

Gas Sensing Characteristics of Low-powered Dual MOSFET Hydrogen Sensors

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Abstract

A low-powered hydrogen sensitive dual-MOSFET device was designed, fabricated and characterized for self compensation to electric signal degradation. Differential outputs in both sensitive and reference FETs were stable for changes in the outer environments due to the same dependence of the electrical characteristics. The proposed sensor design showed low power consumption (45.5 mW at 150°C) by achieving complete heat isolation. Stable responses to H₂ gas were observed over a range of temperatures and the optimal point in the micro-heater operation was approximately 150°C (The highest sensitivity was 111.17 μ A to 5,000 ppm H₂ gas, the response and recovery times were 18 sec and 19 sec, respectively.). From the experimental results, the increased sensitivity to various H₂ concentrations corresponded to the Langmuir relationship.

Key words: gas sensor, hydrogen, MOSFET, low power and silicon micromachining

Introduction

Hydrogen gas monitoring has attracted considerable interest in many fields, such as the chemical industry, semiconductor manufacturing process and fuel cells, mainly for gas leak detection and monitoring [1]. Hydrogen sensors based on Pd – MOS field effect transistors have been used over the past 35 years [2,3]. Some research groups have recently worked on thermally isolating the electronic components on the membranes by silicon micromachining and CMOS technologies [4,5], but few have examined MOSFET-type gas sensors. Previous studies utilized SOI (Silicon on Insulator) wafers, which were unsuitable for the low cost gas sensor fabrication, and two process steps for the thermal isolation structures, which were quite difficult fabrication process. For these reasons, this study proposed a simple route for thermally isolated sensing components in a MOSFET type gas sensor chip frame via a modification of the two step bulk micro-machining process.

In this study, a compensation method was developed using a reference FET with no hydrogen gas response and a sensitive FET with the same electrical performance. The electrical characteristics, thermal properties and hydrogen gas sensing performance were analyzed in the fabricated sensors.

Experimental

A compensation method was developed using a sensitive component for hydrogen sensing and a reference with the same electrical characteristics. Figure 1 shows the low powered dual-MOSFET sensor. The FET with the same gate metal, which had an identical work function, was unaffected by hydrogen gas, and was integrated with a gas sensitive-FET. To control the operation temperature, a micro-heater was integrated into the sensor chip using the same gate material, Pt thin film, for the simple fabrication steps. The entire fabrication process was accomplished using six masks for the photolithography steps. These six lithography masks were prepared to develop gas sensor fabrication processes for Arsenic ion implantation and diffusion, gate insulation layer (SiO₂), gate and metal contact line (Pt pattern), passivation layer, and bulk micromachining patterns. A discrete silicon island structure was produced by two successive micromachining process-steps to reduce the heat loss inside the dielectric membrane [6].

The gas sensing measurements were performed in a continuous gas flow system to control the H₂ gas concentration. The gas sensing signals to H₂ gas were examined by measuring the drain current changes in the output curves (V_{DS} - I_D).

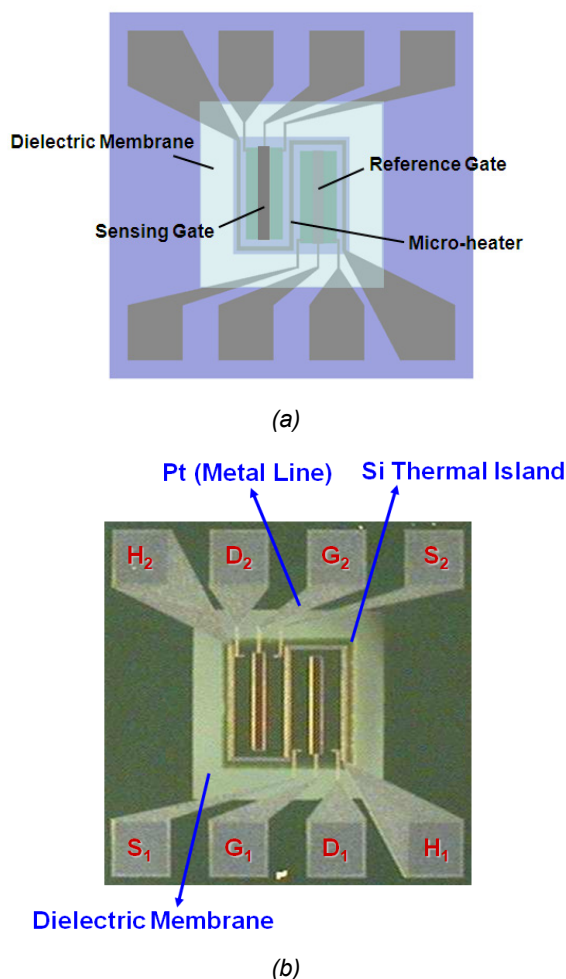


Fig. 1. Low powered dual-MOSFET sensors: (a) the schematic diagram, and (b) photographs of the fabricated sensor device.

The hydrogen response was measured using voltage follower circuits to determine the changes in the drain current of both FET devices. The gas sensing properties to H_2 gas (5,000 ppm) were analyzed at sensing element temperatures from room temperature to 250 °C. The gas responses to various H_2 concentrations were also evaluated from 100 ppm to 10,000 ppm of H_2 gas at the optimum operating temperatures

Result and Discussion

The thermal mass and power dissipation of the sensor were minimized by the thermal island design. To increase the heating efficiency, dual (sensing/reference) FETs and a heater were located in a silicon island isolated from the chip frame by a dielectric membrane. The effect of the silicon island structure was examined using a FEM simulation. Precise temperature control of the sensing element and the power consumption of the fabricated sensor device were achieved using a micro-heater operation. The fabricated sensor device showed low

power consumption; 45.5 mW and 68.4 mW at 150°C and 200°C, respectively. This shows that the proposed sensor design could achieve the thermal isolation and reduce the heat loss by Si thermal island formation through two successive bulk micromachining steps.

At the gas sensing characterization for H_2 gas (5,000 ppm) in Figure 2, the changes in the drain currents of the sensing FET were 54.41 μA , 60.17 μA , 83.72 μA , 111.17 μA , 74.11 μA and 70.50 μA at a micro-heater temperatures of room temperature, 50°C, 100°C, 150°C, 200°C, and 250°C, respectively. In particular, the drain current changes increased gradually with increasing temperature of approximately 150°C, but the gas sensing signals decreased at high temperatures. As shown in Figure 3, the response and recovery times also appeared to be shorter at 150°C than at the other temperatures. From these experimental results, the sensor operation at 150°C showed the best performance to hydrogen gas due to the highest sensitivity and stable response/recovery characteristics at this temperature.

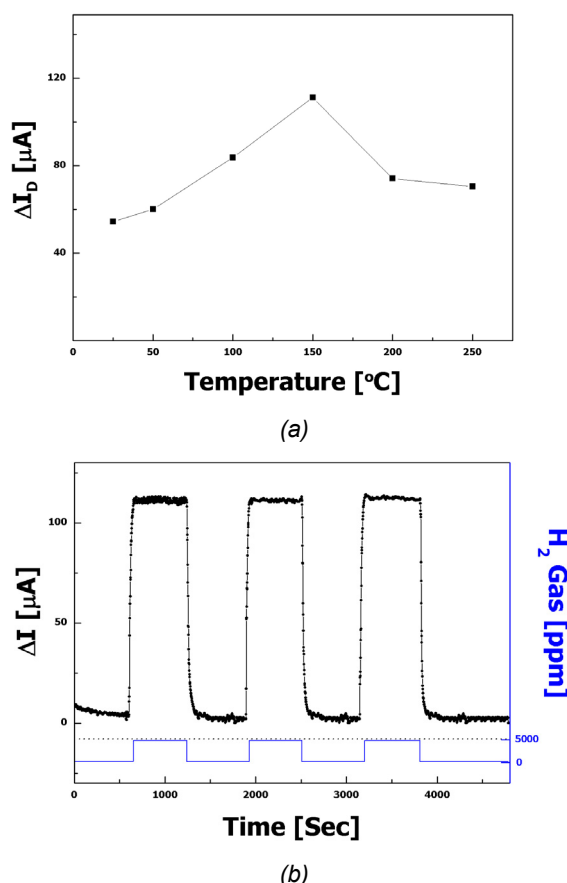


Fig. 2. Gas sensing characteristics of the dual-FET sensors: (a) drain current changes at various operating temperatures, and (b) transient responses for 5,000 ppm H_2 gas injections at 150°C.

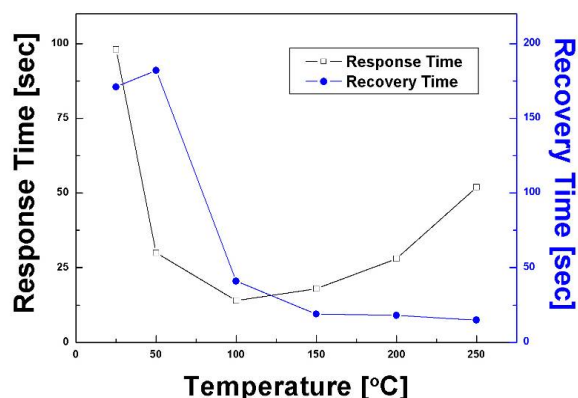


Fig. 3. Gas sensing characteristics of the dual-FET sensors at various operating temperatures: data plots for the comparison of response/recovery times (at 5,000 ppm H₂ gas injections)

Figure 4 shows the drain current change with various hydrogen concentrations from 100 to 10,000 ppm. The sensor operation temperature was 150 °C, and the sensor signal increased with increasing hydrogen concentrations. At all gas concentrations tested, the signals were achieved quickly a steady state. The gas sensitivities to H₂ gas at concentrations of 100, 500, 1,000, 2,000, 5,000, and 10,000 ppm were 8.46 μA, 16.38 μA, 31.27 μA, 67.24 μA, 111.17 μA, and 167.81 μA, respectively. The dotted line in the figure corresponds to the Langmuir relationship expressed simply as;

$$\Delta I_{\max} = \Delta I_{\max} \frac{\sqrt{C/C_0}}{1 + \sqrt{C/C_0}} \quad (1)$$

where ΔI_{\max} represents the maximum value of the drain current change, C is the hydrogen concentration in dry air and C_0 is a hydrogen concentration at $\Delta I = \Delta I_{\max}/2$. Both ΔI_{\max} and C_0 might be obtained by fitting the experimental values.

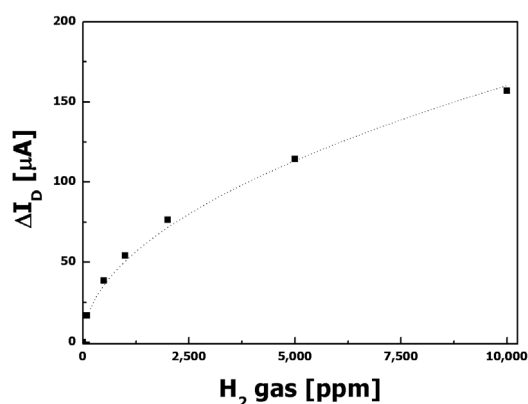


Fig. 4. Gas sensing characteristics of the dual-FET sensors at various H₂ gas concentrations.

Conclusion

The dual-gate FET hydrogen sensor was integrated with a micro-heater and two Pt-gate FETs (sensing/reference devices) for hydrogen detection. The identical output of the sensitive-FET and reference-FET contributed to the stable output in the higher temperature ranges. The proposed sensor design could achieve complete thermal isolation inside the dielectric membrane. The optimal operating point of the Pt-FET sensor was approximately 150°C, showing the highest sensitivity (111.17 μA) to 5000 ppm H₂ gas, as well as a faster response and recovery (18 sec and 19 sec) than at other temperatures. The increased sensitivity for various H₂ concentrations corresponded to the Langmuir relationship. The dual MOSFET H₂ gas sensor is suitable for a range of applications in several fields because of its low-power consumption, thermal stability and rapid response/recovery performance.

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