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Hydrogen Sensing Properties of an Anodized TiO\textsubscript{2} Film Equipped with a Pd-Pt Electrode

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An anodized TiO\textsubscript{2} sensor equipped with a Pd-Pt electrode was subjected to heat treatment in air (air-treated) and additionally in N\textsubscript{2} (N\textsubscript{2}-treated), and then its responses to H\textsubscript{2} balanced with air or N\textsubscript{2} were investigated under dry and wet conditions. Among the conditions tested, the N\textsubscript{2}-treated sensor showed the largest H\textsubscript{2} response in dry N\textsubscript{2} atmosphere. But, H\textsubscript{2} response of the air-treated sensor increased with the existence of water vapor, while that of the N\textsubscript{2}-treated sensor decreased with the existence of water vapor. As a result, H\textsubscript{2} response of the air-treated sensor in wet air was quite comparable with that of the N\textsubscript{2}-treated sensor in wet N\textsubscript{2}. Thus, it was revealed that the existence of water vapor reduced the pretreatment- and measurement atmosphere-dependent H\textsubscript{2} response of the sensor.

Introduction

Our previous studies have revealed that a TiO\textsubscript{2} thin film having sub-micron pores could be fabricated by anodic oxidation of a Ti plate, and that the anodized TiO\textsubscript{2} thin film equipped with a Pd top electrode and the Ti plate bottom electrode exhibited high H\textsubscript{2} response in a wide range of H\textsubscript{2} concentration as a diode-type sensor under flowing both air and N\textsubscript{2} atmospheres (1-4). In addition, alloying of Pd with Pt was quite effective in improving the reproducibility of H\textsubscript{2} response and its long-term stability (5-7). In the present study, sensing properties of an anodized TiO\textsubscript{2} sensor equipped with a Pd-Pt alloy top electrode to H\textsubscript{2} balanced with air or N\textsubscript{2} were investigated under dry and wet atmospheres.

Experimental

Preparation and Characterization of an Anodized TiO\textsubscript{2} Thin Film

A half part of a Ti plate (5.0 × 10.0 × 0.5 mm\textsuperscript{3}) was anodically oxidized in a 0.5 M H\textsubscript{2}SO\textsubscript{4} aqueous solution at 20\textdegree C for 30 min at a current density of 50 mA cm\textsuperscript{-2}. Microstructure of the anodized film was observed by scanning electron microscopy (SEM; JEOL, JSM-7500F).

Fabrication and Measurement of a Pd-Pt/TiO\textsubscript{2} Sensor

Figure 1 shows schematic drawing of a diode-type sensor fabricated using the anodized TiO\textsubscript{2} thin film and a Pd-Pt (Pd : Pt = 36 : 64 (wt\%) alloy top electrode (Pd-Pt/TiO\textsubscript{2}
sensor). The Pd-Pt alloy electrode (3.0 × 3.0 mm²) was fabricated on both the TiO2 thin film and the Ti plate by radio-frequency magnetron sputtering (Shimadzu, HSR-552S, output power: 300 W(Pd) - 200 W(Pt), sputtering time: 7 min) and the electrical contact to Au lead wires was achieved by application of a Pt paste and then was ensured by subsequent firing at 600°C for 1 h in dry air (air-treated sensor). Thus, the actual electrode configuration was the Pd-Pt/TiO2/Ti plate. A dc voltage of 1 or 100 mV was applied to the Pd-Pt/TiO2 sensor under forward bias condition (Pd-Pt(+)-TiO2-Ti(-)), and the H2 sensing properties were measured at 250°C to 50~8000 ppm H2 balanced with air or N2 under dry and wet conditions (absolute humidity (AH) range: 0 ~ 30.4 g m⁻³). The H2 response properties of the sensor subjected to the additional treatment in dry N2 at 600°C for 1 h (N2-treated sensor) were also measured. For easy comparison, air- and N2-treatments are expressed as Tair and TN2, respectively, and measurements in air and in N2 atmosphere are indicated as Mair and MN2, respectively. Current (I)-voltage (V) characteristics of the sensor were measured in a range of -1~1 V.

![Fig. 1 Schematic drawing of a Pd-Pt/TiO2 sensor.](image)

**Results and Discussion**

**Microstructure of an Anodized TiO2 Thin Film**

Figure 2 shows SEM photographs of the surfaces of a Ti plate, an anodized TiO2 thin film and the anodized TiO2 thin film coated with a Pd-Pt alloy electrode. Formation of submicron-sized pores was observed at the surface after the anodic oxidation, as shown in Fig. 2(b). The pore size decreased obviously after the sputtering of the Pd-Pt alloy electrode, as shown in Fig. 2(c).

![Fig. 2 SEM photographs of the surfaces of (a) a Ti plate, (b) an anodized TiO2 thin film and (c) the anodized TiO2 thin film coated with a Pd-Pt alloy electrode.](image)
I-V Characteristics of a Pd-Pt/TiO₂ Sensor

Figure 3 shows I-V curves of the Pd-Pt/TiO₂ sensor in 8000 ppm H₂ balanced with air and N₂ at 250ºC. A nonlinear I-V curve, which is typical for a diode-type sensor, was observed for the air-treated sensor in dry air, but it changed to an almost ohmic I-V curve in wet air, i.e. current values increased with the existence of water under the forward bias conditions, as shown in Fig. 3(a). On the other hand, the I-V curve for the N₂-treated sensor in dry N₂ showed better linearity than that in dry air, and little change in current was induced by the existence of water in N₂, as shown in Fig. 3(b). It is reasonable to consider that the surface of the Pd-Pt electrode is partially covered with chemisorbed oxygen or partially oxidized in the case of the air-treated sensor. During the H₂ response measurement in dry air (dry environment under the T_air-M_air conditions), it is anticipated that chemisorbed oxygen cannot be consumed completely by the reaction with H₂ (a small but a certain coverage of chemisorbed oxygen is maintained), but almost no oxygen chemisorption may be easily achieved under the H₂ response measurement in dry N₂ (dry environment under the T_N₂-M_N₂ conditions). Thus, it is considered that the chemisorbed oxygen on the electrode contributes to the formation of the Schottky barrier at the interface between the Pd-Pt electrode and the anodized TiO₂ thin film, since the existence of chemisorbed oxygen on the electrode further promotes electron extraction from the anodized TiO₂ thin film than the level expected from the difference between the work function of the electrode and the electron affinity of the anodized TiO₂ thin film. In addition, the results shown in Fig. 3 confirm that the existence of water vapor under the T_air-M_air conditions weakens the above role of chemisorbed oxygen.

H₂ Response Properties of a Pd-Pt/TiO₂ Sensor

Figure 4 shows response transients of the Pd-Pt/TiO₂ sensor to 8000 ppm H₂ at 250ºC under a forward bias voltage of 1 mV. The air-treated sensor showed very small H₂ response in dry air, as shown in Fig. 4(a) and the N₂-treated sensor showed the largest H₂ response in dry N₂ among the conditions tested, as shown in Fig. 4(b). The H₂ response of the air-treated sensor was increased by the existence of water vapor. In contrast, the H₂ response of the N₂-treated sensor was decreased by the existence of water vapor in this case.
Fig. 4  Response transients of a Pd-Pt/TiO₂ sensor to 8000 ppm H₂ balanced with (a) air or (b) N₂ at 250°C. The sensor was pretreated at 600°C for 1 h in (a) dry air and (b) dry N₂ (applied voltage: 1 mV). AH: absolute humidity

Fig. 5  Variations in (a) sensor current and (b) response and recovery times of a Pd-Pt/TiO₂ sensor in 8000 ppm H₂ operated at 250°C under a forward bias voltage of 1 mV with absolute humidity.

Figure 5(a) depicts the variations in H₂ response of the sensor with absolute humidity in the measurement atmosphere. The magnitude of the H₂ response of the air-treated sensor in wet air was quite comparable to that of the N₂-treated sensor in wet N₂ (a response current range of 3.0–4.5×10⁻⁴ A), and it showed little absolute humidity dependence. Thus, it was revealed that the existence of water vapor reduced the pretreatment- and measurement atmosphere-dependent H₂ response of the sensor. Figure 5(b) shows the variations in response and recovery times of the sensor with absolute humidity in the measurement atmosphere. In dry atmosphere, a longer response time was observed under the T_air-M_air conditions, in comparison with that under the T_N₂-M_N₂ conditions. This is because the response time under the T_air-M_air conditions contains the time necessary to remove chemisorbed oxygen to a certain level before the dissociative adsorption of H₂ and subsequent dissolution of H atoms into the electrode which is the main sensing mechanism of this type sensor. On the other hand, the T_air-M_air conditions
offered a shorter recovery time than the T_{N2-MN2} conditions, implying that the gaseous oxygen accelerates release of H atoms from the electrode. The response time became longer with the existence of water vapor on the whole under both the T_{air-Mair} and T_{N2-MN2} conditions. Thus, it is obvious that water vapor and/or chemisorbed water molecules on the electrode interferes the dissociative adsorption of H₂ and subsequent dissolution of H atoms into the electrode from the viewpoint of response time. However, the recovery time remained almost unchanged with the existence of water vapor under both the T_{air-Mair} and T_{N2-MN2} conditions.

**H₂ Concentration Dependence of Response of a Pd-Pt/TiO₂ Sensor**

The response transients of the Pd-Pt/TiO₂ sensor to 50~8000 ppm H₂ balanced with dry air and dry N₂ under a forward bias voltage of 100 mV are shown in Fig. 6(a). The sensor current decreased drastically with decreasing H₂ concentration under the T_{air-Mair} conditions. And then the sensor current in 50~500 ppm H₂ became extremely small. In contrast, much larger responses to 50~8000 ppm H₂ were observed under the T_{N2-MN2} conditions than the T_{air-Mair} conditions, especially in the H₂ concentration range (C_{H₂}) less than 500 ppm. In addition, the sensor current in H₂ is directly proportional to the H₂ concentration under the T_{air-Mair} conditions, while it is proportional to the logarithm of H₂ concentration under the T_{N2-MN2} conditions, as shown in Fig. 6(b). From these results, it was confirmed that oxygen in the measurement atmosphere lowered the H₂ response, especially in the low concentration range less than 500 ppm.

![Fig. 6](image-url)
Similar measurements were also conducted with the Pd-Pt/TiO$_2$ sensor to 50–8000 ppm H$_2$ in wet atmosphere (AH: 17.3 g m$^{-3}$), as shown in Fig. 7(a). The sensor current decreased drastically with decreasing H$_2$ concentration in wet atmosphere under both the T$_{air}$-M$_{air}$ and T$_{N2}$-M$_{N2}$ conditions. Especially, the H$_2$ response in the H$_2$ concentration range less than 500 ppm became very small. From the comparison between Figs. 6 and 7, we could confirm the effects of water vapor on the H$_2$ response explained by referring to the results shown in Figs. 5(a) and 5(b), i.e. water vapor enhances the H$_2$ response under the T$_{air}$-M$_{air}$ conditions, but reduce the H$_2$ response under the T$_{N2}$-M$_{N2}$ conditions, over the whole H$_2$ concentration range studied. In addition, it was found that the sensor current in wet H$_2$ atmosphere was well proportional to the logarithm of H$_2$ concentration under the T$_{air}$-M$_{air}$ conditions (1000–8000 ppm) and the T$_{N2}$-M$_{N2}$ conditions (500–8000 ppm), as shown in Fig. 7(b). This behavior is similar to that observed under the dry T$_{N2}$-M$_{N2}$ conditions shown in Fig. 6(c) in all the H$_2$ concentration range, but the slope of the current in H$_2$ under the wet T$_{air}$-M$_{air}$ conditions is apparently smaller than that under the T$_{N2}$-M$_{N2}$ conditions in the H$_2$ concentration range higher than 1000 ppm. Under both T$_{air}$-M$_{air}$ and T$_{N2}$-M$_{N2}$ conditions the sensor showed very small H$_2$ responses in the H$_2$ concentration range less than 500 ppm H$_2$. Poor linearities were observed between the sensor current and the H$_2$ concentration under both the T$_{air}$-M$_{air}$ and T$_{N2}$-M$_{N2}$ conditions, as shown in Fig. 7(c). Thus, water vapor may induce a similar effect to that of oxygen from a view point of H$_2$ sensing mechanism, more precisely the H$_2$ concentration dependence of response, though the details are not clarified yet.

Fig. 7  (a) Response transients and (b–c) variations in sensor current of a Pd-Pt/TiO$_2$ sensor to 50–8000 ppm H$_2$ (C$_{H2}$) in (i) wet air and (ii) wet N$_2$ (AH: 17.3 g m$^{-3}$) at 250ºC (applied voltage: 100 mV).
Conclusions

H₂ sensing properties of an anodized TiO₂ sensor equipped with a Pd-Pt alloy top electrode were investigated in air and N₂ under dry and wet conditions. It was revealed that the existence of water vapor reduced the influence of pretreatment- and measurement atmosphere-dependent H₂ sensing properties of the anodized Pd-Pt/TiO₂ sensor. It is also suggested that the H₂ sensing mechanism is affected by oxygen as well as water vapor.

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References