Improvement of H2S Sensing Properties of SnO2-Based Thick Film Gas Sensors Promoted with MoO3 and NiO

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Abstract: The effects of the SnO2 pore size and metal oxide promoters on the sensing properties of SnO2-based thick film gas sensors were investigated to improve the detection of very low H2S concentrations (<1 ppm). SnO2 sensors and SnO2-based thick-film gas sensors promoted with NiO, ZnO, MoO3, CuO or Fe2O3 were prepared, and their sensing properties were examined in a flow system. The SnO2 materials were prepared by calcining SnO2 at 600, 800, 1,000 and 1,200 °C to give materials identified as SnO2(600), SnO2(800), SnO2(1000), and SnO2(1200), respectively. The Sn(12)Mo5Ni3 sensor, which was prepared by physically mixing 5 wt% MoO3 (Mo5), 3 wt% NiO (Ni3) and SnO2(1200) with a large pore size of 312 nm, exhibited a high sensor response of approximately 75% for the detection of 1 ppm H2S at 350 °C with excellent recovery properties. Unlike the SnO2 sensors, its response was maintained during multiple cycles without deactivation. This was attributed to the promoter effect of MoO3. In particular, the Sn(12)Mo5Ni3 sensor developed in this study showed twice the response of the Sn(6)Mo5Ni3 sensor,
which was prepared by SnO$_2$(600) with the smaller pore size than SnO$_2$(1200). The excellent sensor response and recovery properties of Sn(12)Mo5Ni3 are believed to be due to the combined promoter effects of MoO$_3$ and NiO and the diffusion effect of H$_2$S as a result of the large pore size of SnO$_2$.

**Keywords:** sensor; SnO$_2$; pore size; H$_2$S; MoO$_3$; NiO

1. Introduction

Hydrogen sulfide (H$_2$S) is an unwanted and toxic by-product of the coal, coal oil, and natural gas industries [1]. When hydrogen sulfide is emitted into the atmosphere, it is converted to SO$_x$, which is a precursor to acid rain [2]. Accordingly, there is increasing demand for sensing devices that monitor low H$_2$S concentrations. Well-known materials used to detect H$_2$S include BaTiO$_3$ [3], SnO$_2$-Pd [4], Ag-SnO$_2$ [5], SnO$_2$-Al$_2$O$_3$ [6], SnO$_2$-CuO [7–11], SnO$_2$-CuO-SnO$_2$ [12,13], SnO$_2$-ZnO-CuO [14] and SiO$_2$-doped Cu-Au-SnO$_2$ [15]. Among the sensors described in the literature, CuO-modified thin-film or thick-film SnO$_2$ sensors are promising for the sensitive and selective detection of H$_2$S [1].

SnO$_2$-based thick-film gas sensors have been used to detect toxic gases [16–28] on account of their high sensor response, simple design, low weight and low price. SnO$_2$-based thick film gas sensors can achieve greater sensitivity to H$_2$S through control of the particle size [17] and the addition of suitable promoters [13,14]. Wagh et al. reported that SnO$_2$-ZnO-CuO thick-film sensors had significantly better response and recovery times than SnO$_2$-ZnO or CuO doped SnO$_2$ sensors [15]. Nevertheless, most studies on the sensing behavior of CuO-modified SnO$_2$ thick-film gas sensors focused on concentrations of tens to hundreds of ppm. Until now, there have been very few studies of SnO$_2$-based gas thick-film sensors for the detection of <1 ppm H$_2$S.

In our previous papers, we described a SnO$_2$-based thick-film gas sensor promoted with MoO$_3$ and NiO, which was developed for the detection of dimethyl methylphosphonate (DMMP) and dichloromethane [26–28]. During the course of this earlier study, NiO and MoO$_3$ promoters were found to play important roles in the sensor response and the recovery of the SnO$_2$-based sensor, respectively, for the detection of toxic organic compounds containing P and Cl [26–28]. In the case of H$_2$S detection, a SnO$_2$-based thick-film sensor promoted with NiO and MoO$_3$ showed improved recovery properties [2]. Nevertheless, the response of this sensor was decreased by promoting MoO$_3$ despite the good recovery properties. Considering that the sensor response is an important factor in addition to the recovery properties, the improvement in the sensor response is necessary to develop a new SnO$_2$-based thick-film gas sensor for the detection of <1 ppm H$_2$S.

The aim of this study was to improve the response of a SnO$_2$-based thick-film gas sensor promoted with NiO and MoO$_3$ developed in a previous study for the detection of H$_2$S at concentrations of <1 ppm. Accordingly, this study examined the effects of promoters and the textural properties of SnO$_2$ on the sensing behaviors of SnO$_2$-based thick-film sensors.
2. Experimental Section

2.1. Preparation of the Materials and Sensors

The SnO$_2$ used as a source for the SnO$_2$-based sensors was prepared from SnCl$_4$ using a previously described ammonia-based precipitation method [2,26–28]. The products were calcined in a muffle furnace at various temperatures (600, 800, 1,000 or 1,200 °C). The SnO$_2$-based materials were prepared by physically mixing two or three of the following promoters, NiO, ZnO, MoO$_3$, CuO and Fe$_2$O$_3$, with SnO$_2$. All products were calcined in a muffle furnace at 600 °C for 4 hours. The temperature ramp rate was 3 °C/min. The thick–film sensors were fabricated on an alumina substrate by screen-printing using a variety of physical mixtures, such as a SnO$_2$-based powder and an organic binder (90% α-terpineol, Aldrich) [2,26–28]. The printed thick-film sensors were dried and calcined at 600 °C for 1 hour. This paper describes the sensors as SnO$_2$(600) or Sn(6)Mo5Ni3, where (600) represents the calcination temperature, Sn(6) represents SnO$_2$ calcined at 600 °C, Mn5 and Ni3 represent 5% MoO$_3$ and 3% NiO, respectively, on a weight/weight basis.

2.2. Sensor Testing System

The sensing behaviors were examined in a flow system equipped with a 0.1 L chamber. The H$_2$S gas was diluted with dry air to a concentration of <4.0 ppm. The total flow rate of the gas mixture was 400 mL/min. H$_2$S gas was injected into chamber for 10 minutes. In the present study, the sensor response was defined using the following equation:

$$\text{Sensor response} \, \% = \left( \frac{R_a - R_g}{R_a} \right) \times 100$$

where $R_a$ and $R_g$ are the electric resistance in air and test gas, respectively. The sensor recovery was defined by the following equation:

$$\text{Recovery} \, \% = \left( \frac{S_m - S_r}{S_m} \right) \times 100$$

where $S_m$ and $S_r$ represent the maximum sensor response over a period of 10 minutes and the minimum sensor response in air, respectively.

2.3. Characterization of Materials

The crystalline phases in the materials were identified by power X-ray diffraction (XRD; Philips, X’PERT) using Cu Kα radiation. The morphology of the SnO$_2$ powder was observed by transmission electron microscopy (TEM; Hitachi, H-7100), and the textural properties of the materials were examined using an Hg porosimetry (Micromeritics, AutoPore IV 9500).

3. Results and Discussion

3.1. Effects of SnO$_2$ Pore Size on Sensor Properties

To examine the effects of the textural properties of SnO$_2$ on the sensing properties, the SnO$_2$ materials were prepared by calcining SnO$_2$ at temperatures of 600, 800, 1000, and 1,200 °C.
Figure 1 shows XRD patterns of the SnO$_2$ materials.

**Figure 1.** XRD patterns of SnO$_2$ materials calcined at (a) 600; (b) 800; (c) 1,000; and (d) 1,200 °C; (◆) SnO$_2$.

Diffraction peaks were observed at 26.6, 33.8, 37.9, 51.8, 54.8, 61.9, 64.7, 65.9 and 71.3° 2θ, and the intensities of these diffraction peaks increased with increasing temperature, indicating an increase in the crystallite size and the crystallinity [29,30], but the structures of SnO$_2$ were retained. To confirm these results, the sizes of the SnO$_2$ crystallites were calculated from the XRD patterns using Scherrer’s equation Equation (3). As expected, the crystallite size of SnO$_2$ increased from 19 to 54 nm with increasing calcination temperature (Table 1).

$$t = \frac{(K \cdot \lambda)}{(W_{size} \cdot \cos \theta)} = \frac{(0.9 \cdot \lambda)}{(FWHM \cdot \cos \theta)}$$  \hspace{1cm} (3)

**Table 1.** Crystallite sizes calculated using XRD and TEM data.

<table>
<thead>
<tr>
<th>SnO$_2$ materials</th>
<th>Wave Length (nm)</th>
<th>2θ (°)</th>
<th>FWHM (cm$^3$/g)</th>
<th>Crystallite Size (nm)</th>
<th>TEM Crystallite Size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnO$_2$(600)</td>
<td>0.154</td>
<td>26.611</td>
<td>0.4095</td>
<td>19</td>
<td>10–20</td>
</tr>
<tr>
<td>SnO$_2$(800)</td>
<td>0.154</td>
<td>26.581</td>
<td>0.3104</td>
<td>26</td>
<td>25–30</td>
</tr>
<tr>
<td>SnO$_2$(1,000)</td>
<td>0.154</td>
<td>26.585</td>
<td>0.1690</td>
<td>47</td>
<td>40–50</td>
</tr>
<tr>
<td>SnO$_2$(1,200)</td>
<td>0.154</td>
<td>26.604</td>
<td>0.1488</td>
<td>54</td>
<td>50–70</td>
</tr>
</tbody>
</table>

In a separate experiment, TEM images of these SnO$_2$ materials were investigated. Table 1 lists the crystallite sizes obtained from TEM images, which concur with those determined by XRD. Table 2
lists the textural properties of SnO\textsubscript{2} materials, as determined by Hg porosimetry. The surface areas decreased with increasing calcination temperature, whereas the average pore diameters increased, presumably because the pore diameter is dependent on the crystallite size.

**Table 2.** Textural properties of the SnO\textsubscript{2} materials produced by Hg porosimetry.

<table>
<thead>
<tr>
<th>SnO\textsubscript{2} Materials</th>
<th>Surface Area (m\textsuperscript{2}/g)</th>
<th>Pore Volume (cm\textsuperscript{3}/g)</th>
<th>Average Pore Diameter (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnO\textsubscript{2}(600)</td>
<td>24.8</td>
<td>0.4918</td>
<td>79</td>
</tr>
<tr>
<td>SnO\textsubscript{2}(800)</td>
<td>16.4</td>
<td>0.5047</td>
<td>122</td>
</tr>
<tr>
<td>SnO\textsubscript{2}(1000)</td>
<td>9.4</td>
<td>0.5226</td>
<td>222</td>
</tr>
<tr>
<td>SnO\textsubscript{2}(1200)</td>
<td>8.0</td>
<td>0.6263</td>
<td>312</td>
</tr>
</tbody>
</table>

Figure 2 shows the response curves, responses and 80% response times of SnO\textsubscript{2}(600), SnO\textsubscript{2}(800), SnO\textsubscript{2}(1000) and SnO\textsubscript{2}(1200) gas sensors at a H\textsubscript{2}S concentration of 1.0 ppm at 350 °C. The responses of the SnO\textsubscript{2}-based sensors increased in the following order: SnO\textsubscript{2}(600) < SnO\textsubscript{2}(800) < SnO\textsubscript{2}(1000) < SnO\textsubscript{2}(1200). The response time of the SnO\textsubscript{2}(1200) sensor was much shorter than that of the SnO\textsubscript{2}(600) sensor, even though sensor recovery was incomplete in air. These results mean that the response time decreases with increasing pore diameter, as shown in Table 1 and Figure 2(II), and the sensor response increases. However, the important point to note is the incomplete recovery of the sensors after the detection of H\textsubscript{2}S, despite the high sensor response. It is thought that this result is because sulfur compounds are adsorbed on the sensor’s surface, and that they progressively pollute the surface of tin dioxide.

*Figure 2. (I) Response curves, (II) responses, and (II) 80% response times of SnO\textsubscript{2}-based gas sensors, such as (a) SnO\textsubscript{2}(600); (b) SnO\textsubscript{2}(800); (c) SnO\textsubscript{2}(1000); and (d) SnO\textsubscript{2}(1200) at a H\textsubscript{2}S concentration of 1.0 ppm at 350 °C.*

Figure 3 shows SEM images of the surfaces of the SnO\textsubscript{2}(600), SnO\textsubscript{2}(800), SnO\textsubscript{2}(1000) and SnO\textsubscript{2}(1200) thick-film sensors. The particle size of SnO\textsubscript{2} increased with increasing calcination temperature in the following order: SnO\textsubscript{2}(600) < SnO\textsubscript{2}(800) < SnO\textsubscript{2}(1000) < SnO\textsubscript{2}(1200). Liu et al. reported that the sensor sample based on SnO\textsubscript{2} nanocrystals produced by the gel combustion method had higher response and shorter response times, which might be due to the more porous nano-crystallinity (~50 nm in size) than the sample prepared from hydrothermal-synthesized SnO\textsubscript{2}.
nanocrystals, where smaller SnO$_2$ nanocrystals (~12–13 nm) are densely packed and agglomerate into large entities (secondary particles), approximately 2–3 μm in size [17]. However, in this study, particle size after screen-printing, as well as average pore diameter of SnO$_2$, is directly related to the crystallite size (Table 1) and the crystalinity of SnO$_2$, which is in contrast to Liu et al.’s results. This result is because the crystallite size and the crystalinity of SnO$_2$ was controlled by calcining the SnO$_2$ material, which was prepared by precipitation, at various temperatures (600, 800, 1,000 and 1,200 °C), and the SnO$_2$ thick-film sensors were fabricated on an alumina substrate by screen-printing using these calcined materials. From these results, it is clear that the sensor response and response time for the detection of H$_2$S gas are directly affected by the SnO$_2$ pore diameter rather than to the surface area due to the diffusion of H$_2$S gas. In particular, the important point to note is that the response time of the SnO$_2$ sensor, as well as sensor response for the detection of H$_2$S, can be enhanced by increasing the crystallite size of SnO$_2$ by calcination.

**Figure 3.** SEM images of the SnO$_2$ thick-film sensors: (a) SnO$_2$(600); (b) SnO$_2$(800); (c) SnO$_2$(1000); and (d) SnO$_2$(1200).

3.2. **Promoter Effects on Sensor Response and Recovery**

The sensor recovery properties are an important consideration for sensors designed for H$_2$S. To improve the sensor recovery, SnO$_2$(1200)-based sensors were prepared by physically mixing with ZnO, Fe$_2$O$_3$, MoO$_3$, NiO, or CuO promoters, which are referred to as Sn(12)Zn, Sn(12)Fe5, Sn(12)Mo5, Sn(12)Ni5, and Sn(12)Cu5, respectively. The effects of the promoters on the sensor
recovery properties were investigated at a H$_2$S concentration of 1.0 ppm at 350 °C. The results obtained are summarized in Figure 4. The Sn(12)Zn5, Sn(12)Ni5 and Sn(12)Cu5 sensors showed a slight increase in the sensor response compared to the SnO$_2$ sensor, but their recoveries were incomplete at 350 °C. On the other hand, Sn(12)Fe5 and Sn(12)Mo5 showed complete recovery, but exhibited much lower responses than the SnO$_2$(1200) sensor. In particular, the Sn(12)Mo5 sensor showed a faster recovery time than the Sn(12)Fe5 sensor, and a response that was approximately 42% higher than that of the SnO$_2$(600)-based sensor containing 5 wt% MoO$_3$ [Sn(6)Mo5]. The reason for excellent recovery properties of the Fe5 and Mo5 sensors is not clear yet, but it is thought that Fe$_2$O$_3$ and MoO$_3$ promoters added to SnO$_2$ play an important role in the desorption of sulfur compounds. To identify the effects of the promoters on the sensor response and recovery, the SnO$_2$-based sensors promoted with various amounts of metal oxides (MoO$_3$, NiO$_3$, and ZnO) were examined at 1 ppm H$_2$S and 350 °C. These results are shown in Figure 5. As shown by Figures 5(b,c) and (d), the Sn(12)Mo5 sensor achieved a recovery of 100%, even though the sensor response was decreased by the MoO$_3$ promoter. Previous studies found that NiO plays an important role in enhancing the sensor response of the SnO$_2$-based sensor promoted with MoO$_3$ for the detection of dimethyl methylphosphonate (DMMP) and dichloromethane [23,24]. In the present study, the sensor response for the detection of H$_2$S was increased by NiO (Figure 5). As expected, the Sn(12)Mo5Ni3 sensor, which was promoted with both MoO$_3$ and NiO, showed a sharp increase in the sensor response and maintained the sensor recovery properties (Figure 5(f)). In particular, the Sn(12)Mo5Ni3 sensor exhibited much higher sensor response and recovery than the Sn(6)Mo5Ni3 sensor [2] (39.2% and 91%, respectively). These results are attributed to diffusion effects caused by the larger pore size of SnO$_2$ and the promoter effects of NiO and MoO$_3$. However, further study is required to verify the sensing mechanisms and the roles of NiO, ZnO, CuO, MoO$_3$, and Fe$_2$O$_3$ promoters in the sensor response and recovery properties.

**Figure 4.** Response curves of the SnO$_2$-based gas sensors promoted with various metal oxides at a H$_2$S concentration of 1.0 ppm at 350 °C.
Figure 5. Responses and recoveries of the SnO$_2$-based gas sensors promoted with various amounts of metal oxides at a H$_2$S concentration of 1.0 ppm at 350 °C; (a) SnO$_2$(1200); (b) Sn(12)Mo1; (c) Sn(12)Mo3; (d) Sn(12)Mo5; (e) Sn(12)Mo5Ni1; (f) Sn(12)Mo5Ni3; (g) Sn(12)Mo5Ni5; (h) Sn(12)Mo5Zn3; and (i) Sn(6)Mo5Ni3.

Figure 6 shows the response and recovery of the Sn(12)Mo5Ni3 sensor as a function of temperature at a H$_2$S concentration of 1.0 ppm. The sensor response decreased slightly with increasing detection temperature, whereas the sensor recovery increased between 250 °C and 350 °C. Considering the sensor response and recovery, the optimum temperature for the detection of H$_2$S was 350 °C.

Figure 6. Responses and recovery of the Sn(12)Mo5Ni3 sensor as a function of the detection temperature at a H$_2$S concentration of 1.0 ppm.

Figure 7 shows the response of the Sn(12)Mo5Ni3 sensor at concentrations between 0.25 ppm and 4 ppm at 350 °C. The response of this sensor increased almost linearly between 0.25 ppm and 4 ppm. The Sn(12)Mo5Ni3 sensor had a high sensor response of approximately 59% at low H$_2$S concentrations of 0.25 ppm.

Figure 7. Response of the Sn(12)Mo5Ni3 sensor at concentrations between 0.25 ppm and 4 ppm at 350 °C.
**Figure 7.** Response of the Sn(12)Mo5Ni3 sensor as a function of the H₂S concentration.

![Graph showing response of Sn(12)Mo5Ni3 sensor as a function of H₂S concentration.]

Figure 8 shows the repeatabilities of the SnO₂(1200), Sn(12)Mo5Ni3, and Sn(6)Mo5Ni3 sensors at a H₂S concentration of 1 ppm and 350 °C. The response of the SnO₂(1200) sensor decreased gradually over multiple detection and recovery tests. On the other hand, the Sn(12)Mo5Ni3 sensor maintained its response over multiple tests without deactivation. The response of the Sn(12)Mo5Ni3 sensor was approximately double that of the Sn(6)Mo5Ni3 sensor.

**Figure 8.** Repeatabilities of the (a) SnO₂(1200); (b) Sn(12)Mo5Ni3; and (c) Sn(6)Mo5Ni3 sensors.

![Graph showing repeatability of SnO₂(1200), Sn(12)Mo5Ni3, and Sn(6)Mo5Ni3 sensors.]

Figure 9 shows XRD patterns of Sn(6)Mo5Ni3 and Sn(12)Mo5Ni3 materials. Their XRD patterns showed MoO₃ (JCPDS No. 89-7112), NiO (JCPDS No. 89-7390) and SnO₂ (JCPDS No. 88-0287) phases. The diffraction peaks of these two materials were similar, as shown in Figure 9(a,b), which suggests that the observed enhancement in sensor response cannot be explained by structural differences alone. SEM images of the Sn(6)Mo5Ni3 and Sn(12)Mo5Ni3 sensors were observed at ×50 K and these results were shown in Figure 10. There is no change in the morphologies of those sensors as compared with the SnO₂(600) and SnO₂(1200) sensors. Table 3 lists the textural properties of the Sn(6)Mo5Ni3 and Sn(12)Mo5Ni3 materials determined by Hg porosimetry. The mean pore diameter of Sn(12)Mo5Ni3 was approximately double that of Sn(6)Mo5Ni3 (Table 3). This means that...
the pore size of SnO₂ and the promoter play important roles in the sensor response to H₂S. Based on these results, we believe that it is possible to prepare an excellent SnO₂-based sensor for the detection of H₂S at concentrations of < 1 ppm with a high sensor response and excellent recovery properties using SnO₂ with a large pore size, in conjunction with NiO and MoO₃ promoters.

**Figure 9.** XRD patterns of the (a) Sn(6)Mo₅Ni₃ and (b) Sn(12)Mo₅Ni₃ materials; (◆) SnO₂, (n) MoO₃, and (nd) NiO.

![XRD patterns](image)

**Figure 10.** SEM images of the (a) Sn(6)Mo₅Ni₃ and (b) Sn(12)Mo₅Ni₃ sensors.

(a) ![SEM image](image) (b) ![SEM image](image)

**Table 3.** Textural properties of the Sn(6)Mo₅Ni₃ and Sn(12)Mo₅Ni₃ by Hg porosimetry.

<table>
<thead>
<tr>
<th>SnO₂ Materials</th>
<th>Surface Area (m²/g)</th>
<th>Pore Volume (cm³/g)</th>
<th>Average Pore Diameter (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn(6)Mo₅Ni₃</td>
<td>11.8</td>
<td>0.5197</td>
<td>175.6</td>
</tr>
<tr>
<td>Sn(12)Mo₅Ni₃</td>
<td>4.7</td>
<td>0.4019</td>
<td>338.6</td>
</tr>
</tbody>
</table>

**4. Conclusions**

A new large pore size SnO₂-based thick-film gas sensor promoted with MoO₃ and NiO [Sn(12)Mo₅Ni₃] was developed for the detection of H₂S at 350 °C. This sensor exhibited 100%
recovery at 350 °C and a maximum sensor response of 75%, and maintained a sensor response of 75% over many operating cycles without deactivation at a H2S concentration of 1 ppm and 350 °C. In addition, its response increased almost linearly between 0.25 and 1 ppm. Furthermore, the sensor exhibited a high response (59%) at a H2S concentration of only 0.25 ppm. In particular, the Sn(12)Mo5Ni3 sensor exhibited double the response of the corresponding Sn(6)Mo5Ni3 sensor, which was prepared by adding MoO3 and NiO to SnO2 calcined at 600 °C. These results are explained by the promoter effects of MoO3 and NiO, and the diffusion effects associated with a large SnO2 pore size.

Acknowledgments

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