

A Disc-shaped Power Supply Line-free Mass Sensor for Measuring Biomarker

Masaki Yamaguchi, DongSu You, Yuki Nakayama

Biomedical Engineering & Robotics Laboratory
 Graduate School of Engineering, Iwate University
 e-mail: masakiy@iwate-u.ac.jp

Abstract—The purpose of this research is to demonstrate a new design for a mass sensor with a disc-shaped resonator that is free of power supply lines. The line-free mass sensor comprises a resonator and a piezoelectric element for vibrating it. Since electrical power is used to actuate the piezoelectric element, the resonator is free from power lines. Target molecules become attached to the resonator, changing its resonant frequency. The geometric shape and dimensions of the resonator were designed using the finite element method (FEM). The resonator was fabricated in the shape of a circular plate of diameter 4 mm by photolithography, so that the radial oscillation primary mode of vibration would be 3.68 MHz. The concentrations of glucose solutions were measured using the line-free mass sensor. The sensitivity of the line-free mass sensor was estimated to be 0.06 fg when a frequency resolution of 1 mHz was used.

Keywords—mass sensor; resonator; power supply line; resonant frequency; photolithography.

I. INTRODUCTION

Micro-cantilever transducers have certain advantages in terms of detecting and identifying chemical and biological elements in air or liquid environments with high sensitivity [1][2]. The sensitivity of micro-cantilever transducers is superior to those of traditional quartz crystal microbalances (QCM) [3] and surface acoustic wave (SAW) [4] transducers. It has been reported in one theoretical study that the potential measurement sensitivity of micro-cantilever transducers is 2.34×10^{-19} g [5].

Crystal oscillators and piezoelectric elements can be used to excite vibrations in micro-cantilever transducers. When the excitation source is directly fixed to the micro-cantilever, the electrical power required to feed it seriously degrades the vibrations. Moreover, capacitive coupling of the vibrator influences the frequency and decreases the quality factor (Q-factor) of the micro-cantilever transducers. We have already proposed a power supply line-free mass sensor for measuring biomarkers [6]. Our study indicates that, if an optical displacement sensor with a frequency resolution of 1 mHz is used, a sensitivity of 76.2 ng/ml can be achieved with a line-free mass sensor.

The purpose of this research is to improve the sensitivity of a line-free mass sensor to as high as the tens of fg/Hz range. The geometric shape and dimensions of a disc-shaped resonator were designed using FEM and the resonator was fabricated by photolithography. The measured results of glucose concentrations using the fabricated line-

free mass sensor were discussed.

II. MATERIALS AND METHODS

A. Structure and Principle

The line-free mass sensor consists of a resonator, a piezoelectric element (20 mm diameter and 0.5 mm thickness, NEC Tokin Corporation, Japan) to excite the resonator as the vibrator, an alternating current power source, and an optical non-contact displacement sensor. Since the power source is used to actuate the vibrator, the sensing element, i.e. the resonator, is free from power lines (Figure 1(a)). A microscope-type Laser Doppler vibrometer (KV-100, Denshigiken Corporation, Japan) and a spectrum analyzer (frequency resolution: 1 mHz, Advantest Corporation, Japan) were used for measuring the resonant frequency of the resonator (Figure 1(b)).

Firstly, the target material adheres to the resonator

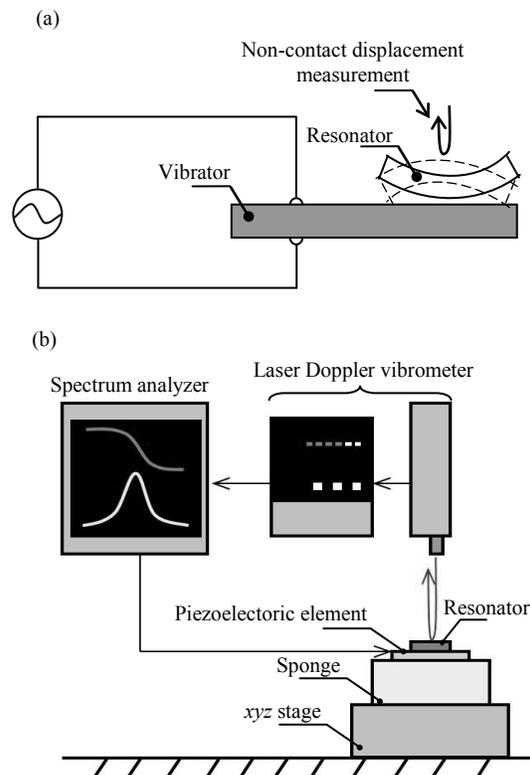


Figure 1. Principle of a line-free mass sensor ((a): Schematic of mass sensor, (b): Block diagram of resonant frequency measuring system).

without chemical bonding. Then the resonator is placed on the piezoelectric element. When the piezoelectric element is excited at an arbitrary frequency, the vibration is transmitted to the resonator mounted on it, which then vibrates at its resonant frequency. The resonator will never fall from the piezoelectric element because the amplitude of vibration is smaller than a nanometer scales. The change in resonant frequency is proportional to the mass of target material adhering to it.

B. Design of Disc Resonator

A disc-shaped resonator was designed to have a resonant frequency of several MHz (Fig.2). The outer diameter and thickness were 4.0 and 0.5 mm, respectively. The detecting area, d , was used as a parameter to design the resonator, then two types of resonator were fabricated (type A and B). Using an eigenvalue-eigenvector analysis employing a FEM was calculated to compare the resonance frequency of the two types of the resonator. The boundary conditions at the outer peripheral edge of the resonator were set to free edge. The density, longitudinal modulus of elasticity, and Poisson's ratio were set to 2,329 kg/m³, 185 GPa, and 0.28, respectively

C. Fabrication of Disc-shaped Resonator

A photolithography technique such as deep-reactive-etching (DRIE) was used to fabricate the disc-shaped resonators with several diameters of detecting area from a 4-inch sized silicon wafer. The entire photolithography process was carried out in three steps; 1st wet etching, 2nd wet etching, and DRIE process (Fig.3).

1st wet etching process: A wafer was coated with a positive-type photoresist (OFPR-800, Tokyo Ohka Kogyo Co., Ltd, Japan) using a spin coater (ASC-4000, Actes Inc., Japan). The photoresist exposed to the UV light using a photomask α and a mask aligner (MA6, Suss MicroTec, Japan). After the developing, the silicon was liquid (wet)-etched to remove the unprotected oxide. The SiO₂ was removed using hydrogen fluoride. Finally, the photoresist was removed from the substrate using heating sulfuric acid treatment.

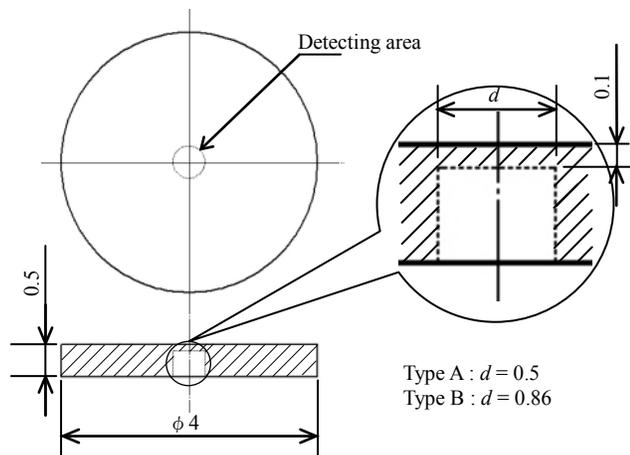
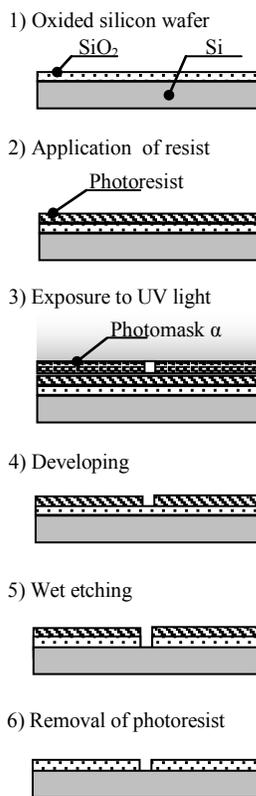


Figure 2. Cross sectional view of a disc-shaped resonator used for the line-free mass sensor (Units in mm).

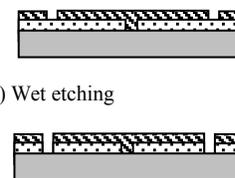
2nd wet etching process: The wafer was coated with a positive-photoresist (PMER P-LA900, Tokyo Ohka Kogyo Co., Ltd, Japan) using the spin coater. The photoresist was exposed using a photomask β and the mask aligner. After that, the developing and the wet etching were processed.

DRIE process: The 1st DRIE was performed for 23 min using a DRIE system (MUC-21, Sumitomo Precision Co. Ltd., Japan). After the photoresist was removed, a supporting substrate was adhered using the positive-type photoresist. The 2nd DRIE was performed for 90 min using the DRIE system. Finally, the supporting substrate was peeled using a stripping solution (Microposit Remover 1165, Shipley Co., Inc., US).

I 1st wet etching

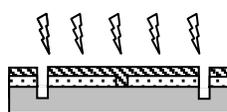


3) Developing



III DRIE

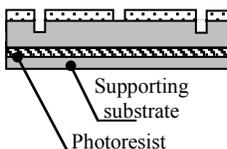
1) 1st DRIE



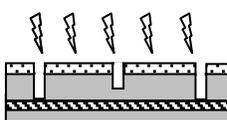
2) Removal of photoresist



3) Adhere to substrate



4) 2nd DRIE



5) Peeling of substrate



II 2nd wet etching

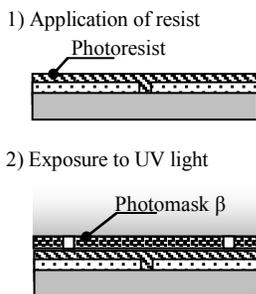


Figure 3. Photolithography of a disc-shaped resonator for deep etching including a two-step exposure process.

D. Measurement of Resonant Frequency

The resonant frequencies of each mode of vibration of the disc-shaped resonators were measured using a microscope-type Laser Doppler vibrometer, a spectrum analyzer, and a xyz stage.

E. Measurement of Glucose Concentration

As a typical human blood biomarker, glucose was selected as a sample material to evaluate the sensitivity of the line-free mass sensors. A set of D(+)-glucose (180.16, CAS No. 50-99-7, Wako Pure Chemical Industries, Ltd., Japan) solutions with concentrations between 250 ng/mL and 100 mg/mL was used.

A 0.1 μL sample of each solution was dropped on the detecting area of the disc-shaped resonator by a precision dispenser (SMP-3, Musashi Engineering, Inc., Japan). After that, the disc-shaped resonator was dried at room temperature for 10 min. The change in resonant frequencies compared to those without the sample solutions was then measured for each glucose concentration.

The disc-shaped resonator was cleaned using an ultrasonic washing machine (2210DTH, Emerson Japan Ltd., Japan) for 5 min. and dried for 30 min. in order to refresh and reuse it.

III. RESULTS AND DISCUSSION

A. Design and Fabrication of Disc Resonator

The calculated results of the resonant frequencies for types A and B at 1st mode were 3.919 and 1.934 MHz, respectively (Table I). The surface areas of types A and B were 0.2 and 0.6 mm², respectively. The type A condition was selected to fabricate the disc-shaped resonator.

A disc-shaped resonator was fabricated from a silicon wafer.

B. Measurement of Resonant Frequency

The measured results of the resonant frequency of type A was 3.682 MHz, which agreed well with the theoretical

TABLE I. CALCULATED RESULTS OF THE RESONANT FREQUENCY FOR EACH VIBRATION MODE.

		Circumferential oscillation mode of vibration	
		1st	2nd
Radial oscillation mode of vibration	1st		
		Type A	
		3.919 MHz	6.473 MHz
		Type B	
	1.934 MHz	3.707 MHz	
	2nd		
Type A			
12.162 MHz		14.087 MHz	
Type B			
5.612 MHz	7.216 MHz		

results obtained using FEM (Fig.4). The Q-factor was calculated to be 10,000, which was particularly high compared with those given in previous reports [1] [3]. It was considered that the noise of frequency was reduced enough to synchronize with the exciting frequency by use of the spectrum analyzer.

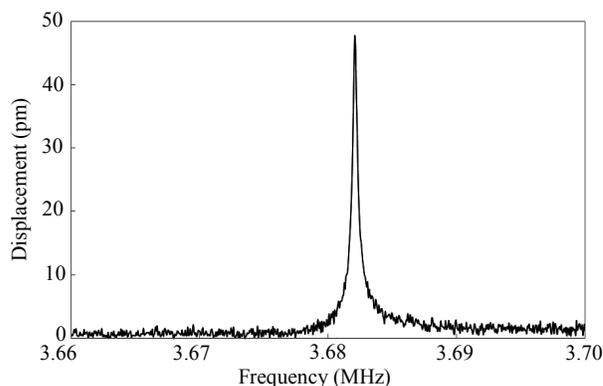


Figure 4. Measured results of the resonant frequency using a disc-shaped resonator at the primary mode.

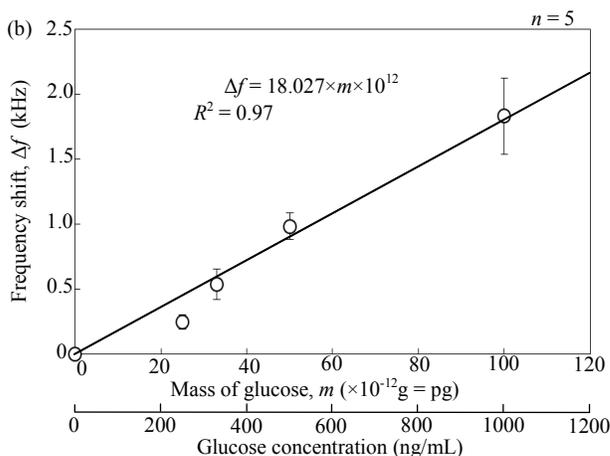
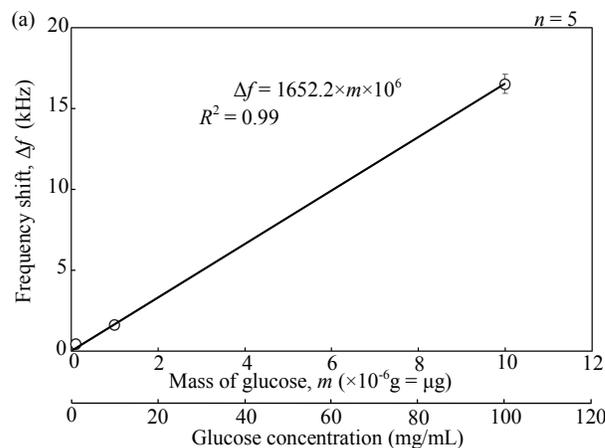


Figure 5. Relationship between the frequency shift and the mass of glucose for the line-free mass sensor ((a): 100 ng – 10 μg of mass of glucose, (b): 25 – 100 pg of mass of glucose).

C. Measurement of Glucose Concentration

The glucose concentrations were converted into a mass of glucose per 0.1 μ L of sample volume (Fig.5). The frequency shifts for the 0.1, 1 and 10 μ g masses of glucose were 0.45, 1.64, and 16.52 kHz, respectively (Fig.5 (a)). The frequency shifts for the 0, 25, 33, 50 and 100 pg of glucose samples were 0, 0.24, 0.54, 0.98, and 1.83 kHz, respectively (Fig.5 (b)). The results of a linear regression analysis between 0 – 100 pg for the line-free mass sensor showed the R^2 value to be 0.97. The calibration curve between the frequency shift, Δf , and the mass of glucose, m , is given by $\Delta f = 18.027 \times m \times 10^{12}$ (Hz), showing that the frequency shift is proportional to the concentration of m in the sample solution. Since the frequency shifts by 18.03 Hz per 1 pg mass of glucose, the sensitivity is calculated as being 55 fg/Hz. Finally, the sensitivity of the line-free mass sensor was estimated to be 0.06 fg because the optical displacement sensor has a frequency resolution of 1 mHz.

IV. CONCLUSION

We designed and analyzed the performance of a line-free mass sensor, comprising a disc-shaped resonator and a separate excitation source. Our study indicates that, if an optical displacement sensor with a frequency resolution of 1 mHz is used, a sensitivity of 0.06 fg can be achieved with this line-free mass sensor. This sensitivity is adequate for the required level in order to carry out salivary hormone analysis.

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REFERENCES

- [1] M. Sepaniak, P. Datskos, N. Lavrik, and C. Tipple, “Peer Reviewed: Microcantilever Transducers: A new Approach in Sensor Technology”, *Anal Chem*, Vol.74, pp. 568A-575A, 2002.
- [2] E. A. Wachte and T. Thundat, “Micromechanical sensors for chemical and physical measurements”, *Review of Scientific Instruments*. Vol.66, pp. 3662-3667, 1995.
- [3] A. Janshoff, H. J. Galla, and C. Steinem, “Piezoelectric Mass-Sensing Devices as Biosensors – An Alternative to Optical Biosensors?”, *Angewandte Chemie - International Edition* Vol.39, pp. 4004-4032, 2000.
- [4] E. Benes, M. Gröschl, W. Burger, and M. Schmid, “Sensors based on piezoelectric resonators”, *Sensors and Actuators: A. Physical* Vol.48, pp. 1-21, 1995.
- [5] N. V. Lavrik, M. J. Sepaniak, and P. G. Datskos, “Cantilever transducers as a platform for chemical and biological sensors”, *Rev. Sci. Instrum.* Vol.75, pp. 2229-2253, 2004.
- [6] M. Yamaguchi and Y. Kimura “Proposal for a Power Supply Line-free Mass Sensor for Measuring Total Protein in Human Saliva”, *Sensor Letters*, Vol.12. 2014 in press.