Self-actuating biosensor using a piezoelectric cantilever and its optimization

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Abstract. This paper presents a self-actuating biosensor based on the piezoelectric cantilever optimized by Taguchi method for the label-free detection of specific biomolecules. Until now, even though the optimisation of the cantilever-based biosensors have been performed by changing dimensions one by one, few researches have performed the geometric optimisation considering the overall configuration of the piezoelectric cantilever. This paper suggests a method of optimising the piezoelectric cantilever by the Taguchi method. The first resonance frequency, the separation factor, and the sensing signal of the piezoelectric cantilever were selected as the object functions. The resonator driving circuit will keep the cantilever resonance on the binding of the antigen with antibody. By real-time monitoring of the resonance frequency shift by the frequency sensing circuit, the effects of the protein binding on the change of the cantilever stiffness and mass will be investigated.

1. Introduction
Micromechanical cantilever has advantages as sensors for its versatile application and high sensitivity as well as fast response [1,2]. Therefore, silicon-based cantilevers have recently drawn great attention as biosensors to detect specific molecular interactions, cell adhesion and chemical gases [3-5].

The cantilever biosensors have been developed to operate in either a static mode or a dynamic mode. When a cantilever biosensor operates in static mode, the deflection resulted from the surface stress of the adsorbed biomaterials has been measured by optical measurement system [6,7], which is so bulky and expensive that it is almost impossible to minimize the device size for a Lab-On-a-Chip (LOC) system. There are other detection limitations such as a narrow dynamic range and parasitic deflection in optical measurements [8].

The cantilever biosensor can also be operated in a dynamic mode, where its frequency shift is measured before and after the binding of bimoleculars on the cantilever surface [8-11]. The mass adsorbed on the cantilever surface can be calculated from the frequency shift, provided that the mechanical properties do not change significantly with the adsorbed mass. A micro cantilever with a piezoresistive layer can be implemented as sensing mechanism instead of an optical system [9]. However, the electrical signal due to the cantilever deformation is small and an additional actuator is needed to operate the piezoresistive cantilever. However, if the cantilever is layered with a piezoelectric material such as PZT or ZnO, driving and sensing parts of the piezoelectric cantilever can be fabricated at one process sequence. Moreover, the required components for the operation of piezoelectric cantilevers are not so bulky as the optical system. Therefore, the piezoelectric cantilever biosensor in dynamic mode can be a choice for a minimized LOC system.
To improve the sensitivity of the piezoelectric cantilever biosensor, the geometric optimization of the cantilever biosensors have been performed by analyzing the effects of each dimension on sensitivity one after the other [12]. However, few researches have performed the geometric optimization considering the overall configuration of the piezoelectric cantilever.

This paper suggests optimizing the piezoelectric cantilever by the Taguchi method using the first resonance frequency, the separation factor, and the sensing signal of the piezoelectric cantilever as the object functions. The resonator driving circuit will keep the cantilever resonance by feeding the sensing signal from the cantilever back to the circuit after the binding of the antigen with the antibody on the cantilever surface. By real-time monitoring the resonance frequency shift, the effects of the protein binding on the change of the cantilever stiffness and mass will be investigated.

2. Configuration
Figure 1 shows the overall configuration of a self-actuating biosensor based on the piezoelectric (PZT) cantilever. The bottom electrodes of PZT for driving and sensing are defined by patterning of Ti/Pt. The driving electrode is designed along the edges of the rectangular cantilever surrounding the straight sensing electrode. A Pt layer is deposited on the top of PZT as a common ground electrode. If a sine wave signal is supplied to the driving electrode, the cantilever will oscillate corresponding to the driving signal. The deflected PZT layer will experience stresses generating a voltage to the sensing electrode. Microfluidic channels are fabricated by PDMS and the PDMS layer is bonded over the biosensor structures. Figure 2 shows a schematic of the overall circuit consisting of the resonator driving circuit and the frequency sensing circuit. Resonator driving circuit will change the driving frequency to the change of the resonance frequency of the piezoelectric cantilever on the binding of the antigen (Ag) with the antibody (Ab). The frequency shift will be real-time monitored by the frequency sensing circuit.

![Figure 1](image1.png)

(a) top view  
(b) side view

Figure 1. Schematic of the overall configuration of a self-actuating biosensor based on the piezoelectric cantilever with three electrodes; common ground, driving, and sensing electrodes.

3. Taguchi optimisation
Until now, the optimization of the cantilever-based biosensors have been performed by changing dimensions one by one [12], however, few researches have performed the geometric optimization considering the overall configuration of the piezoelectric cantilever.

To optimize the sensitivity of the cantilever to the binding between the antigen and the antibody, Taguchi method [13] was employed to maximize the first resonance frequency \(f_1\) and the separation factor \(=\left(\frac{f_2 - f_1}{f_1}\right)\) using four control factors as shown in Figure 1(a); the length of the cantilever \(L_{sub}\), the ratio of the width to length of the cantilever \(\frac{w_{sub}}{L_{sub}}\), the thickness of PZT \(t_{PZT}\), and the ratio of the width of sensing to driving electrodes \(\frac{w_s}{w_d}\). Table 1 shows three factor levels for Taguchi.
Figure 2. Schematic of the overall circuit consisting of the resonator driving circuit and the frequency sensing circuit. Resonator driving circuit will change the driving frequency to the change of the resonance frequency of the piezoelectric cantilever on the binding of the antigen (Ag) with the antibody (Ab). The frequency shift will be real-time monitored by the frequency sensing circuit.

analysis, and Table 2 shows the $L_9$ orthogonal array adopted for four control factors with three factor levels [13]. Higher first resonance frequency is preferred for better sensitivity according to equation (1) with greater separation factor for less cross-talk between the resonating modes. Equation (1) is derived for the cantilever whose mechanical properties or stiffness do not change after the binding between antigen and antibody. Therefore, the larger-the-better type was selected with the $S/N$ ratio of $\eta$ as defined in equation (2). $y_i$ is the analysis results by ANSYS using the element of solid226 for the modal analysis of piezoelectric material.

$$\Delta f = \frac{1}{2} f \left( \frac{\Delta k}{k} - \frac{\Delta m}{m} \right)$$  \hspace{1cm} (1)

$$\eta = 10 \log_{10} (y_i)$$  \hspace{1cm} (2)

Table 1. Four control factors and three factor levels for Taguchi optimization.

| Control factors | Factor levels |
|-----------------|---------------|
| $L_{sub}$       | 1 (40 $\mu$m) 2 (100 $\mu$m) 3 (200 $\mu$m) |
| $w_{sub} / L_{sub}$ | 0.5 1 2 |
| $t_{PZT}$       | 0.5 $\mu$m 1 $\mu$m 2 $\mu$m |
| $w_s / w_d$     | 1 2 3 |

Table 2. $L_9$ orthogonal arrays for Taguchi optimization.

| Control factors | Factor levels |
|-----------------|---------------|
| 1               | 1 1 1 1 |
| 2               | 1 2 2 2 |
| 3               | 1 3 3 3 |
| 4               | 2 1 2 3 |
| 5               | 2 2 3 1 |
| 6               | 2 3 1 2 |
| 7               | 3 1 3 2 |
| 8               | 3 2 1 3 |
| 9               | 3 3 2 1 |
Figure 3. Plots for factor effects for (a) the first resonance frequency and (b) the separation factor.

Figure 3 shows the effects of the first resonance frequency and the separation factor on the signal-to-noise level. The dimensions of the cantilever were decided at 1, 1, 3, and 1 levels for each control factors to have 1.48 MHz and 5.77 of the first resonance frequency and the separation factor, respectively. The current flowing the sensing electrode on deformation should also be analyzed to fully optimize the geometric dimensions. Through the analysis of variance, it was found that $L_{sub}$ and $t_{PZT}$ are main control factors for first resonance frequency and $w_{sub}/L_{sub}$ for the separation factor.

4. Fabrication

Figure 4 shows the overall fabrication sequence of the PZT cantilever biosensor. (a) Low-stress PECVD silicon nitride layer of 300 nm is deposited on the bare silicon wafer and patterned by RIE. (b) Ti (20 nm)/Pt (150 nm) is deposited and patterned by dry etching as bottom electrodes. (c) PZT (2 μm)/Pt (100 nm) is deposited and patterned. (d) To passivate the PZT and electrodes, a silicon nitride layer is deposited with the same thickness of the substrate to eliminate any residual stress effects, and the recess under the cantilever is made by KOH wet etching. (e) PDMS with microfluidic channels were attached and the passivation layer over external electrodes areas were removed by RIE. Figure 5 shows the fabricated silicon nitride cantilever after KOH wet etching.

When devices are fully fabricated, the effects of the binding between antigen and antibody would be deeply investigated to evaluate the change of mass and stiffness of the PZT cantilever.

5. Conclusion

This paper presents a self-actuating biosensor based on the piezoelectric cantilever optimized by Taguchi method for the label-free detection of the prostate-specific antigen. The first resonance frequency and the separation factor were used as the object functions. However, further simulation is required to take the sensing current into consideration. The device would operate with the resonator driving circuit using TTL elements, which automatically change the driving frequency to the change of the resonance frequency of the cantilever after the binding of antigen with the antibody. The resonator driving circuit will keep the cantilever resonating by feeding the sensing signal from the cantilever back to the circuit after the binding of the antigen with antibody on the cantilever surface. When devices are fully fabricated, the effects of the binding between antigen and antibody would be deeply investigated to evaluate the change of mass and stiffness of the PZT cantilever.
Figure 4. Fabrication sequence for the PZT cantilever biosensor.

Figure 5. Fabricated silicon nitride cantilever.

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