MICRO-MACHINED STENT-TYPE FLOW SENSOR FOR EVALUATION OF NASAL RESPIRATION

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ABSTRACT

We present a thermal flow sensor that is suitable for measuring nasal respiration. To fix the flow sensor inside the nasal passage, we integrated it onto a stent structure, which is normally used as a medical device. The sensor was monolithically integrated on the Ti substrate by applying photolithography and wet etching processes. The developed fabrication has advantage that it is able to fabricate the both of the cavity for the thermal isolation and the stent structure during the same process. We mounted the flow sensor onto the inner surface of the silicone tube by inflating the balloon tube. The mechanical strength of the cylindrical stent under the compression condition was also studied, and it showed an elastic deformation when the force was less than 0.08 N. The developed flow sensor could detect the flow direction at the flow range of 0 - 2000 ccm. A response time of less than 260 msec was obtained by forming a cavity under the sensor.

INTRODUCTION

Thanks to the development of semiconductor technologies, many types of physical sensors used in industrial applications have been miniaturized and commercialized. Miniaturized sensors can be used to provide new type of measurement hardware that will be used with current medical diagnosis systems. Human beings breathe through both the mouth and the nose. The bacteria and viruses are trapped in the nose cavity, and therefore the cleaned inspired air only supplied into the inside of the lung. The inspirited air is also humidified here so that it is able to absorb oxygen effectively in the lung. Therefore, the flow characteristics of the air at the nose are closely related to health. We newly propose a stent-type thermal flow sensor for the evaluation of the nasal respiration in this paper.

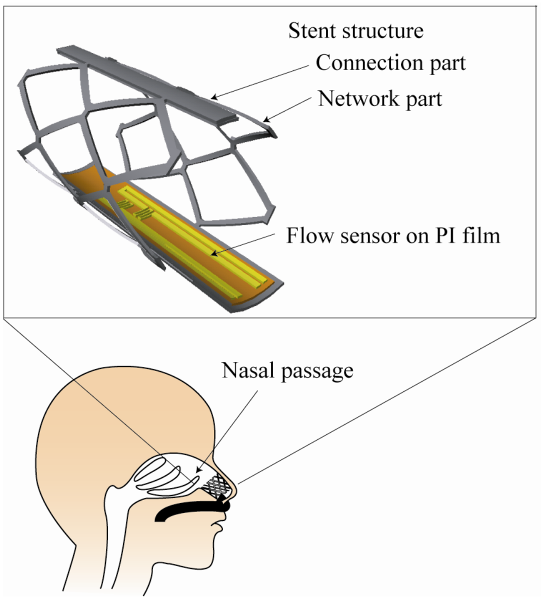

Figure 1: Schematic view of stent-type flow sensor and its application to evaluation of nasal respiration.

STENT-TYPE FLOW SENSOR

There are two challenges to realize the flow sensor for the purpose of the nasal respiration.

(1) As the sensor structure itself disturbs the flow stream, it needs to be as small as possible.
(2) The flow sensor has to be fitted onto the inside surface of nasal passage, which has an irregular and non-constant cross-section.

The mechanism of hot-wire sensing detection is widely used in conventional thermal flow-rate measurements and involves the use of a sensor positioned at the center of a tube [1-4]. However, this positioning disturbs the flow stream. Therefore, this method is difficult to apply to meet our goal. To overcome these two problems, we propose a stent-type flow sensor (Fig. 1). The thermal type of the flow sensor is integrated on the stent structure, which is normally used as a medical device to expand and scaffold blood vessels. Because of the expandability of the stent structure, this sensor fits the inside surface of the nasal passage. Moreover, the structure of the flow sensor does not interfere flow stream because it is mounted on the inner wall surface.

FABRICATION

Planate structure fabrication

As shown in Fig. 2, we developed the fabrication process of the flow sensor by carrying out photolithography and wet etching. We first fabricated a sensor element on the metal substrate and then etched the substrate to form the stent structure and the cavity for the thermal isolation. The details of our developed fabrication method are as follows.

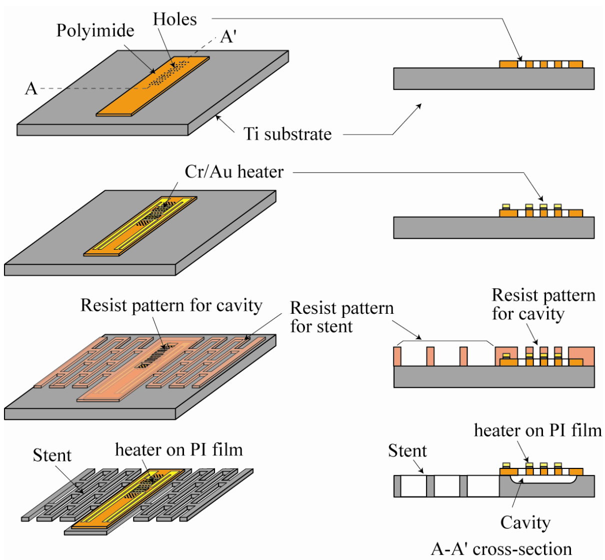

Figure 2: Fabrication process for stent-type flow sensor.

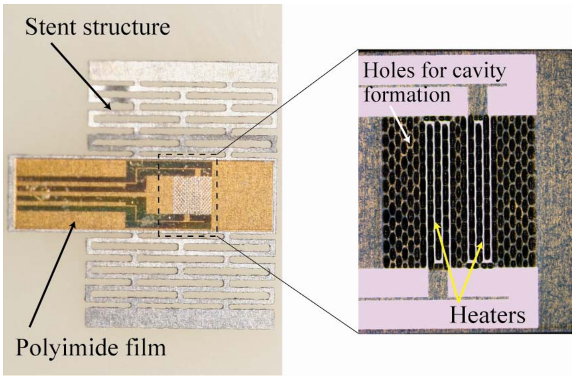

Figure 3: Fabricated planate flow sensor.

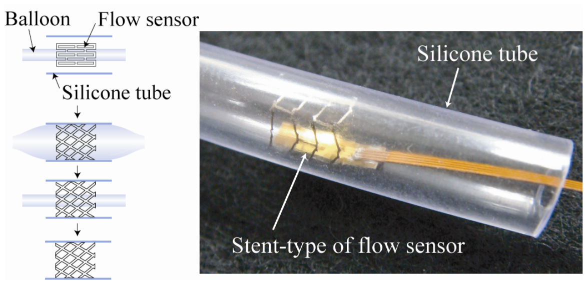

Figure 4: Mounted flow sensor onto inner surface of silicone tube by swelling balloon tube.

(a) An excellent biocompatible material, Ti, is widely used in implant products such as artificial cardiac valves and bones. We therefore used a Ti substrate with a thickness of 50 µm as the material of the stent. A 5.0-µm polyimide (PI) film as a substrate of the thermal flow sensor was deposited on the Ti substrate, and it was patterned by the photolithography for defining the outline and for forming the shapes of holes to form a cavity.

(b) An Au/Cr film (Cr was used as a membrane for adhesion) was deposited on the PI film by sputtering. The thickness of the Au and Cr was 300- and 50- nm, respectively. The metal film structures were patterned by applying the lift-off process. The metal film worked as a sensing heater, and we fabricated two parallel heaters that were used to detect the direction of the flow of aspirated and inspired air.

(c) We coated a photoresist layer onto the Ti substrate and it was patterned to define the both shapes of the stent and cavity for the thermal isolation. The cavity formed under the PI film is one of the important structures that shorten the response time.

(d) Isotropic wet etching was applied to the Ti substrate with the patterned PI and photoresist films. Both the stent and the cavity structures were formed during this process because the size of the hole pattern for the cavity was smaller than that for the stent (Isotropic wet etching was the diffusion-limited process, and therefore the etching rate decreases with the reduction of the hole size). The depth of the fabricated cavity was 30 µm.

The fabricated planate flow sensor is shown in Fig. 3.

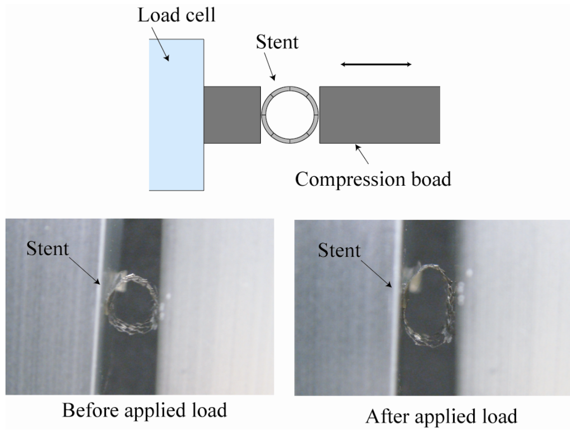

Figure 5: Compression test setup and stent cylindrically deformed

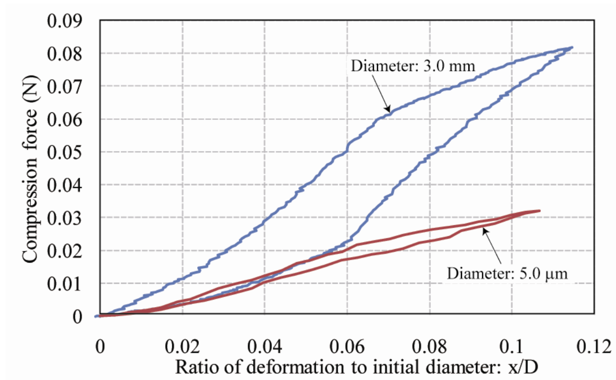

Figure 6: Elastic deformation of the cylindrical stent under compression condition.

Forming cylindrical shape

The planate flow sensor and a flexible printed circuit were bonded by an adhesive, and then the electrical pads on them were connected by conductive silver paste. The planate sensor was then tubulated by wrapping it by hand onto the Teflon rod with a diameter of 2.0 mm. A joint (two opposing sides) was connected by an adhesive, and then the rod was pull from the stent structure. Using Teflon material enabled the rod to be easily pulled from the tabulated sensor.

Mounting onto the inner surface of tube

To measure the flow characteristics, we fixed the sensor onto the inside surface of the silicone tube by inflating the balloon tube (Fig. 4). We first inserted the balloon into the inside of the cylindrical sensor, and then it was inflated to expand the stent structure. At this step, the flow sensor was extended by using the inflated balloon, and it was fixed onto the inner surface of the silicone tube. Finally, the balloon was deflated, and extracted from the silicone tube. We confirmed that the sensor was able to be fixed to the inside surface of a tube with an inner diameter of up to 5.0 mm.

EXPERIMENTAL RESULTS

Mechanical strength

We first measured the mechanical strength at the radial direction of the extended cylindrical stent. Two different sized stent structures with extended sizes of 3.0- and 5.0-

mm in diameter were prepared. The schematic view of the experiment was shown in Fig. 5. The compression force was applied to the stent by the movable load, and the applied force was detected by the using the load cell. The applied load and the deformation curves at the both stents are shown in Fig. 6. Extended stents showed an elastic deformation when the deformation was less than about 10 %. The maximum applied forces at 5.0 m and 3.0 in diameter were 0.03 N and 0.08 N, respectively.

Temperature coefficient of resistance (TCR)

We investigated the relationship between the sensor temperature and the electrical resistance change. The resistance linearly increased as the temperature increased, as shown in Fig. 7. From this graph, we obtained a TCR value of $0.0022K^{-1}$.

Relationship between sensor outputs versus flow rate

To evaluate the flow sensing performance, we fixed the sensor onto the inside surface of the silicone tube with an inner diameter of 3.0 mm.

As describe in "Fabrication", two sensing heaters were formed on a cavity structure to detect the flow direction. As shown in Fig. 8, to shorten the response time in the experiments, both heaters were operated by individual constant temperature circuit. The output signal from each circuit was put into the other final amplifier circuit. The output from each circuit was the same as when the sensor was in the no-flow condition, as a result, the output at the final circuit becomes zero. When the flow occurred, the output signals at each circuit changed because the warmed air by the upstream heater passes through the downstream heater. Therefore, we are able to detect the flow rate and the flow direction by measuring the magnitude and the polarity of the final output signal, respectively [3, 6].

The relationship between the sensor outputs and the flow-rate at both forward and reverse flow conditions is shown in Fig. 9. The applied flow rate ranged from 0 to 2000 ccm, which was enough to evaluate the inspired and expired air flows in a human nasal passage. We confirmed that the both output signals obtained at the forward- and the backward-direction of the flows obeyed the equation of King, which is known to show the typical signal curve of a thermal flow sensor.

Response time

To detect the inspired and expired air performances, the response time must be less than a few hundred of ms. Therefore, to evaluate the response time performance of the sensor, we used a three-port solenoid valve located between the sensor and the mass flow controller. We rapidly changed the flow rate by switching the tube connection and measured outputs of sensors with and without cavity, respectively. The response waveform at the various flow rate conditions is shown in Fig. 10. The fabricated sensor without the cavity needs a long time to steady its outputs because heat escapes to the polyimide film. In contrast, by forming the cavity under the sensing PI film, the sensor output initially increased rapidly and reached 90% of the maximum value within 260 msec.

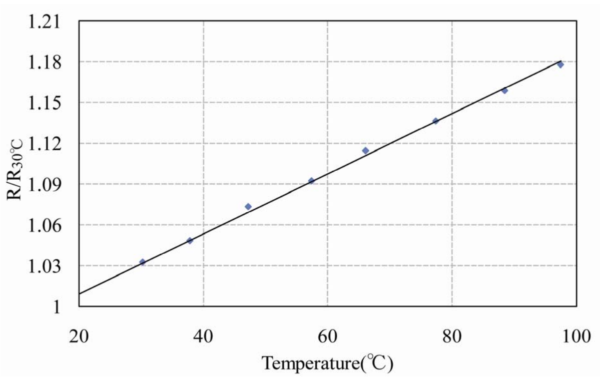

Figure 7: Change in resistance of thermal flow sensor versus temperature.

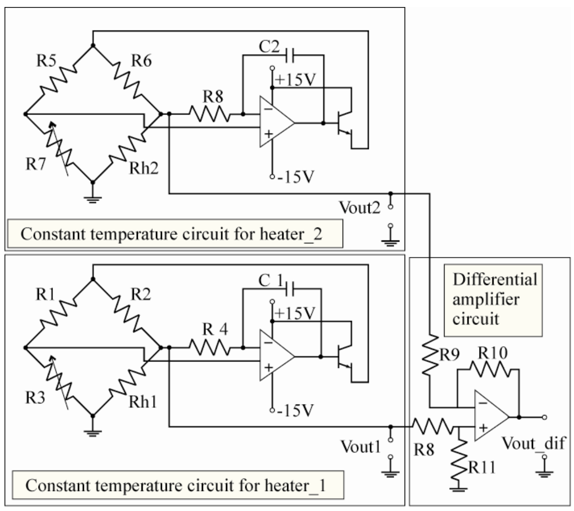

Figure 8: Constant temperature circuit.

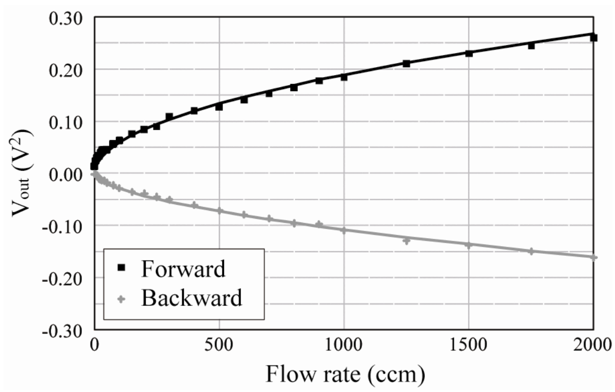

Figure 9: Relationship between flow rate and sensor output when flow was both forward and backward.

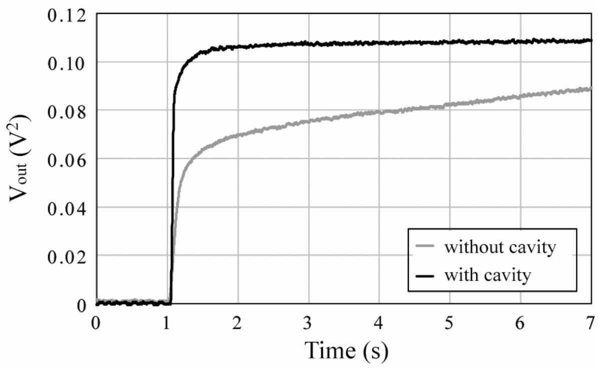

Figure 10: Response time of fabricated sensor.

CONCLUSION

We developed a stent-type flow sensor for evaluation nasal respiration. The sensor part was integrated on the stent structure, and it was fixed onto the inside surface of the silicone tube by using the expandability of the stent structure. The flow characteristics of the developed sensor **were as follows.**

(1) The developed sensor showed an elastic deformation when the force was less than 0.08 N.
(2) Relationship between the input power of the sensor and the flow-rate obeyed the equation of King under both forward and reverse flow conditions through 0 to 2000 ccm.
(3) Response time of less than 260 msec was obtained by forming cavity under the sensor.

These results suggest that we believe that this sensor will be able to evaluate flow characteristics in the nasal passage.

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