Extended Abstracts of the 1997 International Conference on Solid State Devices and Materials, Hamamatsu, 1997, pp. 376-377

Highly Sensitive MOSFET Gas Sensors with Porous Platinum Gate Electrode

Hisashi Fukuda, Hiroaki Seo, Kouichirou Kasama, Toshiaki Endoh and Shigeru Nomura
Department of Electrical and Electronic Engineering, Faculty of Engineering,
Muroran Institute of Technology, 27-1 Mizumoto, Muroran, Hokkaido 050, Japan
Phone:+81-143-47-3260, Fax:+81-143-47-3288, E-mail:fukuda@waspet.cc.muroran-it.ac.jp

1. Introduction

Noble metals such as palladium (Pd), silver (Ag), gold (Au) and platinum (Pt) have potential gas detection capabilities for solid-state gas sensors [1-5]. Gas detection based on this technique relies largely on a change of the metal work function in the Schottky diode and/or MOSFETs induced by a catalytic reaction on the solid surface.

In recent years, further development of these gas sensors has resulted in the incorporation of additives such as antimony (Sb) and/or Pt in tin oxide (SnO_x) thin film [6]. Another approach is the integration of catalytic metal and SnO_x to allow the detection of oxygen (O_2) and carbon monoxide (CO) gases [5]. Thus, surface modifications have the potential to enhance the sensitivity and selectivity of the sensors.

We have developed a novel MOSFET gas sensor for hydrogen (H_2) detection that operates at room temperature. For this purpose, a thin porous Pt layer with a catalytic reaction was formed and applied as the gate electrode of the MOSFET gas sensor. In this study, we present experimental results on the gas sensing characteristics and discuss the physics of the sensing mechanism involved in the detection of H_2 at lower temperatures than those of conventional gas sensors.

2. Device Fabrication

The devices were fabricated on boron-doped p-type Si (100) wafers. The wafers were first cut into 15×15 mm^2 square chips. These chips were rinsed in deionized water and methyl alcohol, and were cleaned by a standard RCA method. A 500-nm-thick field-oxide film was then formed on the Si. The source and drain regions were formed by solid phase diffusion through phosphorus-doped SiO_2 film. Then, a 15-nm-thick gate SiO_2 film was formed in dry oxygen ambient at 900℃ for 10 min. A porous Pt gate electrode was formed by dropping an ethanol solution containing 0.5 wt % hexachloroplatinic (IV) acid onto the gate oxide film, and was heated at 300 ℃ for 10 min in H_2 atmosphere. The amount of hexachloroplatinic (IV) acid was controlled to form a porous Pt layer with a thickness less than 1 μm. The MOSFETs fabricated had a channel length and gate width of 30 μm and 2.25 mm, respectively. Electrical measurements for the devices were performed at room temperature (27 ℃) under dark conditions in a vaccuum desiccator. Hydrogen gas was introduced into the desiccator using a syringe, at concentrations ranging from 0 to 500 ppm.

3. Results and Discussion

Figure 1 shows a scanning electron microscopy (SEM) micrograph of the porous Pt metal surface of MOSFETs. It is clearly observed that the Pt (the white part in the micrograph) surface is in the form of islands and shows the agglomeration of roughly spherical particles of 0.5 μm in size.

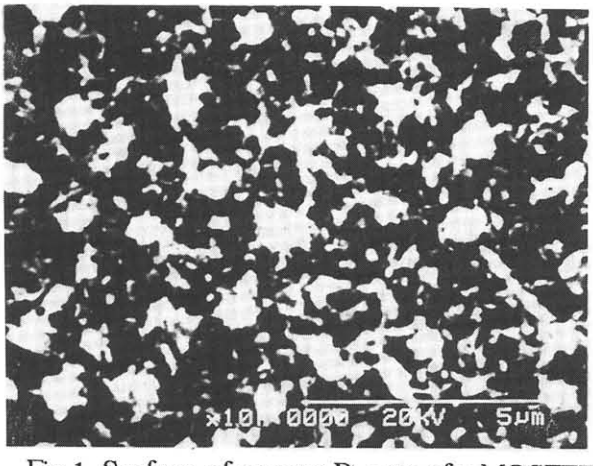

Fig.1 Surface of porous Pt gate of a MOSFET gas sensor imaged by SEM.

Typical characteristics of drain current (I_d) versus gate voltage (V_g) with and without hydrogen are shown in Fig.2. The data that threshold voltage (V_{th}) of the transistor decreases in the presence of hydrogen. In addition, ΔV_{th} seems to saturate with increasing exposure time. It is also interesting to note that the hydrogen sensitivity is about 10 times higher than that of an unmodified Pt surface (not shown). Thus, surface modifications may be effective for increasing the sensitivity of gas sensors. We believe that the device works in the following way.

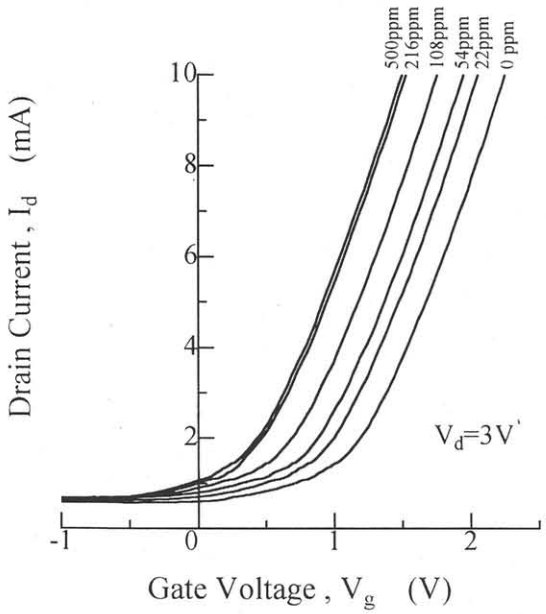

Fig.2 Change in the threshold voltage in different hydrogen concentrations during operation at 27℃.

Hydrogen (H_2) is adsorbed and dissociated, at the outer part of the Pt surface, to adsorbed atomic hydrogen (H_a). Some of the adsorbed atoms diffuse rapidly into the porous Pt in the form of dissolved atomic hydrogen (H_{pd}), some of which is trapped as atomic hydrogen (H_{ai}), at the inner Pt surface near the Pt/SiO_2 interface. The dipole moments of the hydrogen atoms changes the work function of the Pt at the Pt/SiO_2 interface, and therefore directly affect V_{th} of the transistor.

The physics of the gas sensing mechanism can be analyzed by considering the following atomistic reaction kinetics at the Pt/SiO_2 interface of the MOSFET [1]. Some hydrogen atoms are dissolved in the Pt layer and adsorbed onto the Pt/SiO_2 interface,

$$H_a \underset{d_1}{\overset{c_1}{\rightleftarrows}} H_{ai}, \qquad (1)$$

where c_1 and d_1 are the adsorption and desorption rate constants, and H_a and H_{ai} are adsorbed species on the Pt surface and at the Pt/SiO_2 interface, respectively. The coverage, θ, of hydrogen atoms at the interface is given by

$$\theta/(1-\theta) = (c_1 P_{H2}/d_1)^{1/2} \qquad (2)$$

$$\theta = \Delta V_{th}/\Delta V_{th(max)}, \qquad (3)$$

where $\Delta V_{th(max)}$ is the maximum threshold voltage shift (obtained from extrapolations to $P_{H2}=\infty$). The plots of $1/\Delta V_{th}$ versus $(P_{H2})^{1/2}$ indicate that $\Delta V_{th(max)}$ is

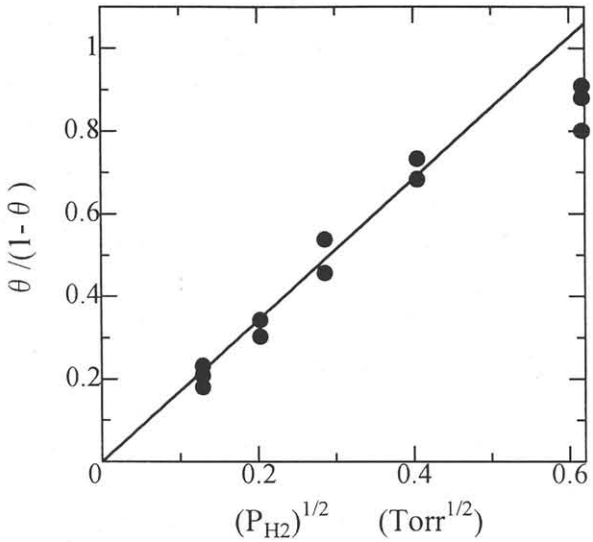

Fig.3 $\theta/(1-\theta)$ versus $(P_{H2})^{1/2}$ at a steady state.

1.66 V. Figure 3 shows the plots of $\theta/(1-\theta)$ versus $(P_{H2})^{1/2}$ at a steady state, where $(c_1/d_1)^{1/2}$ is obtained from the slope of the plots. It is observed that all data are in good agreement with the sensing mechanism proposed.

4. Conclusion

In summary, we have shown that porous Pt metal-oxide-Si MOSFET gas sensors can be used as highly sensitive detectors for hydrogen in a lower temperature range (27℃) than that of conventional solid-state gas detectors (> 200℃). The device detection mechanism presented is in good agreement with the experimental data. The porous Pt structure is more sensitive to hydrogen than an unmodified Pt gate structure.

Acknowledgements

We would thank Dr. H. Sohma of Muroran Techno Center Foundation for surface analysis and fruitful discussion.

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