/QR/PMMA nanofibers.<sup>60</sup> It is worth mentioning that the process of electrostatic spinning caused the CdSe-CdS QRs and Ag NPs to be directed toward the center of the PMMA nanofibers (Figure 2b).

The freestanding Ag/QR/PMMA sensing materials were used to conduct the photoluminescence experiments. It was found that the freestanding Ag/QR/PMMA sensing materials produce enhanced polarized light emission at the position of 90 and 270° (Figure 3) in the measurement. We reasonably propose that the rod-like CdSe–CdS QRs preferred to align vertically with respect to the PMMA nanofibers. This resulted in the shrinkage of PMMA nanofibers upon solvent evaporation.



**Figure 3.** Polarization effect on photoluminescence spectra of the freestanding Ag/QR/PMMA sensing materials.

The flow of solvent evaporation promoted the rod arrangement of CdSe–CdS QRs in the center of the fiber.

Etching on the Freestanding Ag/QR/PMMA Sensing Materials. To increase the specific surface area of the freestanding Ag/QR/PMMA sensing materials, we etched the specimen's surface with UV-ozone in three ways: 30 min singlesided etching, 15 min double-sided etching, and 30 min doublesided etching. It is noteworthy to observe the difference between the single-sided etching and the double-sided etching on the freestanding Ag/QR/PMMA sensing materials. From the SEM images (Figure 4), the surface area of the freestanding Ag/QR/ PMMA sensing materials gradually eroded as the etching time increased. For the sample with the 30 min single-sided etching, the morphology of the fiber changed slightly as shown in Figure 4b. When the sample was double-side etched for 15 min, the specific surface of the fiber was enriched as shown in Figure 4c. When the double-side etching time reached 30 min (Figure 4d), the morphology of the fiber was heavily etched. It is noted that extending the etching time only increased the depth of the etching cavities, but not the area of the surface treatment. We infer that the sensitivity of the sensing material is related to the specific surface area of the Ag/QR/PMMA nanofiber. The double-sided etching would generate the second surfacemodified plane to increase the specific surface area, thus making the sensitivity of the freestanding Ag/QR/PMMA sensing materials better than that of the single-side etched ones. It would be more responsive to VOC detection.

Benefit of the Surface Treatment. The freestanding Ag/ QR/PMMA sensing material was placed in a quartz vessel and was exposed to a concentration of 10 000 ppm chlorobenzene vapor for 120 min. A UV-vis spectrometer was applied to identify its extinction intensity. As shown in Figure S4a, the nonetched freestanding Ag/QR/PMMA sensing material had similar extinction spectra on the exposure to chlorobenzene. The extinction variation was small for the 30 min single-sideetched freestanding Ag/QR/PMMA sensing material (Figure S4b). The extinction change was quite noticable for the 15 min double-side-etched freestanding Ag/QR/PMMA sensing material (Figure S4c). However, for the 30 min double-side-etched freestanding Ag/QR/PMMA sensing material, the electrospun fibers had been eroded too much, resulting in a higher light transmittance (Figure S4d). The related specific surface area of various surface-treated Ag/QR/PMMA sensing materials were studied by the Brunauer-Emmett-Teller (BET) and Barrett-Joyner-Halenda methods, as shown in Table S1. For the 15 min double-side-etched Ag/QR/PMMA sensing materials, the BET surface area has increased compared to that of the nonetched ones. However, the BET surface area of the 30 min single-sideetched Ag/QR/PMMA sensing materials decreased dramatically. This is attributed to the huge deformation of the electrospun fibers. The data are in support of the previous morphological observation shown in Figure 4 that the diameter of the electrospun fibers increased as the etching time prolonged. We suggest that the over-etched fibers were too fragile to maintain their shape and easily reacted with VOCs, resulting in reduced sensitivity. To keep the sensitivity, we selected the 15 min double-side-etched sensing materials for their structural stability and good sensing response in the subsequent detection of VOCs (Figure 5).

**Effect of Polarization.** To investigate the effect of polarization, we repeated the 10 000 ppm chlorobenzene extinction change experiment, rotating the freestanding Ag/QR/PMMA sensing materials 30° counterclockwise each time.



Figure 4. SEM images of Ag/QR/PMMA fibers with UV-ozone etching: (a) nonetched, (b) 30 min single-side etched, (c) 15 min double-side etched, and (d) 30 min double-side etched.



Figure 5. Extinction changes of nonetched, 30 min single-side-etched, 15 min double-side-etched, and 30 min double-side-etched free-standing Ag/QR/PMMA sensing materials exposed to 10 000 ppm chlorobenzene.

Schematic diagrams of the freestanding Ag/QR/PMMA sensing materials rotating in a counterclockwise direction are shown in Figure S5. It was found that the optical signal of extinction change had the strongest response at 90 and  $270^{\circ}$  in each VOC exposure time (Figure 6). The stronger response of the



**Figure 6.** Extinction changes of the freestanding Ag/QR/PMMA sensing materials exposed to 10 000 ppm chlorobenzene at various polarization angles with respect to various exposure times.

freestanding Ag/QR/PMMA sensing materials is a reliable indicator to detect the VOCs in the environment. Herein, the mechanism of polarization for the Ag/QR/PMMA sensing material could be speculated as follows. When the linearly polarized light passed through the horizontally aligned QR, the penetration depth increased, improving the absorption of the aligned QRs. This was attributed to dichroism and then the amplification of the PL emission and optical extinction. The enhanced extinction was changed due to the fiber deformation. Therefore, the extinction change might be directly increased in each VOC exposure time.

Detection Limit and Response Time for Different VOCs. The lowest explosion limit (LEL) is the minimum concentration of a VOC vapor that is capable of producing an explosion in the air. A series of legal thresholds of various countries are listed in Table S2. For practical application, VOC vapor needs to be detected much below the LEL. The detection limit should be comprehensively investigated to identify the possibility of practical use. The response of extinction changes toward various concentrations of various VOC atmospheres is presented in Figure 7. A control experiment using water simulates the moisture in the background (i.e., air) and is used as a relative reference to avoid detection mistakes. Since the maximum extinction change of water is 0.013, the value of 0.015 was used as a standard reference to screen noise/background. When the detected value exceeded 0.015, it was considered as a true/reasonable detection signal and the response time can be defined in this moment. The common alcoholic solvents, 1propanol and 1-butanol, were first used to test the sensing experiments under a high VOC concentration at 10 000 ppm. The result from 1-butanol and 1-propanol testing showed excellent extinction differentiation. Further, 10 000 ppm ester atmospheres, 1-propyl acetate and ethyl acetate, were used in the measurement of extinction differentiation. It is noted that the freestanding Ag/QR/PMMA sensing materials were more sensitive to the VOCs with a long alkoxyl chain length. Lastly,



**Figure 7.** Extinction changes of the freestanding Ag/QR/PMMA sensing materials exposed to various concentrations of (a) toluene, (b) chlorobenzene, (c) ethyl acetate, (d) 1-propyl acetate, (e) 1-propanol, and (f) 1-butanol.

10 000 ppm of the aromatic VOCs, toluene and chlorobenzene, were put to the sensitivity test of the freestanding Ag/QR/PMMA sensing materials. The Ag/QR/PMMA exhibited a better sensitivity in chlorobenzene than in toluene at the same time interval. The response time is summarized in Table 1. It

Table 1. Response Time of the Freestanding Ag/QR/PMMA Sensing Materials when Exposed to Various VOC Concentrations

VOCs	concentration (ppm)	response time (min)
toluene	10 000	<16
	1000	<30
	100	<100
chlorobenzene	10 000	<2
	1000	<2
	100	<28
ethyl acetate	10 000	<4
	1000	<8
	100	<90
1-propyl acetate	10 000	<2
	1000	<4
	100	<10
1-propanol	10 000	<1
	1000	<1
	100	<2
1-butanol	10 000	<1
	1000	<1
	100	<1

shows that the freestanding Ag/QR/PMMA sensing materials have superior sensitivity for the detection of alcoholic solvents. Herein, we proposed the possible mechanism in the general VOC response, which can be divided into three stages. In the first stage, VOC retention on the sensing material was induced by a molecular interaction force. Secondary bonding, including hydrogen bonding and polar mole-induced dipole bonding, arose when the alcohols, esters, and aromatics faced toward PMMA fibers. Basically, the force of hydrogen bonding is stronger than that of other polar-induced dipole bondings. It can be predicted that alcohols and esters were retained on PMMA fibers easily. Subsequently, the VOC adsorption and condensation becomes an important factor. The adsorption rate depends on the condensation of VOCs, indicating that the boiling point should directly influence the adsorption properties. After intense adsorption, swelling and dissolution occurred on the PMMA fiber, and it is related to the solubility parameter. In this case, PMMA etched by UV ozone treatment would be linked with lots of hydroxide groups, and its solubility parameter might be increased due to the approximation based on the analytical solution of the group contribution method. We found that the solubility parameters of 1-propanol and 1-butanol are similar to that of PMMA. Thus, it indicated that the hierarchical structure of PMMA fibers collapsed dramatically. Meanwhile, it is important to know that the noticeable extinction changes occurred within 1 min, even when the freestanding Ag/QR/ PMMA sensing materials were exposed to a 100 ppm 1-butanol atmosphere. On the other hand, we studied the recyclability and repeatability of Ag/QR/PMMA sensing materials that have been exposed to VOCs (Figure S7). The recyclability test showed undesirable recyclability due to dramatic deformation of fibers after exposure to VOCs. Even at a VOC concentration below 100 ppm, irreversible deformation was occurring and the related  $\Delta E$  decreased below the response threshold. However, the repeatability of 1-butanol detection revealed few deviations in the extinction change curve, representing the high reliability of Ag/QR/PMMA sensing materials by using the developed technique. The error bars and box chart of the extinction change for the Ag/QR/PMMA sensing material under each exposing concentration calculated by 10 tests are shown in Figure S8. Thus, the unique performance of this sensing material, including high sensitivity, real-time detection, room-temperature operation, and low-cost, is still remarkable. Compared to previous literature (Table 2), the Ag/QR/PMMA sensing material can rapidly detect specific VOCs, including 1-propanol and 1butanol, within 1 min at room temperature. Besides, the easy measurement by a UV-vis spectrometer in the visible region implies the great potential in practical development. The Ag/ QR/PMMA sensing material might be regarded as a disposable sensing chip and can be used for practical applications.

#### CONCLUSIONS

In this study, freestanding aligned Ag/CdSe-CdS/PMMA texture sensing materials were successfully fabricated by using the electrospinning technology, enhanced by the knowledge of surface plasmonic resonance and the polarization of semiconducting quantum nanorods. Metal frame substrates were double-side etched for 15 min using the UV-ozone etching technique. A higher specific surface area was successfully obtained on the freestanding Ag/QR/PMMA sensing material, enabling an advanced VOC-sensing efficiency. The freestanding Ag/QR/PMMA sensing material has the characteristics of polarization at 90 and 270°. When exposed to visible light, it amplifies extinction changes to a significantly sensitive level for the detection of various VOCs. Moreover, the freestanding Ag/ QR/PMMA sensing material exposed to a high concentration of 10 000 ppm of volatile organic gases, alcohols, esters, and aromatics can detect them instantly. The results also showed that even at a low concentration of 100 ppm, 1-butanol can still be detected within 1 min.

Table 2.	Comparison of the	Performance of V	Various Type	s of VOC Sensors	Toward Several	Common	VOCs
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sensor type	VOCs	detection limit (ppm)	response time (min)	operation temperature	refs
resistant	ethanol	10 000	3	RT	61
	acetone	0.005	6	300 °C	62
	ethanol	0.001	0.45	300 °C	63
fiberoptic Fabry–Perot interferometric (FFPI)	ethanol	0.74	N/A	RT	64
	acetone	0.93	N/A		
quartz crystal microbalance (QCM)	ethanol	100	10	60 °C	12
	acetone				
	toluene				
	1-octane				
optical	toluene	500	20	RT	7
	acetone	44	N/A	RT	65
	1-propanol	100	<2	RT	this work
	1-butanol	100	<1		

# ASSOCIATED CONTENT

# **Supporting Information**

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.9b12333.

BET surface area, pore size, and pore volume; summarized permissible limits; preparation of the electrospinning precursor solution; sensing material and VOC detection; optical microscopy images and diameter distribution; extinction spectra; rotation angles; etching methods; recyclability and repeatability (Figures S1–S8; Tables S1 and S2) (PDF)

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#### Notes

The authors declare no competing financial interest.

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