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Air Gap Control Method and Sensitivity Improvement in Capacitive MEMS Hydrogen Sensors

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Abstract

In this paper, we present a method for improving the sensitivity in capacitive MEMS hydrogen sensors. A coverage of two TiN layers of a movable membrane and a hydrogen actuator is changed to control an air gap. Finite element analysis shows that we can control the gap between capacitive electrodes and improve the sensitivity by arranging TiN patterns. Measurement results demonstrate the sensitivity to hydrogen increased by 14 times compared to the conventional design.

1. Introduction

Hydrogen is expected to increasingly serve as a source of clean energy that does not emit CO_2. However, because hydrogen gas is explosive at concentrations between 4 and 75 vol% in air, fast detection of hydrogen leaks is important for ensuring safety [1]. Therefore, hydrogen sensors must be low power consumption and respond quickly. We have, thus, proposed a capacitive MEMS hydrogen sensor using a Pd-based metallic glass (PdCuSi) [2-3]. In view of detecting early leakage, high sensitivity hydrogen sensors are required. The air gap between a movable and a fixed electrode is a critical factor in the sensitivity of capacitive MEMS sensors. In this paper, we present a method for controlling the air gap in the capacitive MEMS hydrogen sensor.

2. Concept of Air gap control method

Structure and concept

Our sensor consists of hydrogen actuators with a PdCuSi film, a movable membrane with an embedded electrode and a fixed electrode as shown in Fig. 1. TiN films are symmetrically arranged in the actuator and the membrane to suppress bending. The actuator and the membrane are connected via a spring structure. Hydrogen absorption in the PdCuSi film generates compressive stress that deforms the actuator. This deformation is then transmitted to a movable membrane via a spring. As a result, the capacitance between movable and fixed electrode increases due to the change of the air gap. Assuming a parallel plate model, capacitance sensitivity can be approximated as

$$\frac{dC}{dg} \cong -\frac{\varepsilon_0 A}{g^2}$$

where C, ε_0, A, g is the capacitance, the permittivity of vacuum, the area of the capacitive electrode and the air gap

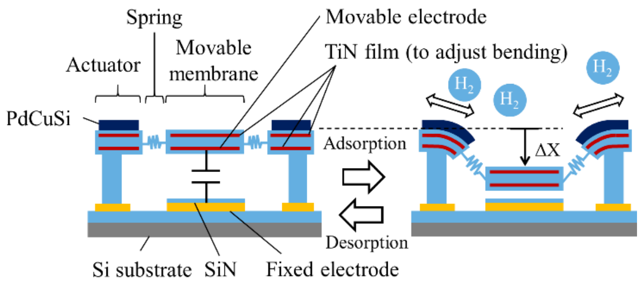

Fig. 1 Cross sectional structure and operating principle of the capacitive MEMS hydrogen sensor.

between electrodes, respectively. This equation shows that the sensitivity is improved by narrowing the air gap between capacitive electrodes. However, the tensile stress of the PdCuSi film induces upward bending in the actuator, and, as a result, the sensitivity degrades. Therefore, we propose to control the air gap by changing the coverage of top and bottom TiN layers in the actuator and the membrane as shown in Fig. 2.

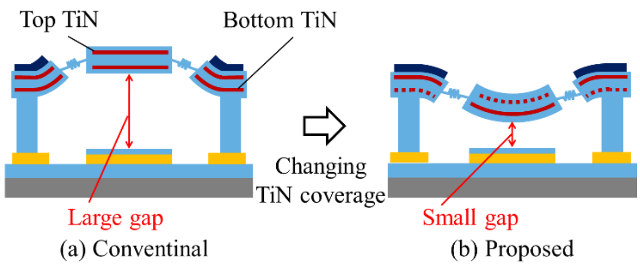

Fig. 2 Method for controlling the gap in the capacitive MEMS hydrogen sensor.

Design

We performed a finite element analysis to examine our method. Fig. 3 (a) shows the top view, the cross section and film stress values of the simulation model. Note that a SiN film is divided into two layers to express the distribution of the film stress in the direction of film thickness in this model. We simulated sensor structures using (1) the coverage of the top TiN layer in the movable membrane and (2) the bottom TiN layer in the actuator as parameters. The coverage was defined as a ratio of the TiN area to the SiN area. The simulation results show that the capacitance value increases as the coverage of the TiN layers are reduced in the membrane and the actuator as shown in Fig. 3 (b). Model A corresponds to the conventional structure in Fig. 2 (a). It is found that the shape of the movable membrane shows convex in the case of

Model A. On the other hand, that of Model B, in which capacitance is the highest among these simulations, shows concave as expected (Fig. 3 (c)).

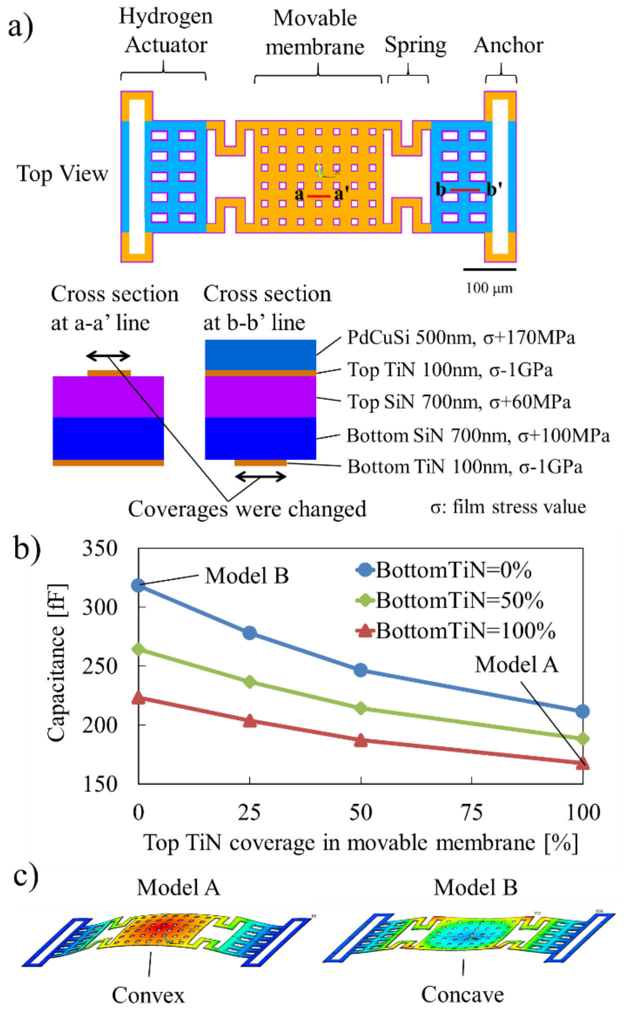

Fig. 3 Models and results of finite element analysis (a) Schematic of the model used in this simulation, (b) TiN coverage dependence of capacitance, (c) perspective views of two simulated models.

3. Measurement results and discussion

Based on the simulation results, we fabricated samples of Model A and B in the Fig. 3 utilizing a process reported in [4]. Fig. 4 (a) shows interference microscope images for fabricated samples. The movable membrane was convex and the actuator bended upward in Model A. On the other hand, in Model B, the membrane was concave and the bending of the actuator was suppressed. This result is consistent with the simulation. The capacitance measured in air of Model B was 1.8 times larger than that of Model A, which is also agreement with the simulation result (Fig. 4 (b)).

We measured the hydrogen concentration dependence of ΔC, which was defined as a value of the difference from the capacitance in air. The measurement was performed at 25°C, and dry air was used as the carrier gas. The flow rate was 5 l/min. As expected, ΔC of Model B was larger than that of Model A at all measured hydrogen concentrations; it was 14 times larger than that of Model A at 3000 ppm (Fig. 5). Therefore, these results prove that our method is able to improve the sensitivity of the capacitive MEMS hydrogen sensor.

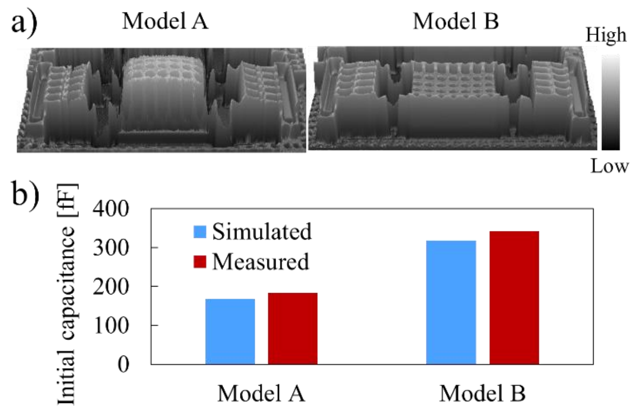

Fig. 4 Comparison of Model A and Model B (a) Interference microscope images for fabricated samples, (b) Comparison of the initial capacitances.

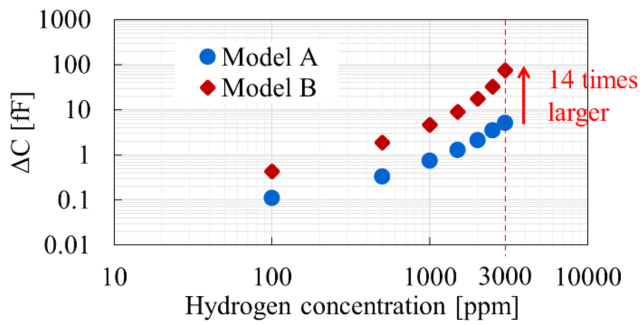

Fig. 5 Comparison of hydrogen concentration dependence of sensor outputs.

4. Conclusion

We proposed a method for controlling the gap and improving the sensitivity of surface micro-machined capacitive MEMS hydrogen sensors. By applying this method, the gap between capacitive electrodes was narrowed and the sensitivity of our capacitive MEMS hydrogen sensor successfully increased. Therefore, the proposed method is effective for development of high sensitive capacitive MEMS hydrogen sensors.

Acknowledgements

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References

[1] T. Hübert *et al.,* Sensors and Actuators B: Chemical **157** (2011) 329.

[2] Y. Hayashi *et al.,* International Journal of Hydrogen Energy **43** (2018) 9438.

[3] H. Yamazaki *et al.,* Electronics and Communications in Japan **102** (2019) 70.

[4] Y. Hayashi *et al.,* IEEJ Transactions on Sensors and Micromachines **140** (2020) 158 (in Japanese)