Silver Gate Field Effect Transistor for Oxygen Gas Sensor

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***Abstract*— A silver gate field effect transistor (FET) integrated thermal controller was developed for a new type of oxygen gas sensor. It showed a threshold voltage change at a temperature as low as 80˚C. Oxygen response characteristics of the FET prepared with different productions of silver materials using a vacuum-evaporated membrane, printed material using silver-nanoparticles and silver epoxy were compared. The FET with a gate of silver epoxy showed the largest sensitivity of 135 mV/decade in the oxygen concentration range from 5% to 40% at 120˚C.**

Keywords-FET; oxygen gas; silver gate

I. INTRODUCTION

The oxygen gas sensor is one of the most commonly used chemical sensors. There are many types of sensor such as potentiometric, resistive, amperometric and optic sensors. Miniaturization and mass-production are desired for sensor devices, especially in multipoint measurement such as in sensor networks. A solid-state sensor is suitable for such demands. At present, oxygen sensors based on yttria-stabilized zirconia (YSZ) electrolytes as solid-state are being successfully utilized for automobile and industry monitoring. An oxygen sensor with YSZ is suitable for high temperature conditions such as in automobile exhausts and furnaces. On the other hand, it is limited to low temperature operation lower than 500˚C because the resistivity of YSZ is too high at low temperatures. Recently, solid-state oxygen sensors operable at low temperature have been reported. For example, a ZnO nanowire-based sensor [1] and platinum-doped In_2O_3 nanocrystals [2] operable at room temperature showed resistance change to oxygen. One of the authors reported a field effect transistor (FET) type oxygen sensor operable at room temperature, and the FET-type sensor showed a sensitivity of 6 mV/decade to oxygen partial pressure [3]. The FET-type sensor has a gate of about 10-nm-thick platinum/ YSZ layer deposited on the gate insulator of FET. The interface between the YSZ layer and the Pt layer was an active site for oxygen dissociation. However, it was very difficult to optimize the gate structure because the interface of gas-Pt-YSZ had to exist on the gate surface. Silver is an oxygen selective material and acts as a catalyst to oxygen; therefore gas diffusion electrodes with silver catalysts have been investigated for fuel cells, batteries, etc [4]. In this study, we applied silver as the gate material for the FET-type gas sensor.

II. EXPERIMENTAL

The developed FET has a gate structure of upper silver material as the oxygen sensitive layer, and double insulator layers of a 125-nm-thick Si_3N_4 and a 43-nm-thick SiO_2 (Fig. 1), which are based on a similar structure to that of the previous reported hydrogen sensor [5]. The FET is an n-channel type FET with a channel 40 μm long and 390 μm wide. To investigate the optimization of the silver gate, three types of fabrication method were compared. One is a thin film that was fabricated by vacuum evaporation. The second material was fabricated using silver-nanoparticles. The FET insulator gate was coated with the silver-nanoparticles ink (nanometal ink L-Ag, ULVAC), and then baked at 120˚C. The third material was silver epoxy (CircuitWorks®), which was fabricated by a printing mixture of epoxy and hardener, and then cured at room temperature. To control the temperature of the Ag-gate FET sensor, a temperature sensor using a p-n junction diode and a heater using Ti/Ni/Au resistance were integrated into the same chip. To measure the oxygen response, voltage follower circuits were used to determine the threshold voltage change of the FET. The voltage follower circuits worked to maintain the constant drain-source voltage and current of the FET. To maintain the constant gate voltage, the Ag-gate was connected to the electrode. This circuit configuration operated such that the output voltage change of the circuit was the same as the work-function change of the silver. The work-function change was equal to the threshold voltage change of the FET. Sample gases with different oxygen concentration were prepared by a gas mixture using oxygen and nitrogen gases. The gas sensor was installed in a flow-through cell, and sample gas was flowed into the cell at a flow rate of 0.5 l/min.

III. RESULTS AND DISCUSSION

The oxygen gas response of the developed sensor was evaluated by the gas flow system. To control oxygen concentrations, pure oxygen and nitrogen gas were mixed. First, the sensor reproducibility as a function of oxygen concentration ranging from 10% to 20% was studied at 100˚C (Fig. 2). The oxygen sensor with silver epoxy showed the largest sensitivity and best stability. In contrast, the sensor with silver nanoparticles showed poor response. The sensitivity of the FET with silver epoxy was 50 mV/decade, and it was larger than the Nernstian response

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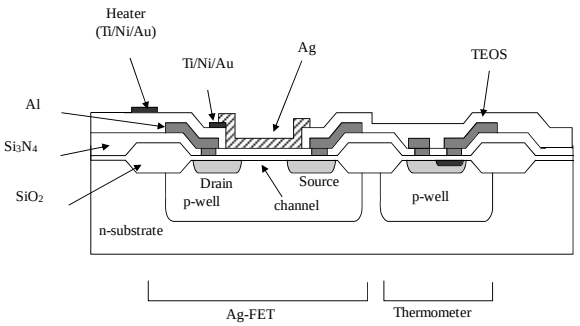

Figure 1. Schematic diagram of the structure of the integrated silver-gate FET with thermal control.

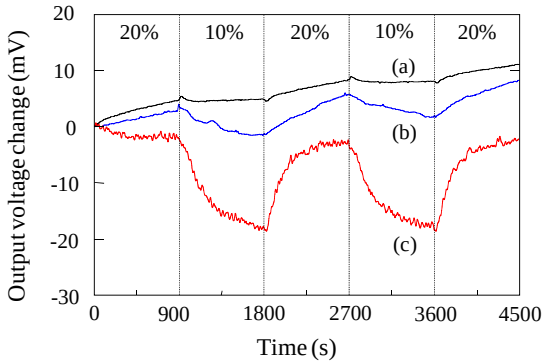

Figure 2. Comparison of oxygen response characteristics of the FET-type sensor using different silver membranes at 100˚C: (a) silver nanoparticle membrane, (b) silver vacuum evaporation membrane, (c) silver epoxy membrane.

sensitivity (19 mV/decade at 100˚C) based on the equilibrium reaction as below.

$$\frac{1}{2}O_2 + 2e^- \leftrightarrow O^{2-} \quad (1)$$

If the reaction occurs at the membrane surface, the silver membrane potential changes according to the Nernst equation below:

$$\emptyset_m = \text{const} - \left(\frac{RT}{4F}\right) \ln P_{O_2} \quad (2)$$

where ϕ_m is the membrane potential, F is Faraday's constant, R is the gas constant, T is absolute temperature, and P_{O2} is the partial pressure of oxygen. The sensitivity of the sensor with the silver vacuum evaporation was 20 mV/decade, and it was nearly equal to the Nernstian response.

To investigate the response difference, membrane structures were observed by scanning electron microscopy (Fig. 3). The silver vacuum evaporation membrane showed a very smooth surface whereas the silver nanoparticle membrane showed a crushed surface. This was due to the poor adherence to the Si3N4 gate insulator, and therefore it showed the lowest response. The silver epoxy membrane showed a porous and rough surface. This created the largest surface, so active sites of the silver membrane were considered to be rich. The silver vacuum evaporation membrane had a very smooth surface, where it was assumed that the smooth surface created the monolayer reaction at the activated site on the membrane, and then the membrane potential was described by the Nernst equation. On the other hand, the sensor with the silver epoxy had a porous and rough surface, and it created the multilayer of the dissociated oxygen inside the gate membrane. The higher sensitivity was considered due to the dissociated oxygen diffusion inside the silver gate.

The oxygen response was obtained over 80˚C, and sensitivity was increased according to the temperature increment (Fig.4). It was not linear. According to the temperature increment, activation energy increased and then oxygen dissociation reaction was accelerated. The oxygen response to a wider oxygen range from 5% to 40% was investigated. The sensor showed a linear response to

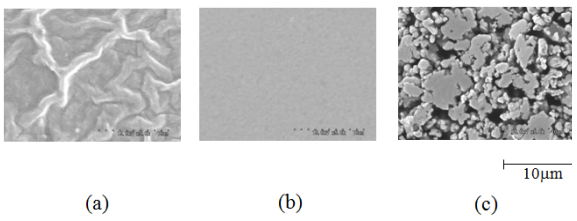

Figure 3. SEM images of the silver membrane: (a) silver nanoparticle membrane, (b) silver vacuum evaporation membrane, (c) silver epoxy membrane.

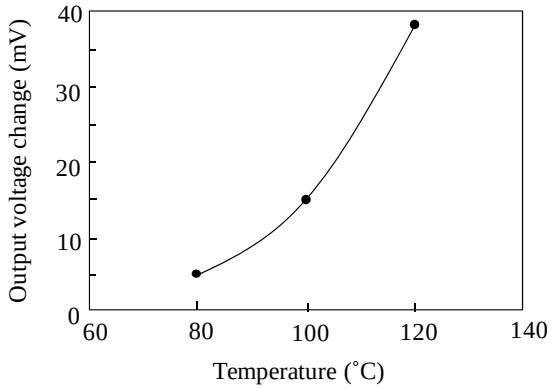

Figure 4. Temperature dependence of the sensitivity of FET-type oxygen sensor with silver epoxy gate.

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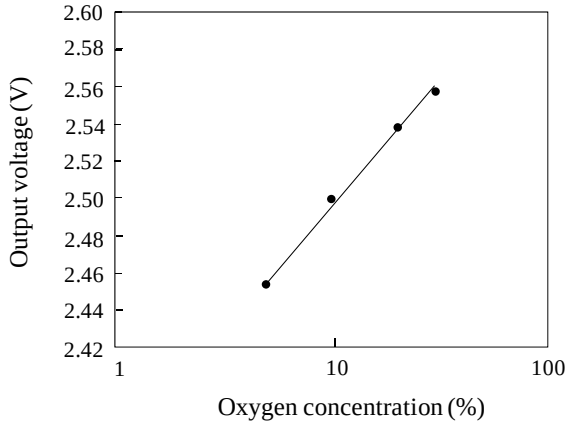

Figure 5. Calibration curve of the FET-type oxygen sensor at 120˚C.

logarithmic oxygen concentration, and it was 135 mV/decade at 120˚C (Fig. 5).

In this study, we proposed a new oxygen sensor for the silver-gate FET. The silver-gate FET using silver epoxy showed the largest sensitivity compared with other silver membranes. This was considered due to the sterically-congested dissociated oxygen at the silver membrane.

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