Preparation of Macroporous Semiconductive Materials for the Sensing of Sulfur Compounds

No-Kuk Park, Tae Hoon Lee, Min Jung Kim and Tae Jin Lee*

School of Chemical Engineering and Technology,
214-1 Daedong Gyeongsan, Gyeongbuk 712-749, Korea

(Received July 14, 2014; accepted December 16, 2014)

Key words: macroporous, tin oxide, gas sensor, hydrogen sulfide

In this study, macroporous SnO$_2$ was prepared for the sensing of sulfur compounds, which are used as odorants to improve the safety of natural gas. Macropores in the semiconducting SnO$_2$ were formed using polystyrene nanobeads as a template. The mixing ratio of the polystyrene colloid and tin chloride solution used as the precursors was controlled to form an ordered array of macropores. The chemical sensing properties of the macroporous SnO$_2$ were investigated by injecting sulfur compounds into the sensing chamber using an $I-V$ source meter. The macroporous SnO$_2$ materials were highly sensitive to sulfur compounds.

1. Introduction

Semiconducting tin oxide exhibits good chemical gas sensing properties towards a range of gases.$^{(1)}$ One of the most common ways to tune the sensitivity and selectivity of these materials is to dope them with various noble metals.$^{(2)}$ The gas sensing performance of various sensing materials can simply be enhanced by controlling their morphological features during chemical synthesis. In particular, the generation of highly specific surface areas and uniform systems of large pores increases the probability of a gas interacting with a semiconductor, which is likely to increase the sensitivity of the material. The concept of utilizing self-assembled arrays of amphiphiles to synthesize well-ordered mesoporous materials$^{(3)}$ has recently been applied to tin oxide (SnO$_2$). SnO$_2$ is the most widely used n-type semiconductor in gas-sensing devices because of its ability to detect combustible gases, such as CH$_4$, C$_2$H$_5$OH, CO, and H$_2$. The SnO$_2$-based sensor is generally operated at 250–500 °C in air. SnO$_2$ adsorbs oxygen from the atmosphere, forming an electron-depleted zone. Reducing gases react with the adsorbed oxygen, increasing the electron concentration in the material and decreasing the electrical resistance.

*Corresponding author: e-mail: tjlee@ynu.ac.kr
Recently, a coal gasification process, which produces a synthetic gas (syn-gas), has been developed for electrical power generation and coal-to-liquid oil processes. However, sulfur compounds of 5000 ppmv are contained in the syn-gas produced in the coal gasification process, and cause the corrosiveness problems of the facilities and catalyst in the electrical power generation and catalytic chemical conversion processes. Therefore, sulfur compounds must be removed for a stable energy process. Thus, the detection of sulfur compounds contained in syn-gas is very important. Various SnO$_2$-based gas sensors were developed for the detection of hydrogen sulfide.$^{(6–9)}$ The metal-doped SnO$_2$ and SnO$_2$-transition metal oxide composite materials were synthesized in order to enhance the sensitivity of a gas sensor. The calcination temperature for the synthesis of SnO$_2$ was controlled for high-crystallinity SnO$_2$.$^{(10,11)}$ In this study, macroporous SnO$_2$ was prepared and used as a gas-sensing material for the detection of small-content H$_2$S in the syn-gas purified in the sulfur removing process. Although the sensitivity of a SnO$_2$-based sensor increases with increasing H$_2$S content, it decreases at a low H$_2$S content. Therefore, the increases in contact area over the sensor and gas diffusion rate were carried out with the synthesis of macroporous SnO$_2$ in this study.

In this study, macroporous SnO$_2$ was prepared using a polystyrene (PS) nanobead template in order to provide an effective pathway for the sensing of sulfur compounds, such as H$_2$S. It could be expected that the macroporous SnO$_2$ has better sensing properties than nonporous SnO$_2$ because the macroporous SnO$_2$ has a larger surface area and an interconnected macroporous structure enhances gas diffusion. The macroporous SnO$_2$ was prepared by the addition of polystyrene nanobeads as a template. Polystyrene nanobeads were synthesized by the suspension polymerization method. The sensing properties of the macroporous SnO$_2$ were compared with those of the nonporous SnO$_2$, which was prepared by a precipitation method.

2. **Materials and Methods**

2.1 **Synthesis of polystyrene nanobeads**

A polystyrene colloid was used as a template additive for the formation of pores in the semiconducting materials and synthesized as spherical particles by the polymerization of a styrene monomer (Sigma-Aldrich, C$_6$H$_5$CH = CH$_2$, MW = 104.15). The polystyrene nanobeads were prepared in an experimental setup equipped with a 500 ml jacketed glass vessel, a magnetic stirrer, a condenser, a vacuum system, a nitrogen flow system, and a thermocouple by the suspension polymerization method. The temperature was controlled using a PID controller and kept within ±0.1 °C. The narrowly dispersed latex was prepared by the surfactant-free emulsion polymerization of styrene. Millipore water (468 ml) and styrene (0.11 mol) were charged in the reactor. The reactor was purged with alternate cycles of nitrogen and evacuation, and finally left under a nitrogen atmosphere. After heating the reaction mixture to 70 °C with constant stirring at 400 rpm, the initial solution (0.42 g, 1.5 mmol of KPS in 10 ml of water) was injected into the reactor through a syringe. The reaction was allowed to proceed under these conditions for 12 h.
2.2 Synthesis of macroporous SnO$_2$

The synthesis of macroporous SnO$_2$ was carried out in a rotary vacuum evaporator. A mixture solution (100 ml), consisting of a 0.05 M SnCl$_4$ solution and a polystyrene colloid (50 ml), was placed in a 500 ml round flask. The volumetric ratio of SnCl$_4$ and the polystyrene colloidal solution was fixed to 1/1. The glass substrate was placed at the bottom of a glass container. The water in the mixture solution was removed by vacuum evaporation at 50 °C. After evaporation, the resulting solid mixture, which consisted of polystyrene spherical nanobeads and SnCl$_4$, was calcined at 600 °C for 4 h on an alumina substrate to thermally decompose the polystyrene used as the template. The physical properties of the macroporous SnO$_2$, such as surface area, crystal structure and surface morphology, prepared in this study were also examined by the nitrogen adsorption method, X-ray diffraction (XRD) and scanning electric microscopy (SEM). The alumina substrate, 10 × 10 mm$^2$ in size and coated with a platinum thin layer, was used as the electrode material for the fixation of macroporous SnO$_2$, as shown in Fig. 1. The macroporous SnO$_2$ powder was prepared as a slurry phase using isopropyl alcohol as a dispersant. The macroporous SnO$_2$ in the slurry phase was deposited over the alumina substrate.

2.3 Measurement of sensing properties of macroporous SnO$_2$

The electrical properties of the macroporous SnO$_2$ used as the chemical gas-sensing material were examined using an $I-V$ meter (SourceMeter 2635A, Keithley) and the electrical current of the macroporous SnO$_2$ at 200 °C was measured by allowing a source voltage of 10 V to pass through a platinum electrode on the substrate. The alumina substrate of the gas sensor was patterned onto a platinum electrode. The electrical properties of the macroporous SnO$_2$-based chemical sensor were analyzed by the adsorption and desorption of H$_2$S in the experimental setup, and the electric resistance was measured over the macroporous SnO$_2$. The experimental setup for the sensing of H$_2$S consisted of a mass flow controller (MFC) to control the gas composition, an electrical oven to control the sensing temperature, a sensing chamber to allow contact between the H$_2$S and macroporous SnO$_2$ coated on the sensor device, and an $I-V$ source.

Fig. 1. (Color online) Schematic diagram of the chemical gas sensor.
meter to measure the electric resistance, as shown in Fig. 2. The sensing temperature was fixed to 200 °C to examine the response of the macroporous SnO₂ used as a chemical sensor, and the H₂S content was fixed at 50.9 ppmv. The H₂S adsorption and desorption steps were repeated for three cycles under all experimental conditions and the adsorption step was carried out at the maximum current. The measured currents were used as the data for analyzing the response with the injection of H₂S.

3. Results and Discussion

3.1 Analysis of the physical properties of macroporous SnO₂

Spherical polystyrene nanobeads were synthesized by the suspension polymerization method, and their size was approximately 300 nm, as shown in Fig. 3. The size of the polystyrene nanobeads was controlled by the concentration of styrene monomer used in the polymerization process. Ordered macroporous materials were synthesized with polystyrene nanobeads owing to their homogeneous spherical size. The macrosized pores formed over the surface of the SnO₂ layer prepared in this study were examined, as shown in Fig. 4. Macropores were formed in the SnO₂ bulk
powder. The size of the pores matched that of the polystyrene nanobeads used as the template for the formation of macropores in SnO$_2$. The ordered macropores formed in SnO$_2$ were spherical. These spherical macropores were interconnected in the SnO$_2$ bulk and dispersed homogeneously, as shown in Fig. 4(b). Therefore, the SnO$_2$-based chemical gas sensor showed a strong response because the gases diffused well into the SnO$_2$ bulk layer.

The surface areas of the macroporous SnO$_2$ and nonporous SnO$_2$, which were prepared by a precipitation method, were measured by the nitrogen adsorption method. The two SnO$_2$ samples showed substantially different surface areas. The surface area of SnO$_2$ prepared by the precipitation method was approximately 17 m$^2$/g and that of macroporous SnO$_2$ was approximately 54 m$^2$/g. SnO$_2$ is a nonporous material, but it is highly sensitive to many types of gases. The isotherm curves obtained by nitrogen adsorption and desorption exhibited a typical low pore volume, as shown in Fig. 5(a). On the other hand, the pore size distribution (PSD) curve measured by nitrogen adsorption and Hg porosimetry confirmed that macroporous SnO$_2$ has meso and macropore sizes of approximately 33 and 130 nm, as shown in Figs. 5(b) and 6.

XRD showed that the macroporous SnO$_2$ had high crystallinity with a tetragonal structure, as shown in Fig. 7(a). The XRD peak pattern of the macroporous SnO$_2$ revealed the same structure as the common SnO$_2$ prepared by the precipitation method, as shown in Fig. 7(b). Therefore, the effects of the surface area and gas diffusion on chemical gas sensitivity can be determined with the formation of macropores in the SnO$_2$ bulk. The peaks of 28, 41, and 51° of 2θ, as shown in Fig. 7(a), agreed with the XRD pattern of KCl, which was formulated from potassium in the initiator (KPS) and chlorine in the precursor (SnCl$_2$).

3.2 Response of macroporous SnO$_2$ for H$_2$S

In this study, the changing electric current of the macroporous SnO$_2$ deposited on the chemical sensor was examined by the addition of hydrogen sulfide or air into the sensing chamber. Hydrogen sulfide and air were introduced alternately into the sensing chamber, and these experiments were performed repeatedly for 3 cycles. Air was used as the purge gas for the desorption of hydrogen sulfide adsorbed over the macroporous SnO$_2$, and the
Fig. 5. (a) Isotherm and (b) pore size distribution curves of macroporous SnO$_2$ measured by nitrogen adsorption and desorption.

Fig. 6. Pore size distribution curve of macroporous SnO$_2$ measured by Hg porosimetry.

Fig. 7. (Color online) XRD patterns of (a) macroporous SnO$_2$ and (b) nonporous SnO$_2$. 
oxygen contained in the air was used as a regeneration gas for the reoxidation of S-doped SnO$_2$ formulated by a gas–solid reaction between hydrogen sulfide and SnO$_2$. Figure 8 shows the response signals obtained with 50.9 ppmv hydrogen sulfide at 200 °C. When H$_2$S was flowed into the sensing chamber, the electric current increased from 20 to 235 μA during the first cycle, from 15 to 240 μA during the second cycle, and from 10 to 253 μA during the third cycle. The consumption times reached by the maximum currents were approximately 250, 350, and 490 at the first, second, and third cycles, respectively. The response time increased with increasing number of cycles and the maximum electric current increased. The current decreased rapidly when the sensing chamber was purged with air and recovered within 50 s. Moreover, the response time for H$_2$S in the macroporous SnO$_2$ was increased about 2 times with only 3 cycles. It was concluded that the response time increased, because the concentration of hydrogen sulfide was reduced by mixing air and hydrogen sulfide in the gas mixing chamber at the injection times of the second and third cycles. The gas mixing chamber was located in front of the sensing chamber for the control of H$_2$S concentration.

Fig. 8. (Color online) Electric currents measured over (a) macroporous SnO$_2$ and (b) nonporous SnO$_2$-based chemical sensors with 50.9 ppmv H$_2$S at 200 °C using an $I$–$V$ source meter, alternately inputting H$_2$S and air.
When nonporous SnO$_2$ was used as the sensing material, the electric current increased slowly with the injection of hydrogen sulfide and reached a maximum value of 20 μA at approximately 1700 s. The sensing response of the nonporous SnO$_2$ was both lower and slower than that of the macroporous SnO$_2$. Gas diffusion was enhanced by the macrosized pores in the SnO$_2$ bulk because the difference in sensing property for hydrogen sulfide depends on the surface area and morphology of the sensitive materials.

4. Conclusions

In this study, macroporous SnO$_2$ was prepared by the addition of polystyrene nanobeads used as the template. These nanobeads were synthesized by the suspension polymerization method. Macroporous SnO$_2$ has a higher surface area than nonporous SnO$_2$. The macropores interconnected in the SnO$_2$ bulk enhance gas diffusion in the sensing materials. Therefore, high sensitivity can be obtained with the formation of macropores in the SnO$_2$ bulk due to the effects of the surface area and gas diffusion.

Acknowledgements

This study was supported by a 2014 Yeungnam University Research Grant and Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. 2013R1A1A2059804).

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