Design and Fabrication of a Drag Force Type air Flowmeter with Poly-Silicon Piezoresistive Layer

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Abstract—In this paper, we designed and investigated a drag force type air flowmeter with reduced temperature effect. For this purpose, poly-silicon was deposited as a piezoresistive layer. Adjusting the doping concentration, the temperature related factor like resistivity can be controlled. In addition, since the gauge factor is larger than other metals, the output signal was improved, and the temperature effect was also minimized. The structure was designed to enhance the air drag force. The two-cantilever structure and the paddle structure were utilized, and the device was perpendicularly placed to the given air flow. The flowmeter measured a wide range air flow rate from 0m/s up to 10m/s in the wind tunnel. The basic experiments for repeatability and the short-term stability were performed, and the stable outputs were obtained. The temperature effect was examined, and the output signal of the device showed a quadratic form according to the air flow, which signifies that the device has reduced temperature effect compared to other flowmeters with platinum piezoresistive layer.

Index Term—Air flowmeter, Drag force type, Poly-silicon, Piezoresistive layer.

I. INTRODUCTION

The measurement of flow rate is one of the important factors used in various fields such as measurement of intake air amount of automobile[1-2], observation of weather environment[3], and measurement of respiration and blood flow rate[4]. As the use of flowmeter increases, a more precise measurement of flowmeter is required[5-17]. While there are three types of flowmeter – Ultrasonic, Vane and MEMS – developed thus far, MEMS type flowmeter has been more widely studied as it is the most inexpensive and easy to mass-produce.

Flow velocity sensors used in the variety of applications in fields are miniaturized using MEMS technology. Although the thermal type flowmeters have been commonly used, they tend to heat up and influence peripheral devices and the environment[5-10]. A large amount of energy is thus required for the constant heat supply. In order to compensate for these disadvantages, a drag force type flowmeter using the deformation by air flow has been researched and developed since the 2000s[11-17]. In this study, a drag force type flowmeter was designed and fabricated with poly-silicon piezoresistive layer to reduce the temperature effect by increasing the resistance and to increase the deformation effect by the high gauge factor.

Basically, the drag force type flowmeter measures the fluid flow (air, liquid, etc) by piezoresistive effect[11-17]. Therefore, the piezoresistive material is clearly needed to detect the flow by deformation of flowmeter. In the previous research the conventional drag force type flowmeter, platinum is generally used as the piezoresistive materials. The platinum has low resistivity, 10.58μΩ-cm, and the resulting current becomes relatively high in spite of low voltage condition[18]. Thus the high heat dissipation happens, and the output values vary with outer circumstances. Thus, the temperature compensation should be applied to the flowmeter so its use in various fields is limited. On the other hand, poly-silicon can achieve a high resistivity as well as high gauge factor value than platinum depending on the doping concentration. It means the deformation effect can be increased and the temperature variation can be minimized. Therefore, the flowmeter without the additional temperature compensation circuit can be achieved.

Furthermore, the device should be designed to make the drag force maximized. In the case of the drag force type flowmeter, the flow rate is measured with respect to air pressure, which changes the resistance of the piezoresistive material. Since the flowmeter also needs a design that changes easily according to the air flow, a cantilever and paddle structure is required. Additionally, the piezoresistive material having a high gauge factor is also necessary. In previously reported researches, platinum was usually deposited as piezoresistive material because it has a relatively high gauge factor of 6 among the metals[19-20]. However, we selected poly-silicon for piezoresistive detection because the gauge factor of poly-silicon can be increased compared to other materials, depending on the doping concentration.

In order to obtain the basic properties of the fabricated flowmeter, the experiments were conducted through a wind tunnel. The short-term stability and repeatability experiments were performed to determine whether a stable output signal occurred. In addition, we compared the output signal of the fabricated flowmeter with that of other flowmeters with platinum layer. Through these comparison and experiments, we intend to verify that the fabricated flowmeter has reduced temperature effect.
II. DESIGN

A. Sensor Design

The MEMS type air flowmeter can be divided into two types using heat and drag force. At present, the thermal type flowmeter is mainly used because of its high sensitivity. However, that kind of flowmeters basically generate heat to measures the flow rate with temperature difference. Thus, the thermal type flowmeter has a drawback that it consumes a lot of energy and affects to the external environment. In order to overcome these difficulties, the drag force type flow has been studied and developed[15-17]. As seen before, the drag force type flowmeter has advantage in energy consumption compared with the thermal type flowmeter. Generally, the drag force type flowmeter measures the air velocity by deformation of the device against the air pressure and has the advantages of less heat consumption and less influence to the external environment. However, in spite of these advantages, the drag force type flowmeter requires the certain amount of current to measure the piezoresistive change by the flow rate, which in turn generates heat incidentally. Such heat can raise the temperature of the device, and the heat incurs the resistance change of it. To reduce this kind of temperature effect, we developed the drag force type flowmeter with other piezoresistive material, poly-silicon.

To complement the above shortcomings, it is necessary to design sensors for minimizing temperature effects. First, the resistance of the flowmeter was increased by changing the piezoresistive aterial. As the resistance increases, the amount of current flowing through the piezoresistive material will decrease, even as the voltage applied to the flowmeter increases. Thus, the heat generation in the piezoresistive material can be reduced. In addition, the piezoresistive material with a high gauge factor was used to increase the output signal. Then, the deformation effect can be magnified, and the temperature effect would be relatively reduced.

In the structural point of view, the flow rate is obviously measured according to the deformation of the flowmeter. So, it is also important to design the flowmeter which can receive high drag force. The overall shape of the device is shown in Fig. 1. The paddle structure was applied to the device to improve the output signal. The device was constructed in a horizontal structure to maximize the resistance to the air and was placed perpendicular to the air flow. The basic structure is a two-cantilevered structure for preventing the undesired distortion by the air flow. In addition, using the poly-silicon with higher gauge factor as the piezoresistive material, it is expected to obtain the higher output signal at the same air flow rate.

B. Sensor Dimensions

Two cantilevered structures with 40μm in width were fabricated for more precise flow measurements while avoiding distortion due to air flow rate. As the piezoresistive layer, a design of poly-silicon having a width of 10μm and a thickness of 0.1μm was adopted. The total length of the device is 500μm and the size of the paddle is 200μm x 200μm. In addition, the flowmeter was made up of a low stress silicon nitride layer with 1.5μm thickness (Fig. 2).

C. Temperature Analysis

The purpose of the fabricated flowmeter is to reduce the effect by temperature change. Most of the reported drag force type flowmeters used platinum as a piezoresistive material. Since the platinum has a resistivity of about 10.6Ω-μm, the resistance of the flowmeter can be smaller. And, when there is a current applied to a resistor, the heat that is formed appears as $I^2R$. Therefore, even if a small voltage is input, a large amount of current flows, and the heat generation can basically be huge, because the resistance is considerably small. The resulting heat generation raises the temperature of flowmeter. Additionally, the raised temperature can be influenced by the air flow, and the resistance of piezoresistive material may be changed. Therefore, a temperature compensation circuit is necessarily required. Fundamentally, if a device with a larger resistance can be used, the current flowing becomes smaller. As a result, the amount of heat generated is reduced, and the temperature change of the flowmeter due to heat can be minimized. For this purpose, it is desired to use poly-silicon as a piezoresistive detection, which is relatively easy to control the resistance.
D. Piezoresistive Effect

Our flowmeter uses the piezoresistive material to measure the flow rate. The piezoresistive effect refers to a change in resistance when a material is stressed by an external force. This piezoresistive effect can be easily implemented through MEMS process and is widely used in flow rate, pressure, and acceleration device. Therefore, a sensitivity equation is used to characterize the piezoresistive material. It is expressed by the rate of change of the resistance against the basic resistance as shown in Equation (1).

\[
\text{sensitivity} = \frac{\Delta R}{R} = G \times \frac{\Delta L}{L} = G \times \varepsilon
\]

(1)

The Equation (1) describes the sensitivity (\(\Delta R/R\)) of the piezoresistive effect where G is the gauge factor. \(\Delta R\) is the actual flowmeter’s deformation data obtained by the oscilloscope and is an important output signal because R is a constant value. \(\Delta L\) is the absolute length variation and \(\Delta L/L\) is the strain (\(\varepsilon\)). As shown in the equation, it is necessary to use a material having a high gauge factor to improve the sensitivity of the piezoresistance. Furthermore, the fabricated flowmeter should be arranged perpendicular to air flow, and a paddle structure should be adapted at the end of the flowmeter to maximize the drag force and the resulting strain.

As shown in Table 1, among materials mainly used in MEMS devices, silicon has the highest gauge factor. Silicon has a gauge factor more than 100 times that of metal. However, our designed flowmeter uses a silicon nitride as a structure, so it’s difficult to deposit the single crystal silicon on the nitride layer. Therefore, in this study, poly-silicon is used as a piezoresistive material due to the process convenience, which has a relatively high gauge factor.

<table>
<thead>
<tr>
<th>Material</th>
<th>Gauge Factor (GF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single crystal Silicon</td>
<td>-125 to 200</td>
</tr>
<tr>
<td>Polysilicon</td>
<td>±30</td>
</tr>
<tr>
<td>Platinum</td>
<td>6.1</td>
</tr>
<tr>
<td>Nichrome</td>
<td>2.1</td>
</tr>
<tr>
<td>Manganin</td>
<td>0.47</td>
</tr>
</tbody>
</table>

E. Structure Analysis

In order to investigate the deformation of the device before the actual flowmeter fabrication, a finite element method was used. When measuring the flow rate using the drag force type flowmeter, the device is subjected to the stress according to the flow rate, and it is necessary to design the flowmeter so it does not break from receiving stress. In addition, a piezoresistive material must be deposited in a portion with a large strain for a given flow rate to increase the output signal. Therefore, it is necessary to analyze stresses and strains for various flow rates.

In this simulation, the air flow rate was changed to the force acting on the device using the Bernoulli equation. Equation (2) shows the dynamic pressure against the flow velocity, and the distribution load of the cantilever beam at the room temperature of 20°C (\(\rho = 1.204\text{kg/m}^3\)) was calculated.

\[
P = \frac{1}{2 \rho v^2}
\]

(2)

Fig. 3 shows the simulation results for the flow velocity of 10m/s. The maximum stress up to 10m/s is graphically presented and comes in the form of the quadratic curve as shown in Fig. 4. When the flow rate of 10m/s was applied, the stress was about 14.2MPa, which is much smaller than the breaking strengths of silicon oxide and nitride films of 100MPa and 900MPa. Therefore, it is confirmed that there is almost no possibility for the device to be broken from the stress of about 14.2%.

![Fig. 3 Simulation results of the suggested air flowmeter at 10m/s](image)

![Fig. 4. Maximum stresses with respect to the air velocity](image)

The strain analysis of the flowmeter was obtained with respect to the distribution load. The results are shown in Fig. 5 by applying a distribution load of 59.2N/m² corresponding to 10m/s to the drag force type flowmeter. As shown in the figure, the largest strain appears at the bottom of the two-cantilevered structure, and the deformation decreases as the distance from the bottom of the cantilever increases. In this study, poly-silicon, which is a piezoresistive material, was deposited only on the cantilever structure, while the paddle structure with low strain
was left clean.

### III. FABRICATION AND EXPERIMENTS

#### A. Fabrication

The drag force type flowmeter was fabricated using the conventional MEMS processes like Fig. 6. The device was fabricated using a 6-inch (100) P-type wafer. The 1μm thick oxide layer is grown with the wet oxidation process and a silicon nitride layer was deposited by LPCVD (Low pressure Chemical Vapor Deposition) to a thickness of 1.5μm as the structure layer. For the piezoresistive detection, the 0.1μm thick poly-silicon was deposited, and boron doses of $0.45 \times 10^{15}$/cm$^2$ were implanted at 15keV. After annealing at 1050°C for 30min, the doping concentration of $2.6 \times 10^{19}$ was obtained. An e-beam evaporator was used to 0.3μm thick gold over the piezoresistive layer for the electrode. The front structure of the flowmeter is etched with the RIE process and the etched flowmeter is released with the deep-RIE. In addition, Fig. 7 shows the final fabricated device. As shown in the figure, the total flowmeter length is 500μm. The paddle structure of the device and the two cantilevered structures are also accurately patterned.

#### B. Experiments

Experiments were achieved to detect the basic properties of fabricated flowmeter. The wind tunnel was used and the various flow velocity were generated in the flow rate range of 1 ~ 10m/s. Fig. 8 shows the wind tunnel equipment. The experiment was conducted based on the TESTO 405-vl flow meter as reference. In addition, the output signal was amplified using a Wheatstone bridge and a Burr-Brown Cooperation INA128P. The amplified output signal was measured, and the data collected using a Tektronix oscilloscope (TDS 2024B). Laboratory environmental condition was around 20°C.

### IV. RESULT OF DRAG FORCE TYPE FLOWMETER WITH POLY-SILICON

#### A. Result of Flowmeter Fabrication

In order to investigate the uniformity of the fabricated flowmeter, its resistance was measured through a probe station. The measurements from the flowmeter No.1 to No. 22 in line 2 and line 3 on the first quadrant plane are plotted. The average resistance of the flowmeter was about 213kΩ. Also, as shown in Fig. 9, it has an error range of about ± 5%. Based on the results, it was confirmed that the device was fabricated with uniformity.
B. Experimental Results in Wind Tunnel

The flow rate experiments were measured in the wind tunnel. Fig. 10 shows the experimental results for the purpose of detecting the basic properties of the fabricated flowmeter. The range of the flowrate is from 0m/s to 10m/s. First, Fig. 11 shows the output result of repeatability at 4.6m/s. Through repeated experiments, it was confirmed that the output signal was constant at the same flow rate. Fig. 12 shows the output result of short term stability at 4.6m/s. As a result, it was shown that a constant output value occurred for a short period of time. Experiments have been carried out to apply various flow rates within the range to the fabricated flowmeter. The output signals were collected through an oscilloscope, and different output values were generated with different flow rates. As a result, it is confirmed that the output signal of the flowmeter is stable. In addition, unlike conventional drag force type flowmeter with platinum, a graph of a quadratic function was obtained.

C. Comparison of Simulation

Therefore, we compared the temperature generated to the piezoresistive material through COMSOL 5.3 before comparing the actual fabricated flowmeter’s output. The temperature generated in the piezoresistive material was analyzed at 20°C with no flow to the device. The basic properties of poly-silicon and platinum, which are contained in the COMSOL, were used. The results are shown in Fig. 13. A result of the poly-silicon analysis in Fig. 13 (a) shows that the temperature at 0 m/s was 21°C with almost no increase. Conversely, as shown in Fig. 13 (b), platinum has a temperature of about 50°C. Therefore, it was confirmed by COMSOL that there were little temperature rising generated from using the poly-silicon.
D. **Comparison Poly-silicon with Platinum in piezoresistive layer**

While platinum is normally used as a piezoresistive material for the drag force type flowmeter, this paper used poly-silicon. It was assumed that the poly-silicon has a higher gauge factor than platinum, and the temperature dependence can be ignored if the doping concentration is properly set. Therefore, we compared the output signal of the device with poly-silicon and platinum at the low flow rate range of 0 ~ 4m/s. The results are shown in Fig. 14. The output signal of poly-silicon flowmeter at the initial low flow rate is expressed in a quadratic form which is similar to simulation result in Fig. 4, while the output value of platinum is increased in a different shape. For platinum flowmeter, the heat generated from the platinum can change the resistance when it reaches a relatively low temperature of the air flow, which is reflected on the graph. On the contrary, it can be assumed that the quadratic form appeared for the poly-silicon flowmeter because there was no change in temperature.

![Graph showing comparison between poly-silicon and platinum flowmeters](image)

**Fig. 14. The comparison between flowmeters with poly-silicon and platinum piezoresistive layers**

V. **CONCLUSION**

In this paper, the drag force type flowmeter with reduced temperature effect was designed and fabricated. In order to achieve this purpose, we raised the resistance of the flowmeter, and use high gauge factor material as piezoresistive detection. Therefore, poly-silicon was selected and deposited instead of platinum to satisfy the above criteria. As a result, the resistance of the flowmeter was increased, and it was confirmed that a low current flows even when a high voltage was input. Additionally, relatively lower heat was generated in the poly-silicon. The air flow experiments were performed with the wind tunnel. As a result, the poly-silicon flowmeter has a graph of a quadratic curve, but platinum flowmeter has different shape of graph because of the temperature influence. Additionally, the repeatability and the short-term stability experiments were obtained stable output signals. Therefore, the output results confirm the possibility that the newly designed and fabricated flowmeter can be used in various fields without the temperature effect.

**ACKNOWLEDGMENT**

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