MEMS FORCE AND DISPLACEMENT SENSOR FOR MEASURING SPRING CONSTANT OF HYDROGEL MICROPARTICLES

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ABSTRACT

This paper reports on a method to measure spring constant of hydrogel microparticles by a MEMS sensor. For calculating spring constant, not only force but also displacement is necessary. The MEMS sensor consists of two sidewall doped piezoresistive cantilevers in the ranges of µN and µm so that both parameters can be measured simultaneously. When one cantilever pushes a target to a wall, the cantilever can measure the restoring force of the target. At the same time, the other cantilever measures the displacement by pushing the wall directly. By measuring both force and displacement on the same sensor chip, the spring constant of targets can be obtained only from the sensor outputs, which makes the sensor system simple and compact. With this advantage, our method can be useful in actual experiments with microscopes and other systems.

INTRODUCTION

Spring constant is one of mechanical properties, which is determined by material and structure. It is often required to directly measure the spring constant of a fabricated device or a component in order to obtain accurate values. Recently, hydrogel microparticles have attracted attention for use in biomedical engineering [1-2]. Hydrogel microparticles are especially useful in tissue engineering since it works as scaffolds or encapsulating materials for mammalian cells, and the rigidity of the scaffolds are known to affect various cellular functions. Therefore, it is important to evaluate spring constant of the scaffolding materials.

Force and displacement measurements are necessary for calculating spring constant. In this study, we report on a method to evaluate the spring constant of hydrogel microparticles by pushing the target to a wall, and measuring restoring force of the target and displacement of the sensor chip at the same time using MEMS cantilevers.

In previous studies, several methods were used to measure mechanical properties of materials and micro structures. Nanoindentation continuous stiffness measurement technique was used to measure hardness and elastic modulus of thin film [3]. Atomic force microscopy (AFM) was used to measure elasticity of cell [4]. However, it is difficult for those methods to measure unfixed sphere-shaped objects in liquid.

To investigate Young's modulus of soft hydrogel microcapsules, MEMS force sensors were used [5]. In the study, the displacements of the targets were collected from microscopic image data. Nevertheless, the displacement resolution can be improved to submicron order by measuring the displacement in the same device as MEMS force sensor [6,7].

Here we propose a MEMS sensor, which can measure force and displacement at the same time in a single device. The schematics of the spring constant measurement is shown in Figure 1. In general, the spring constant is measured from restoring force when applying deformation to the target. When one of the sensor cantilever pushes the target to measure the restoring force, the other cantilever pushes the wall directly to measure the displacement of the sensor chip. Thus, the spring constant can be derived from the measured force and displacement in a single device.

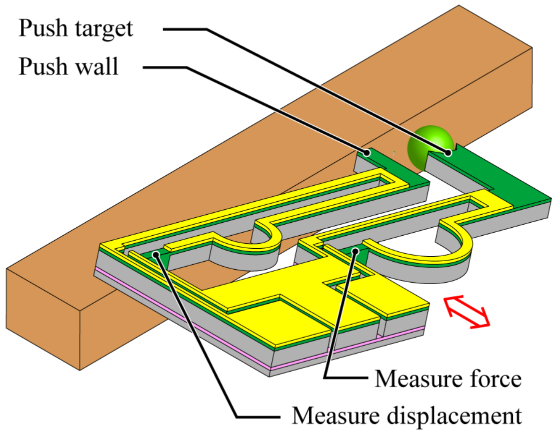
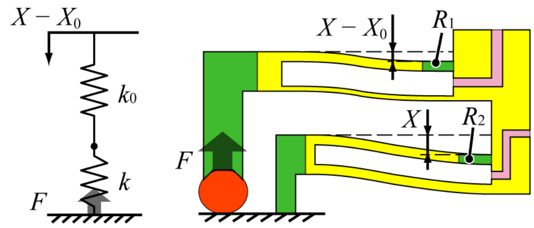


Figure 1: Schematics of measuring spring constant by the MEMS force and displacement sensor.



$$\boxed{k = \frac{1}{\dfrac{X - X_0}{F} - \dfrac{1}{k_0}}}$$

k_0: beam spring constant

k : target spring constant

X_0 : displacement of sensor when the force sensing cantilever contacts the target

Figure 2: Theoretical model of the MEMS force and displacement sensor.

PRINCIPLE

We derived an equation to calculate spring constant from the force and displacement measured by the sensor. The theoretical model of the sensor is shown in Figure 2.

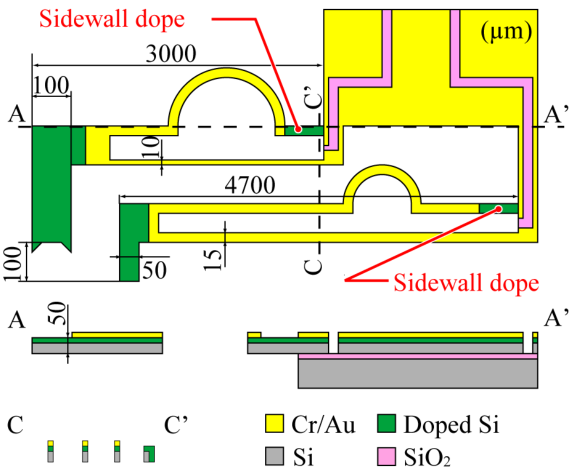


Figure 3: Design of the force and displacement sensor.

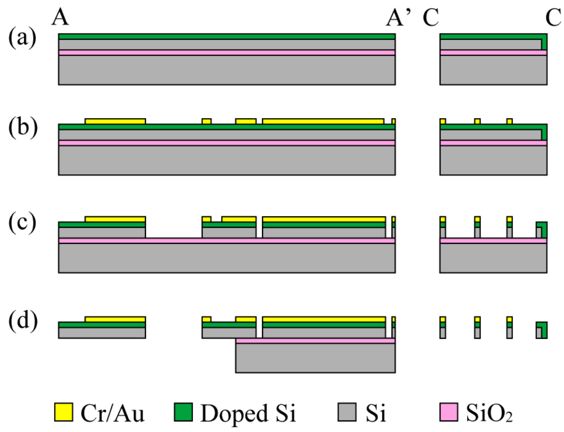


Figure 4: Fabrication process of the sensor chip.

The sensor has a force sensing cantilever and a displacement sensing cantilever. Both cantilevers have side wall doped piezoresistor on their roots. The piezoresistor of the force sensing cantilever and the displacement sensing cantilever are defined as R_1 and R_2, respectively. The force sensing cantilever deforms when it pushes the target to a wall. The displacement sensing cantilever deforms by pushing the wall simultaneously. The deformations are detected by the two resistance changes. Therefore, the applied force F to the tip of the force sensing cantilever can be measured from the resistance change ΔR_1 and the sensor chip displacement X can be measured from the resistance change ΔR_2.

The restoring force of the target is equal to F. Thus, the target spring constant k, the target displacement x, and F have the following relationship:

$$k = \frac{F}{x} \tag{1}$$

As shown in Figure 2, the displacement of sensor when the force sensing cantilever contacts the target is defined as X_0. The spring constant of the force sensing cantilever k_0 can be written as follows:

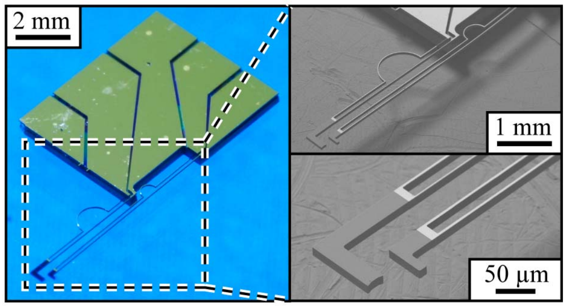


Figure 5: Fabricated sensor chip.

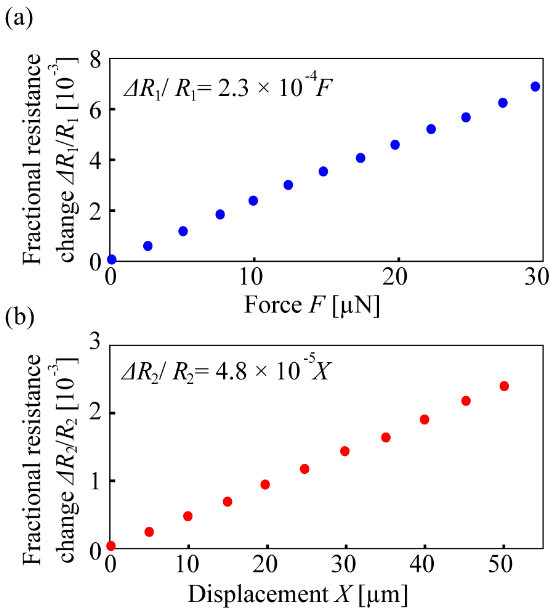


Figure 6: Relationship between (a) the force and the resistance change R_1. (b) the displacement and the resistance change R_2.

$$k_0 = \frac{F}{X - X_0 - x} \tag{2}$$

Substituting equation (2) into equation (1), the target spring constant can be obtained as follows:

$$k = \frac{1}{\frac{X - X_0}{F} - \frac{1}{k_0}} \tag{3}$$

Therefore, the target spring constant can be calculated from the force and displacement measured by one sensor chip.

DESIGN AND FABRICATION

Figure 3 shows the detail design of the force and displacement sensor used in this study. The sensor is designed for measuring the spring constant of hydrogel microparticles which are about 100 µm in diameter [1]. The force sensing cantilever and the displacement sensing cantilever are 3.0 mm and 4.7 mm in length, respectively. The cantilevers are designed to measure in tens of µN and µm scale. The thickness of the beams is 50 µm. The displacement sensing cantilever is out of the line with the

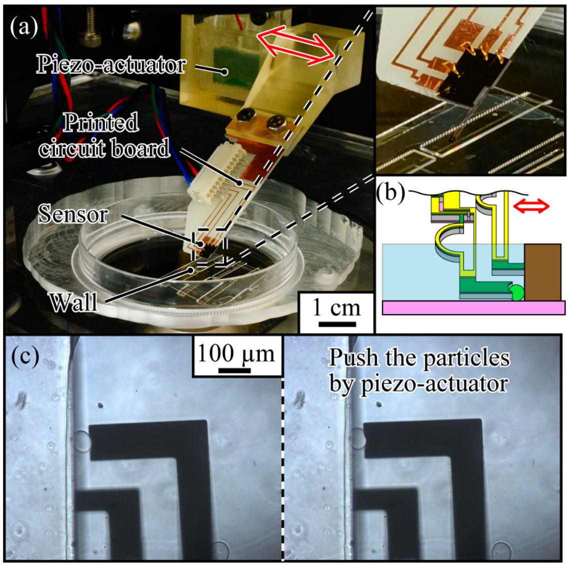


Figure 7: (a) Photograph of the experimental setup. (b) Schematics of the experiment. (c) Photograph of the experiment with a microparticle.

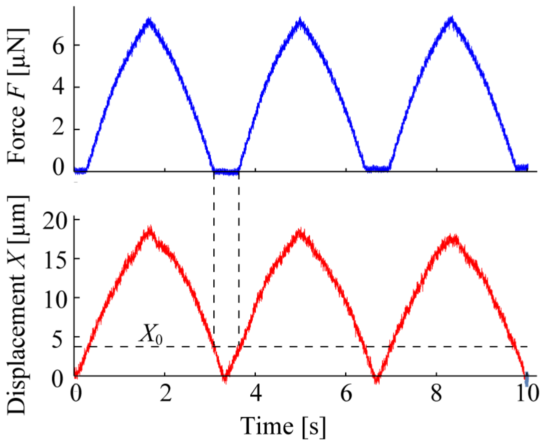


Figure 8: Measured force and displacement of the 3.0 wt% sodium alginate microparticle.

force sensing cantilever with 100 µm so that both cantilevers deform when a microparticle is pushed to a wall.

We used a p-type SOI wafer whose layers were 50 µm, 1 µm and 250 µm in thickness. The process flow is shown in Figure 4. First, a piezoresistive layer was formed at the surface of the Si layer with the side wall of holes (Figure 4(a)). Then, Cr/Au layers for electrical wiring were deposited on the doped Si layer (Figure 4(b)). Next, the shape of the cantilevers was formed by etching the top Si layer (Figure 4(c)). Finally, the handle Si layer and SiO_2 layer were etched (Figure 4(d)).

The fabricated sensor is shown in Figure 5. The force sensing cantilever was calibrated by measuring the relationship between the applied force and the fractional resistance change $\Delta R_1/R_1$. The displacement sensing cantilever was calibrated by measuring the relationship between the applied displacement and the fractional resistance change $\Delta R_2/R_2$. The calibration result is shown

Table 1: The results of the measurement using a 3.0% concentration sodium alginate microparticle. ($F/(X-X_0)$) was the measured force per the measured displacement. k was the target spring constant calculated from Equation 3.)

Times	$F/(X-X_0)$ [N/m]	k [N/m]
1	0.481	14.0
2	0.474	10.1
3	0.468	7.9
4	0.469	8.2
5	0.477	11.4
6	0.467	7.5
7	0.468	7.9
8	0.475	10.6
Average	0.472 ± 0.005	9.7 ± 2.2

in Figure 6. The spring constant k_0 of the force sensing cantilever was 0.49 N/m. The standard deviation of fractional resistance changes $\Delta R_1/R_1$ of the force sensing cantilever was 2.5×10^{-5} with no force applied. Therefore, the force resolution was calculated as 0.11 µN using the coefficient in Figure 6. Whereas the standard deviation of fractional resistance changes $\Delta R_2/R_2$ of the displacement sensing cantilever was 2.8×10^{-5} and the displacement resolution was 0.60 µm.

EXPERIMENT AND RESULT

We measured the spring constant of calcium alginate microparticles suspended in $CaCl_2$ solution using the fabricated sensor as shown in Figure 7. The wall was 500 µm in height which was made from negative photoresists (TMMF S2000, Tokyo Ohka Kogyo Co.) and the wall was fixed on a dish. The sensor was attached to a printed circuit board actuated by a piezo-actuator with 0.3 Hz triangle wave. The experimental setup mentioned above was arranged on the microscopy stage. In the experiments, the sensor was inserted into the solution at the angle of 30 degrees to the horizontal plane and pushed target microparticles.

The hydrogel microparticles were made from sodium alginate. By changing the concentration of sodium alginate, the stiffness of the microparticles can be controlled [1,2]. In this experiment, we used the microparticles with the diameter of 70 µm made from 3.0 wt% sodium alginate.

Figure 8 shows the measured force and displacement of the target microparticle. In the experiment, we measured a single microparitcle 8 times. In each time, the sensor pushed the target microparticle then left from the target completely. Table 1 shows the values of the measured force F divided by the measured displacement X and the calculated spring constant k of the microparticle. The spring constant of the microparticle was 9.7 ± 2.2 N/m. Despite of the standard deviation of $F/(X-X_0)$ within 1%, the standard deviation of the calculated spring constant k became about 23%. The increase of the standard deviation is because the value of spring constant k_0 of the force sensing cantilever was similar to $F/(X-X_0)$. Thus, the standard deviation of calculated spring constant k could be controlled smaller by increasing the value of k_0.

CONCLUSION

We proposed a method to measure the spring constant of unfixed sphere-shaped objects by using a force and displacement sensor which consists of force sensing cantilever and displacement sensing cantilever. The fabricated sensor has force resolution under 0.05 μN and displacement resolution about 0.5 μm. We used the fabricated sensor to measure the spring constant of hydrogel microparticles. In the experiment, the force sensing cantilever pushed the target microparticle to a wall. The displacement cantilever pushed the wall directly at the same time. The experimental result shows the spring constant of a calcium alginate microparticle fabricated from 3.0 wt% sodium alginate solution was 9.7 ± 2.2 N/m. The result shows that our sensor can measure the spring constant with compact sensor system.

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