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Investigation of humidity cross-interference effect on acetone breath sensor based on nanostructured $K_2W_7O_{22}$

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ABSTRACT

Volatile organic compounds (VOCs) can be collected from a human body. They are gases existing in exhaled breath which can be used as biomarkers to diagnose several kinds of disease. The key advantages of this technique are it is noninvasive and has a high potential for portable devices. However, human breath usually contains very high relative humidity (85-95%, RH), and it could be one of biggest challenges for a breath sensor to sensitively detect biomarkers, in particular, at room temperature. A novel nanostructured $K_2W_7O_{22}$ was recently developed and tested on acetone detection, the biomarker of diabetes. Our study finds that nanostructured $K_2W_7O_{22}$ shows much more sensitive to acetone but less sensitive to humidity. This material exhibits less cross-interference effect from humidity and makes the acetone sensor even more durable and stable under such a high RH condition. The study can improve the understanding of the sensing mechanism based on this new material, and thus give ideas for further increasing the sensitivity for acetone detection. Eventually this will result in an advanced material capable to analyze acetone in the exhaled breath for disease diagnosis and monitoring purposes.

KEY WORDS: Biomarkers; Acetone; Diabetes; Nanostructured $K_2W_7O_{22}$; Relative humidity.

ABBREVIATIONS: VOCs: Volatile Organic Compounds; BG: Blood Glucose; GC-MS: Gas Chromatography-Mass Spectrometry; SIFT-MS: Selected Ion Flow Tube Mass spectrometry; PTR-MS: Proton Transfer Reaction Mass Spectrometry; HPLC: High-Performance Liquid Chromatography; IMS: Ion Mobility Spectrometry; CRDS: Cavity Ringdown Spectroscopy.

INTRODUCTION

Human breath contains a number of volatile organic compounds (VOCs). These compounds contain a lot of useful information related to a human's health condition and diseases. Therefore, breath VOCs can be used as biomarkers to provide essential information for disease diagnosis and monitoring. For example, acetone (CH_3COCH_3) can be used to evaluate diabetes,[1,2] toluene ($C_6H_5CH_3$) is the biomarker to evaluate lung cancer.[3] Compared with other traditional methods, such as blood and urine tests, a breath analyzer or a sensor as a tool of disease diagnosis and monitoring has acquired a lot of attention due to its unique advantages. It is non-invasive, simple to operate, harmless, and very convenient in clinical and personal settings. With rapid development of nanotechnology, semiconducting nanomaterials show promising properties in application of portable sensor devices. It makes devices with simple fabrication easily minimized into portable devices. In this paper, we introduce a breath analyzer to detect trace concentrations of acetone in exhaled breath using novel nanostructured $K_2W_7O_{22}$ (KWO).

Diabetes is a chronic disease associated with abnormally high levels of blood glucose (BG) which can lead to many complications such as blindness, kidney failure, nerve damage, and even death.[4] Since early in 1969, Tassopoulos C.N. et al found that breath-acetone and blood sugar have a certain relationship.[5] Further studies have proved that the high blood glucose can result in a change of concentration of acetone in exhaled breath *via* a human's metabolic process.[6,7] This makes acetone in breath a good biomarker for diagnosing diabetes.[8] There are many traditional methods for analyzing the concentration of acetone in exhaled breath, such as gas chromatography-mass spectrometry (GC-MS),[9,10] Selected Ion Flow Tube Mass spectrometry (SIFT-MS),[11] proton transfer reaction mass spectrometry (PTR-MS),[12] high-performance liquid chromatography (HPLC),[13] ion mobility spectrometry (IMS),[14,15] laser spectroscopic techniques including diode laser absorption spectroscopy (TDLAS),[16] cavity ringdown spectroscopy (CRDS)[17] and electronic noses (e-noses).[8] Although, those techniques have relatively high sensitivity and can accurately detect tracing acetone concentration from human breath, they need sophisticated instrument such as vacuum system, inner gas tank, mass spectrometer, laser system etc. Also, those technologies are expensive and unable to be done at home.[18] While, nanostructured semiconductor materials based sensor devices have acquired a lot of attention during recent years due to the promise of low cost, portability, sensitivity, and ease of fabrication. Among many nanostructured materials, our study found that the newly synthetically created material, $K_2W_7O_{22}$, has good response to acetone, that is, showing good sensitivity under realistic breath conditions at room temperature.[19] The primary results show that the good response of acetone on $K_2W_7O_{22}$ is due to the unique properties of $K_2W_7O_2$ such as a good room-temperature ferroelectric property, and a high capability of charge transfer. Also, this material is environmentally friendly. However, there are many factors, such as surface characteristics, temperature, and humidity, which can influence the sensor properties. Humidity is one of important factors to cause potential problems for sensors made by semiconducting materials. Human breath contains very high concentration of water vapor (relative humidity (RH) in breath up to ~90%), which always varies to the conditions of individuals, such as diet, and metabolism. Therefore, a breath sensor should be stable, reliable, and less sensitive to humidity but have high sensitivity to breath biomarkers. In this paper, we studied the water vapor effect on $K_2W_7O_{22}$ to detect acetone at room temperature. We found that the $K_2W_7O_{22}$ nanorods show much less response to water vapor even if relative humidity is high. At 80% RH $K_2W_7O_{22}$ nanorods keep a very sensitive response to a low concentration of acetone.

MATERIAL SYNTHESIS AND EXPERIMENTS

In this part, we briefly describe the synthesis of $K_2W_7O_{22}$ nanorods, sensor sample fabrication, and equipment and procedures used to test nanorods for chemiresistive responses that are presented. Sensing responses of $K_2W_7O_{22}$ nanorods to water vapor with a varied concentration, to acetone with mixing different relative humidity, were measured. A series of experiments were designed to test for comparing the selectivity of $K_2W_7O_{22}$ to acetone, ethanol, and water vapor, the major components in breath.

Material synthesis and characterization

Single crystalline $K_2W_7O_{22}$ nanorods were synthesized using the hydrothermal method described in earlier report.[20] Briefly, it uses a precursor solution containing Na_2WO_4, oxalic acid, K_2SO_4, and HCl. The composition of this material has been analyzed with XPS, revealing that the atom ratio of K:W:O is 2:7:22. A Joel JSM-7000F scanning electron microscope (SEM) was used to characterize the morphology of $K_2W_7O_{22}$, which is made of nanorods as shown in Figure 1(a). An X-ray diffraction (XRD) pattern of "as-synthesized" $K_2W_7O_{22}$ nanorods was obtained with a Bruker F8 Focus Power XRD which confirmed the crystal structure in Figure 1(b).

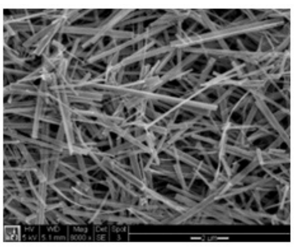
Generation of analyte vapors

Acetone vapor with different concentrations at room temperature from 0 ppm to 50 ppm was generated by mixing pure acetone gas in dry nitrogen (N_2) at different ratios. Different concentrations of water vapor (or relative humidity, RH) is obtained by diluting the saturated water vapor with dry air at a specific ratio. The resistance change and response time of the sample is determined by measuring its resistance between two metal (Titanium, Ti) contacts with an electrometer (Keithley 6514) when the gas applied to the thin film sample is cycled between pure air and air with analyte vapors, as shown in Figure 2.

EXPERIMENTAL RESULTS AND DISCUSSION

In our previous paper[20] we found a novel nanomaterial, $K_2W_7O_{22}$ nanorods, which can sensitively detect the concentration of ace-

a



b

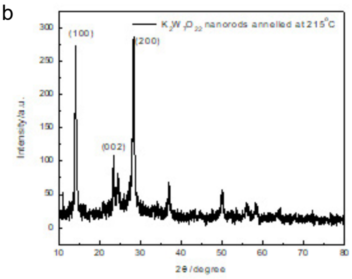


Figure 1: (a) SEM images of $K_2W_7O_{22}$ nanorods synthesized at 215°C. (b) XRD pattern of synthesized $K_2W_7O_{22}$ nanorods at 215°C.

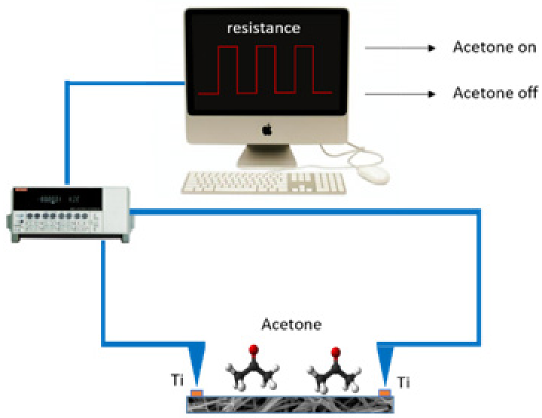


Figure 2: Chemiresistive sensor testing system.

tone vapors as low as 1.2 parts-per-million (ppm) which is lower than the 1.7 ppm threshold for detecting diabetes under relative humidity (RH) around 30% at room temperature. Considering realistic breath conditions, the concentration of water vapor in exhaled breath is generally quite high, up to 90%. The relative humidity in breath is varied due to diet, health condition, and personal daily activities. On the other hand, humidity is also an important factor to influence the sensing performance of semiconducting materials as gas sensors. So, we need to check $K_2W_7O_{22}$ nanorods if it can maintain the reliable and sensitive response to acetone under varied humidity in the environment, and high RH up to 80%. We studied the sensor performance to acetone gas based on varying relative humidity (RH). Interestingly, as shown in Figure 3, compared to the case of room RH level (30%), the nanostructured $K_2W_7O_{22}$-based acetone sensor worked even better when the RH was as high as 80% and the detection of acetone with a concentration as low as 1.2 ppm at room RH level. On the other hand, we tested $K_2W_7O_{22}$ nanorods response to different concentration of water vapor by controlling the relative humidity in the system. The results in Table 1 confirm that the response of $K_2W_7O_{22}$ nanorods to water vapor keeps constant while the relative humidity is changed from 10% to 80%. (Figure 4) presents that $K_2W_7O_{22}$ nanorods even show less sensitivity to high concentrations of water vapor when the relative humidity is up to 80%. These all mean that the performance of $K_2W_7O_{22}$ nanorods is not affected by relative humidity.

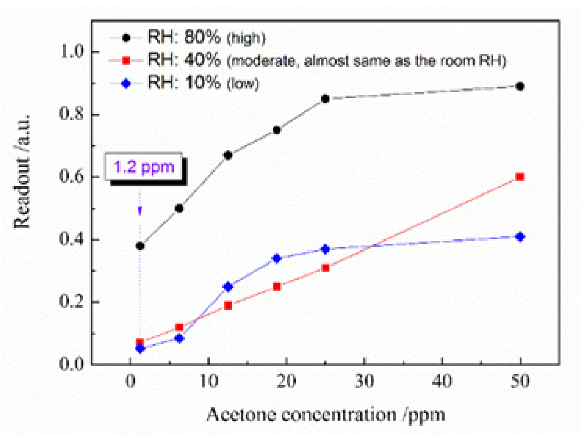


Figure 3: Sensor performance under different RH levels.

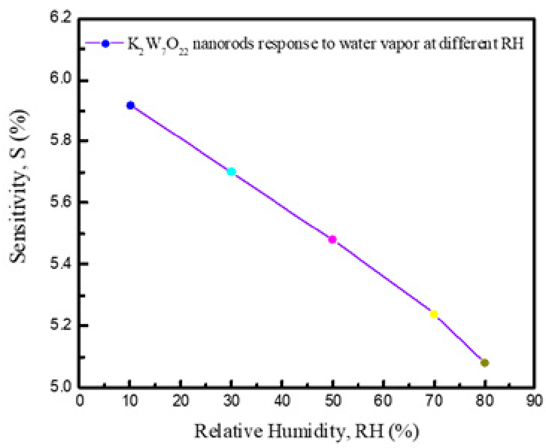


Figure 4: Sensitivity change in different values of RH.

Relative humidity, RH (%)	Resistance change, ∆R (MΩ)	Number of Cycles
10	0.04	300
30	0.04	300
50	0.04	300
80	0.04	300

Table 1: $K_2W_7O_{22}$ nanorods sensing response to water vapor at different RH, room temperature.

In the previous study,[20] the sensing mechanism of $K_2W_7O_{22}$ nanorods detecting acetone at room temperature are mainly due to it being a p-type semiconductor with good charge transfer capability and strong room-temperature ferroelectricity. These result in a strong interaction between the sensing material, $K_2W_7O_{22}$, and high dipole moment molecules-acetone. Water molecules, as we know, are typical electrophiles. While, in a p-type semiconductor, holes are the majority carriers. This could be the reason that H_2O molecules cannot easily be attached onto $K_2W_7O_{22}$. On the other hand, although H_2O molecules are polar, comparing to acetone molecules, its dipole moment (μ=1.855D) is lower than the dipole moment of acetone (μ=2.88D). As a ferroelectric material, $K_2W_7O_{22}$ favors to interact with molecules with a higher dipole moment, acetone. All these factors result in a low sensitivity to water vapor on $K_2W_7O_{22}$ nanorods but high sensitivity to acetone. This makes the nanostructured $K_2W_7O_{22}$ a very competitive material for use as a breath analyzer for detecting exhaled acetone.

CONCLUSION

This paper proposed a breath analysis based on a novel nanostructured material, $K_2W_7O_{22}$, which can be used to diagnose and monitor diabetes as a convenient, reliable, and non-invasive tool. The results exhibit a sensitive response to acetone but with little influence due to the complicated condition of exhaled breath, high water vapor concentration and varied RH. This makes the nanostructured $K_2W_7O_{22}$ a very competitive material for use in acetone sensors, and it has a great potential application for medical purposes.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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