

MINIATURIZATION OF ON-WALL IN-TUBE FLEXIBLE THERMAL FLOW SENSOR USING HEAT SHRINKABLE TUBE

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ABSTRACT

We previously proposed a novel type of on-wall in-tube thermal flow sensor, and experimentally evaluated its performance. The sensor has an advantage that it can measure the flow-rate both at near the tube entrance (hydraulically developing region) [1] and at bent tube (axially asymmetric flow) [2]. With the requirements of further miniaturization of the sensor in the fields of the portable fuel cells and chemical analyzers, we newly developed the fabrication process to miniaturize it less than 2.0 mm in external diameter by using a heat shrinkable tube. The film sensor fabricated by photolithography was inserted inside tube manually. By applying heat shrinking process, the film was automatically mounted on the inner wall surface, and the outer size of the tube was miniaturized to almost of the half size from its original. The final inner and outer diameters of the tube were 1.2 mm and 1.7 mm, respectively. We evaluated the fundamental performance of this flow sensor. The electrical resistance at the sensor linearly increased with temperature. The obtained temperature coefficient of resistance of the sensing element was 0.0023 K^{-1} . We measured the relationship between the input power consumption and the gas flow rate, and finally evaluated the response time. We obtained a value of 100 msec by forming a cavity structure under the heat element.

1. INTRODUCTION

Many types of miniaturized Si-based flow sensors are now widely used to detect the amount of sample fluids and to control gas mixture ratios in various industries. With the requirements for further miniaturization of equipment, such as the gas control systems in chemical analyzers and semiconductor manufacturing equipment, compact heat exchangers [3], and portable fuel cells (Fig. 1), the following requirements have recently been specified for the gas tube configuration.

- (1) Bent tube: To decrease the occupied volume in gas control systems, the use of bent tube configurations is increasing.
- (2) Miniaturized flow channel: Along with the miniaturization of application systems, the size of the flow channel also must be reduced.

As a result, sensors that can measure flow rates in miniaturized bent tubes are needed in cutting-edge areas. Hot-wire sensing is widely used as a detection method in conventional flow-rate measurements. It detects the flow rate at a point in the center of the tube, so it cannot output a constant value when the velocity distribution is asymmetric in the radial direction [4]. Thus, it is difficult to use this type

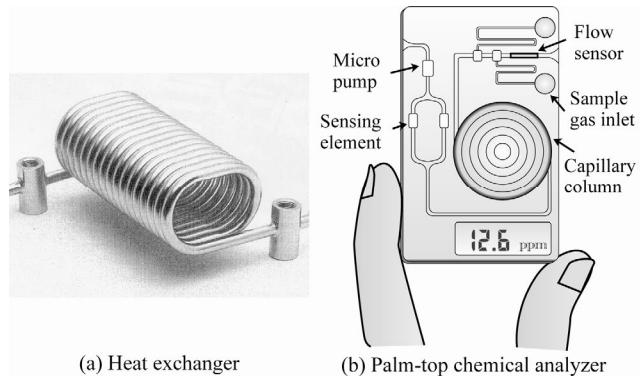


Fig. 1. Schematic diagrams of miniaturized fluidic devices.

of sensing mechanism for measurements performed in bent tubes, where the velocity distribution changes depending on the radius of curvature and the angle of the tube and on the distance from the exit of the curved part to the sensor position. To overcome this problem, we previously devised a novel type of on-wall in-tube thermal flow sensor. We formed a ring-shaped sensing structure on the inner-wall surface of the tube. This sensor averages the circumferentially non-uniform velocity distribution in a distorted flow condition, so it can overcome the above problem. In previous studies, we experimentally confirmed that the sensor can measure a gas flow rate both near the tube entrance (hydraulically developing region) [1] and under radially asymmetric flow conditions in a bent tube [2].

Up to now, we have used a gas tube with inner and outer diameters of 3 and 6 mm, respectively, because this tube size is widely used in gas piping systems. In those previous studies, we manually assembled the film sensor on the tube's inner-wall surface and formed a ring-shaped sensor structure. However, further miniaturization of the sensing structure, for example to an external diameter of less than 2.0 mm to satisfy the second requirement above, is difficult. Therefore, we developed a new fabrication process to miniaturize the sensor by using a heat-shrinkable tube.

2. FABRICATION

We used polymer-MEMS (microelectromechanical systems) technologies to fabricate a flexible film thermal flow sensor and newly introduced a heat-shrinkable tube, as a miniaturizing packaging component, in its fabrication. The details of the developed fabrication method are as follows (Fig. 2).

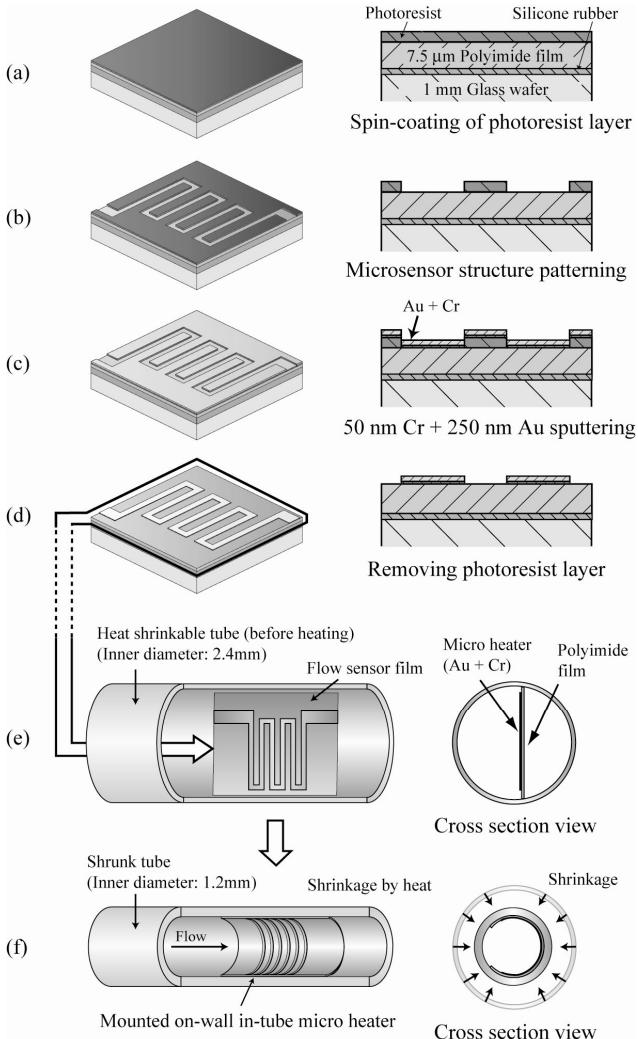


Fig. 2. Fabrication process for miniaturized on-wall in-tube sensor using a heat-shrinkable tube.

- (a) We used a polyimide film as a substrate. The thickness of the film affects the performance of the thermal isolation. Generally, a thicker film is desirable to increase the thermal isolation. However, the film's stiffness also increases with its thickness and this causes tube deformation during the heat-shrinking process because the tube becomes soft when heated. For these reasons, we chose a film thickness ranging from 7.5 to 25.0 μm in the fabrication. To handle such a thin flexible film structure, we first fixed it onto a glass wafer using thin silicone rubber and then coated a 2.0- μm -thick layer of photoresist onto the film.
- (b) The photoresist was patterned using UV light, and the shape of the microsensor was thus defined.
- (c) An Au/Cr film (Cr was used as a membrane for adhesion) was deposited by sputtering. The thicknesses of Au and Cr were 300 and 50 nm, respectively.
- (d) The metal film heater structures were patterned by applying the lift-off process. A flexible film-type of sensor was obtained by peeling it from the silicone rubber on the glass wafer.

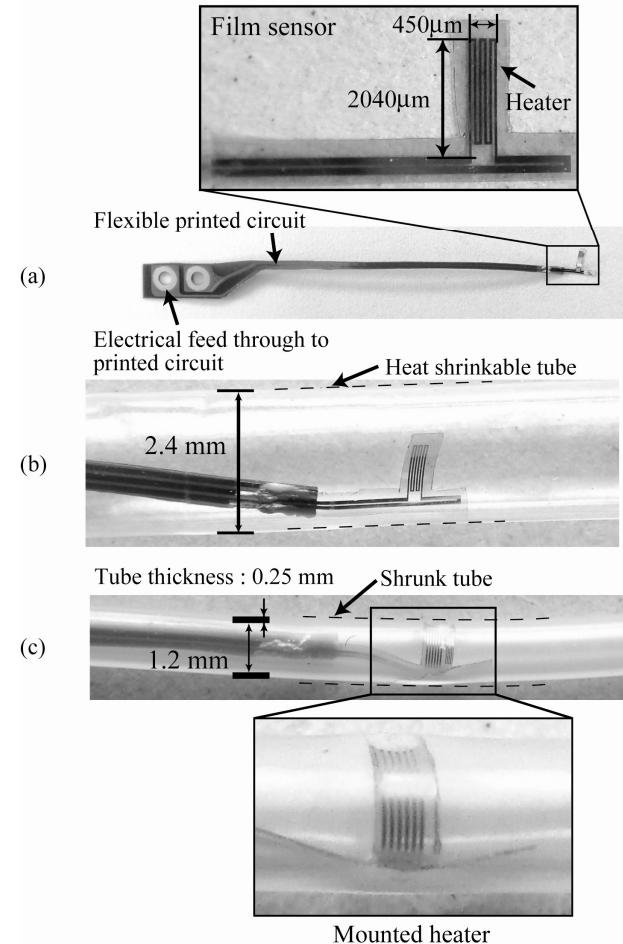


Fig. 3. Details of the sensor and heat-shrinkable tube.

- (e) The flexible film sensor was manually inserted inside the heat-shrinkable tube.
- (f) The heat-shrinkable tube was heated to 140°C. As shown in Fig. 2(f), the tube was shrunk to almost half its original size by the heat, and the film sensor was automatically mounted on inner wall surface during the shrinking process. The film had enough stiffness to deform the outer tube slightly. We therefore think that the film was fixed firmly on the tube surface.

The fabricated sensor device at each stage is shown in Fig. 3. We used a flexible printed circuit for the electrical connections from the film sensor. Figure 3(a) shows the fabricated film sensor and its appearance when assembled on the circuit. The shapes of the film mounted inside the heat shrinkable tube before and after the heating process are shown in Figs. 3(b) and 3(c), respectively. The film was successfully automatically mounted on the inner wall surface after the heat-shrinking process. The inner and outer diameters of the shrunk tube were 1.2 and 1.7 mm, respectively. These values are almost one third those in our previous method. The final tube diameter can be easily selected by changing the type of heat-shrinkable tube. We now think that this packaging method of on-wall in-tube film

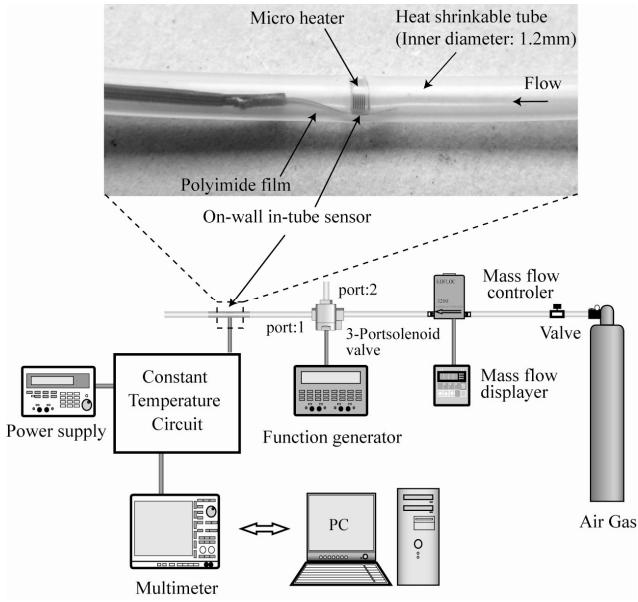


Fig. 4. Experimental setup.

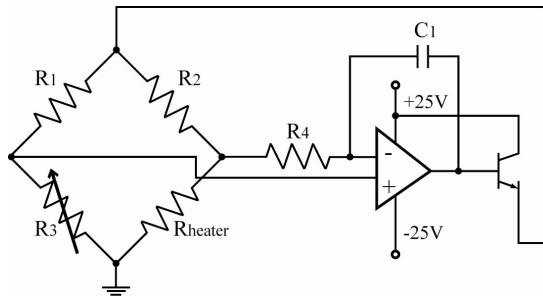


Fig. 5. Constant temperature circuit.

mounting is suitable for sensor miniaturization because the sensor structure itself does not disturb the flow stream. This is because that the flow velocity at the near the surface is much lower than that at the center of the tube.

3. EXPERIMENT

We evaluated the fundamental performance of the developed flow sensor. The experimental setup for the evaluation is shown in Fig. 4. The gas flow passing through the sensor was regulated by a commercially available mass flow controller. The flow rate was measured from the power consumed by the heater operating in constant-temperature mode, as shown in Fig. 5.

3.1 Temperature coefficient of resistance (TCR)

We at first investigated the relationship between the sensor temperature and the electrical resistance change. The resistance linearly increased as the temperature increased, as shown in Fig. 6. From this graph, we obtained a TCR value of 0.0023K^{-1} .

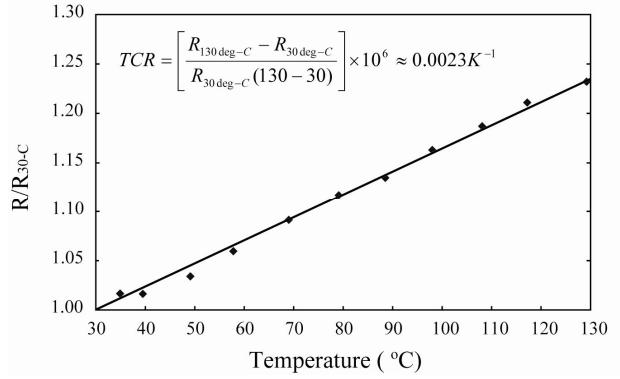


Fig. 6. Change in resistance of thermal flow sensor versus temperature.

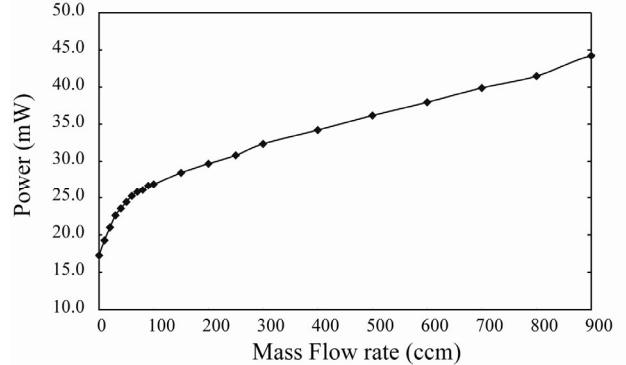


Fig. 7. Relationship between sensor input power and the flow rate.

3.2 Relationship between power consumption versus flow rate

We investigated the relationship between the input power of the sensor and the flow rate. The required input power increased as the mass flow rate increased, as shown in Fig. 7. The developed sensor required input power of 15–45 mW to detect flow rates ranging from 0 to 900 sccm.

3.3 Response time

We used the three-port solenoid valve located between the sensor and the mass flow controller, to evaluate the response time, as shown in Fig. 4. Outlet ports 1 and 2 were used for the sensor performance and gas exhaust evaluations, respectively. The response time was measured by switching the tube connection from port 2 to port 1.

A typical response waveform is shown in Fig. 8. The sensor output initially increased rapidly and reached on some level within 100 msec. However, it still gradually increased with a different time constant after 100 ms and did not show any tendency to saturate. We think that this slight increment was caused by poor thermal isolation of the thin polyimide film (some of the heat generated by the heater on the polyimide film transferred to the surrounding outer tube). This heat leakage caused the sensor output to increase with time and not saturate even after 5 sec. It should be possible to eliminate this phenomenon by improving the thermal isolation.

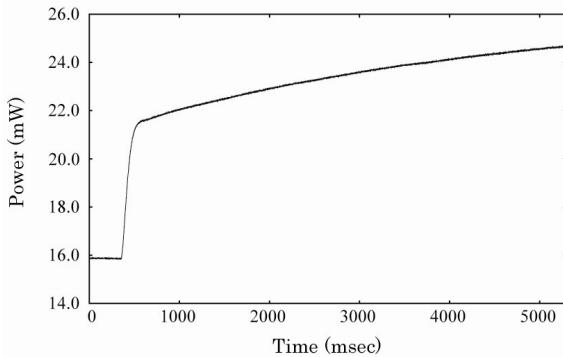


Fig. 8. Response time of the heater mounted on the surface.

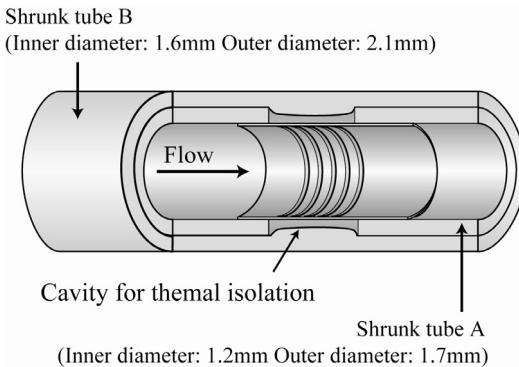


Fig. 9. Improved sensor structure having cavity for thermal isolation.

Generally, diaphragms or bridges are used as heater structures to improve thermal isolation in miniaturized flow sensors [5, 6, 7, 8]. Thus we formed a cavity structure under the heat element to overcome the problem. For making the cavity structure, we added one more a heat shrinkable tube (tube A) having the slit, into the inside of the previous one (tube B), as shown in Fig. 9. The size of the outer diameter of the inner tube was a little bit larger than that of the inner diameter of the outer one, after the heat shrinking process. Therefore, these two tubes were tightly fixed each other after the fabrication process. Typical results for the improved sensor response waveform achieved using this thermal isolation method is shown in Fig. 10. In this case, the sensor output reached 90% of the maximum value within 100 ms.

4. CONCLUSION

To meet the requirements of further miniaturization of sensors for portable fuel cells and chemical analyzers, we developed a new fabrication process to miniaturize the sensor to an external diameter of less than 2.0 mm by using a heat-shrinkable tube. The following results we obtained.

- (1) The film sensor fabricated by photolithography was inserted inside the tube manually. The heat-shrinking process automatically mounted the film on the inner wall surface and reduced the outer size of the tube to almost half its original size. The tube's final inner and outer diameters were 1.2 and 1.7 mm, respectively.

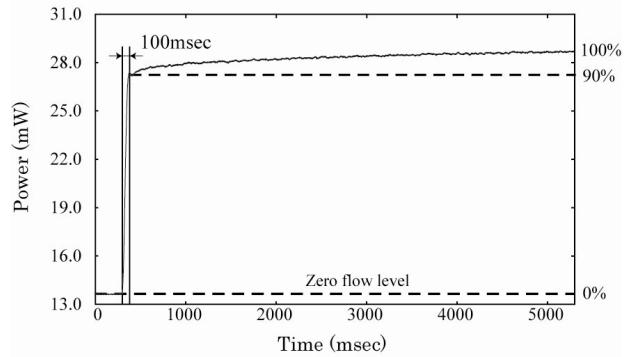


Fig. 10. Response time of the heater which is above the cavity.

- (2) The electrical resistance of the developed flow sensor linearly increased with increasing temperature. The temperature coefficient of resistance obtained for the sensing element was 0.0023 K^{-1} . A response time of 100 msec was obtained by making a cavity for thermal isolation.

From these results, we conclude that our method of on-wall in-tube film mounting is suitable for sensor miniaturization and that the developed flow sensor will be useful in applications for miniaturized gas control systems.

5. ACKNOWLEDGMENT

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REFERENCES

- [1] Z.Y. Tan, M. Shikida, M. Hirota, K. Sato, T. Iwasaki, Y. Iriye, "Experimental and theoretical study of an on-wall in-tube flexible thermal sensor", *J. Micromech. Microeng.* 17 (2007) 679–686.
- [2] J. Naito, Z. Y. Tan, M. Shikida, M. Hirota and K. Sato, "Characteristics of on-wall in-tube flexible thermal flow sensor at wrap pipe condition", *Tech. Dig. Transducers '07* (2007) 2349-2352.
- [3] J. P. Holman, "Heat Transfer Ninth Edition", McGraw-Hill Higher Education, pp 520, 2002
- [4] H. H. Bruun, "Hot-Wire Anemometry", Oxford University Press, 1995.
- [5] B.W. van Oudheusden, "Silicon thermal flow sensors", *Sensor and Actuators A*, Vol. 30 (1992) pp. 5-26.
- [6] H. Batles, O. Paul, O. Brand, "Micromachined thermally based CMOS Microsensors", *Proc. of the IEEE*, Vol. 86, No. 8, pp. 1660-78, Aug. 1998.
- [7] U. Buder, L. Henning, A. Neumann, and E. Obermeier, "AeroMEMS wall hot-wire sensor arrays on polyimide with through foil vias and bottom side electrical contacts", *Tech. Dig. Transducers '07* (2007) 2349-2352
- [8] G. C. M. Meijer and A. W. Herwaarden, "Thermal Sensors", Institute of physics Publishing Bristol and Philadelphia, 1994.