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Improving the sensitivity and accuracy of microcantilever biosensors by a truss structure within air medium

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Abstract: Early diagnosis is a very fundamental issue in treating most diseases and for this purpose microcantilevers are very effective and reliable devices. In this work, four models of biosensor-based microcantilever are compared and a novel design with high sensitivity, quality factor, and accuracy is proposed. A truss structure is designed near the anchored end of the microcantilever, which improves the sensitivity in order to increase detection accuracy. A linear relationship between resonance frequency shift and masses has been estimated for all the designs. High quality factor, which increases the accuracy of measurement, is taken into account as the other benefit of the proposed design. These microcantilevers can be used as an array for multiple early diagnosis of cancer and moreover these features will improve clinical applications of cantilever sensors for early disease diagnosis.

Key words: Microcantilever, nanomechanical sensor, label-free, surface stress, air damping, sensitivity, quality factor

1. Introduction

Microcantilevers (MCLs) are increasingly drawing attention in sensing and actuating applications [1–5]. MCL-based biosensors are one of the basic micromechanical structures, which are free at just one end. MCL biosensors have been used widely for detection of multiple target molecules in a small sample volume for diagnosis as high-performance sensors. In other words, their surfaces are functionalized to detect special molecules such as chemical gas, DNA/RNA, antigen, and enzyme. If these bioelements can be absorbed by the functionalized surface, some attributes of the MCL can change and the biosensor can convert these variations into electrical signals. In one array of MCLs, it is possible to coat every side with a different sensor material [6]. The MCL biosensors include numerous advantages such as high sensitivity, low-cost fabrication, quick response, mass production, and label-free detection, just to name a few.

MCL-based sensors can be studied in static and dynamic modes. MCLs are physical sensors that can respond to changes in surface stress arising from biological and chemical processes and these attractions cause surface stress changes belonging to static mode. In addition to the bending beam, the frequency resonance of the MCL depends on the resonator mass and additional masses. If an extra mass is attached to its surface, the amount of mass can be measured by variation of resonance frequency considered in dynamic mode. In both modes, MCL response can be monitored by optic, piezo-resistivity, piezoelectricity, embedded MOSFET, capacitance, and electron tunneling [7,8]. Although the optical method has high sensitivity, it has some

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drawbacks, which should be matched to advantages such as the requirement of external equipment, periodical alignments, and inability to work in a microarray format. Furthermore, the piezo-resistive or piezoelectric methods are compatible with electronic devices.

The dynamic behavior of the MCL depends on design sensitivity and the characteristics of its operating medium. Therefore, in order to determine the quality factor (Q factor) of a structure, damping in resonators should be studied as an important factor. The effects of medium damping can be seen on resonance frequency and Q factor of MCLs. Bimolecular stimulus is converted to a large deflection of MCLs in a sensitive cantilever design.

MCLs can be operated in liquid, gas, and vacuum mediums. The Q factor, sensitivity, and maximum deflection are less in liquid than in air mediums. Since these sensors show good sensitivity when operated in air, this medium is chosen to be the surrounding medium.

Cakmak et al. introduced a novel method for fast precision measurement of liquid density and viscosity using two cantilevers with different geometries. They found that if cantilevers have different widths, the effects of density and viscosity could be segregated. Their measurement error was lower than 3% in the range 995–1150 kg/m^3 and 4.6% in the range of 0.935–4 mPa.s, respectively, for density and viscosity [9]. Zhang and Turner conducted research on fluid damping for beam resonators with high frequencies. In their work, a general fluid damping law was reported that can be utilized in the design of resonance-based microsensors operating in air or liquid mediums, using simple beam resonators as fluid viscosity sensors and air pressure sensors [10]. Wang et al. proposed a novel MCL biosensor designed with a microcavity in the free end of the cantilever for a local reaction between antibody and antigen, which can reduce the effect of adsorption-induced stiffness coefficient k variation [11].

In the present paper, we investigate the effects of surrounding medium on several types of MCLs and assume that the MCL is isolated from other objects so that anchors and squeeze-film damping are negligible. The effects of different shapes on the MCL are observed within a specific medium and finally a new design of MCL is proposed. In order to increase the sensitivity of the MCL, it is required to decrease its mass to sense the attached mass quickly and accurately. Moreover, the quality factor of the MCL cannot be disregarded. Therefore, MCLs with different windows are designed. As known, one of the most fundamental conditions for designing is related to its solidity, and so the truss structure is stronger than the other windows and reduces more masses. The advantage of this novel design is related to higher sensitivity and Q factor within the same medium; thus it can cause accurate measurement and a high amount of beam deflection. However, fluid damping still has a negative effect on these parameters.

2. Problem definition

As mentioned above, mass loading on one surface of the MCL can vary the resonance frequency of the biosensor in dynamic mode. The sensitivity of the MCL biosensor depends on the design sensitivity of the MCL and the measurement sensitivity of resonance frequency. On the other hand, mass detection by resonance frequency of the MCL is appropriate with vacuum and air mediums and its resolution is poor in solutions. The proposed paper is focused on the enhancement of sensitivity and Q factor of a MCL biosensor within air so as to benefit consumers by early diagnosis of complex diseases [12].

Previous works have some problems related to the sensitivity and Q factor and this leads to some efforts to enhance these parameters. Some researchers used MCLs in static mode but, as known, this mode has greater noise and drift. Furthermore, they do not consider the dimensional parameters of the surrounding medium.

Finally, the pattern of design plays a significant role in increasing sensitivity for MCLs, which is ignored in previous works.

2.1. Design and theory

A 3D geometry of the FE model is considered for solving this problem by COMSOL finite element software in order to determine and compare features of each model. The material of all models is silicon, which has an elastic modulus of 170 GPa, Poisson's ratio of 0.28, and density of 2329 kg/m^3. This medium is the same for all designs as listed in the Table, and all boundaries of that are considered as walls. All MCLs are placed totally within surrounding medium. In fact, these MCLs reside in an air-filled chamber, the design of which is depicted in Figure 1 (according to reported size in this Figure) and listed in the Table.

Table. Dimensions of MCL and its surrounding medium.

	Length (μm)	Width (μm)	Thickness (μm)
MCL	450	80	5
Surrounding medium	500	120	20

The boundaries on the left side of MCLs are considered as their anchored ends. MCLs are subjected to a 1.5 N/m^2 pressure onto their upper surface. Because of the Mach number of the structure, compressibility effects will not be small and compressible flow equations can be used for accurate responses. The symmetry condition is applied on the $x - z$ plate at $y = 0$.

2.2. Theory

Since air damping is related to the surface area of moving parts, it becomes a very crucial factor in micromechanical devices and systems in order to determine their dynamic performance due to the large surface area to volume ratio of a moving part [13]. One can regard a MCL as a second order system to introduce key ideas associated with second order responses. Clearly, the simplest second order system satisfies the equation of motion for a spring and a damper attached to a mass given by [14]

$$m\frac{d^2u}{dt^2} + c\frac{du}{dt} + ku = f \tag{1}$$

where m, c, and k are the mass, damping constant, and spring constant of the MCL, respectively. U, $\frac{du}{dt}$, and $\frac{d^2u}{dt^2}$ are displacement, velocity, and acceleration, respectively. f is equal to 1.5 N/m^2 and c can be calculated as below [15]:

$$c = 2\xi w_n \tag{2}$$

where ξ and w_n respectively represent damping ratio and undamped natural frequency. Damping ratio depends on the material, vibration velocity, and frequency. In the second order system, four states are available:

1. If $\xi > 0$, then the system is stable in the natural response decays. This stable case can be subdivided into three possibilities:

   1.1. If $0 < \xi < 1$, then the system is underdamped and the poles of the system are imaginary components. Lower values of ξ are related to the longer vibrating responses with light damping.

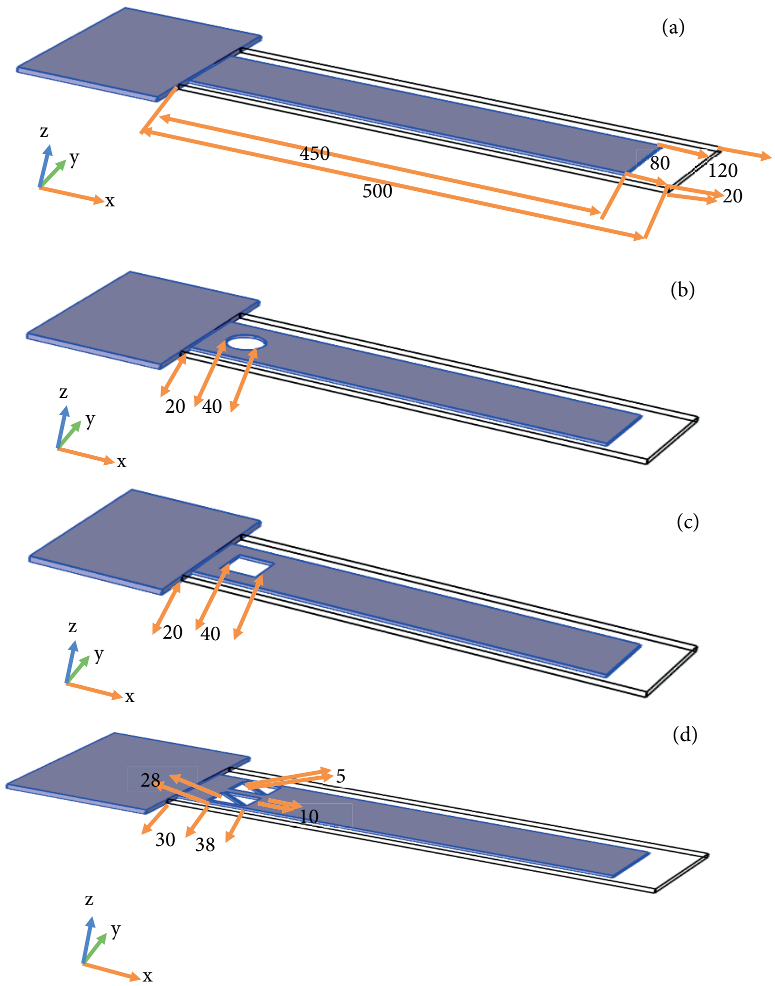

Figure 1. Schematic designs of (a) normal MCL, (b) MCL with a circular hole, (c) MCL with a rectangular hole, (d) truss design of MCL.

1.2. If $\xi = 1$, then the system is critically damped and the poles are placed on the negative real axis at $-w_n$.

1.3. If $\xi > 1$, then the system is overdamped and the poles are on the negative real axis.

2. Otherwise it is as an unstable system.

The equations governing compressible flow are the Navier–Stokes equations (Eqs. (3)–(5)), which are fundamental partial differential equations describing the flow of compressible and incompressible fluids; here compressible equations are used for estimating the displacement, velocity, and acceleration of MCLs. The fluid is presumed to be isotropic, as with gases and simple liquids, and consequently **V** will be an isotropic tensor. Furthermore, since the stress tensor is symmetric then [16]

$$-\nabla p + \mu \nabla^2 v - v \nabla v - \frac{2}{3} \mu \left(\nabla v \right) = \rho \frac{\delta v}{\delta t} \tag{3}$$

$$\frac{\delta\rho}{\delta t} + \rho\nabla v = 0 \tag{4}$$

$$\nabla\sigma = \rho\frac{\delta^2 u}{\delta t^2}, \tag{5}$$

where σ, ρ, and u are stress tensor, density, and solid displacement vector, and p, μ, and v represent pressure, viscosity, and fluid velocity vector, respectively. The total quality factor is related to the dynamic performance via influence of losses on the system. Low-loss systems will have a high quality factor. As the amplitude of vibration is small, it is possible to ignore nonlinear convective inertial effects in the fluid. It is expressed by viscosity and mechanical losses in support, respectively [17].

$$\frac{1}{Q_{tot}}=\frac{1}{Q_{visco}}+\frac{1}{Q_{supp}}, \tag{6}$$

where Q_{visco} and Q_{supp} are the quality factors related to viscosity and mechanical losses in support, respectively. To estimate the quality factor of the system, the relations between undamped natural frequency (f_0) and resonance frequency are described as follows:

$$Q_{tot} = \frac{1}{\sqrt{2(1-({f_r}/{f_0})^2}} \tag{7}$$

and

$\frac{w_{fluid}}{w_{vac}} = (1+\frac{\pi\rho b}{4\rho_c h})^{-\frac{1}{2}}$ [18], (8)

where w_{fluid} and w_{vac} are the resonant frequencies in vacuum and fluid, respectively. ρ_c is beam density, b and h are beam width and thickness, and ρ is fluid density. Because the variation in spring constant is negligible, the resonance frequency, f, of the MCL is calculated according to

$$\Delta f = -\frac{f}{2}\frac{\Delta m}{m^*} \tag{8}$$

and

$$s = \left|\frac{\Delta m}{\Delta f}\right| = \left|-\frac{2m^*}{f}\right| = 0.94\pi b l^3\sqrt{\frac{\rho^3}{E}}, \tag{9}$$

where l and E are the length of the MCL and Young module of the structure, respectively. The resonance frequency f of the oscillating cantilever can be expressed by

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}, \tag{10}$$

where k is the stiffness coefficient for the cantilever.

2.3. Boundary conditions

As discussed earlier, these simulation models consider the fluid–solid interaction to accurately calculate the parameters. The microchannel walls are assumed as no-slip ones. In addition, air density is 1.225 kg/m^3, depending on medium pressure and temperature. The simulation is performed in 293.15 K. Silicon density is set to 2329 kg/m^3 with a constant distance from the floor equal to 10 μm (from $x-y$ plate). Physical properties of the simulations were reported above. The right and left sides of the surrounding mediums are respectively considered as inlet and outlet.

The MCLs are subjected to a 1.5 N/m^2 pressure onto their upper surface so that they begin to vibrate and interact with the air medium, but stop after some moments because of air damping. The boundary no-slip conditions are

$$\left.\begin{array}{l} u_x = 0. \\ u_y = 0. \\ u_z = 0. \end{array}\right\} \qquad \text{(channel walls)} \tag{11}$$

and

$$\left.\begin{array}{l} \frac{\partial u_x}{\delta x} = 0. \\ \frac{\partial u_y}{\delta y} = 0. \\ \frac{\partial u_z}{\delta z} = 0. \end{array}\right\} \qquad \text{(inlet and outlet)} \tag{12}$$

In this work, the mean velocity of initial fluid and pressures at all ends of the microchannel were assigned as zero ($p=0$).

All the designs were for both b = 3 μm and b = 4 μm and their results were compared with each other.

3. Results and discussion

This paper focused on minimizing the energy consumed by air damping and maximizing the motion of mechanical parts with limited supply. Therefore, damping effect estimation in the system is one of the most significant steps in the analysis and design process of MCLs. For all the above-mentioned system designs we had $0 < \xi < 1$, which indicates stability and vibration for all. Firstly, it is worth stating that in order to validate our results, some simulation was done with the same condition as [10]. The results show that the calculated damping coefficient was approximately the same as the paper with limited error (<5%). Then the dimensions of the surrounding medium became smaller as shown in Figure 1.

3.1. Resonance frequency

The finite element analysis of all designs for MCLs was quantified by Eqs. (8)–(10) to complete the simulations of fluid–solid interaction as illustrated in Figure 2 for $b = 3$ μm, reporting the resonance frequency of various MCL designs. One can observe that the response frequency of MCLs is decreased because their masses are diminished by different holes in them. As shown in Figure 2, the resonance frequency of the four designs is equal to 20,672 Hz for the conventional cantilever, 18,419 Hz for the cantilever with a circular hole, 17,512 Hz for the cantilever with a square hole, and 15,852 Hz for the truss structure. The truss structure has the minimum value for resonance frequency.

3.2. Fluid–solid interaction

In order to investigate the quality factor and sensitivity of MCLs under the circumstances of the desired environment, a set of simulations was performed: air damping effect calculation, frequency domain simulation,

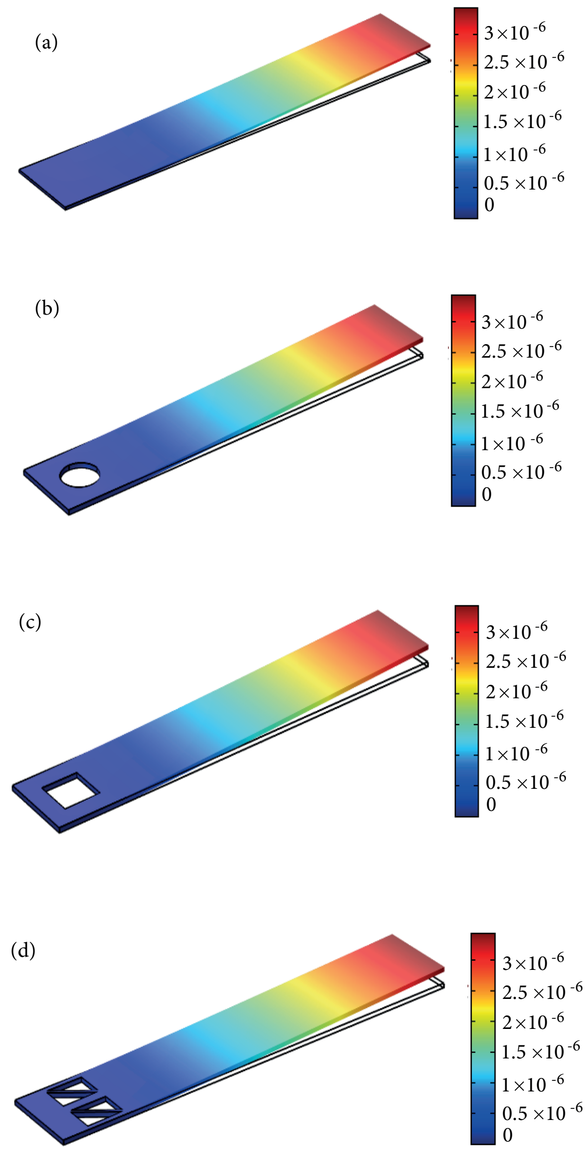

Figure 2. The resonance frequency of (a) conventional MCL, (b) MCL with a circular hole, (c) MCL with a rectangular hole, (d) truss design of MCL.

and sensitivity analysis. First, all designs are immersed in that air volume, start vibrating with the applied force whose amplitudes are equal to $f_x = 0$, $f_y = 0$, $f_z = -1.5$ N/m^2, then interact with air damping, and stop vibrating after moments. Thus, it is needed to simulate a time-dependent study to see the movement or bouncing of MCLs. The effects of air damping on MCL surfaces can be figured out by the help of prementioned expressions (section 2) by Eqs. (3)–(5). Moreover, air damping results are applied to the other simulations for achieving more accurate results.

Figure 3 illustrates the maximum pressure on silicon MCLs caused by air damping and applied force during MCLs' motion. In all simulations, the conditions for medium and applied force are as the same. A $500-\mu m-$long microchannel (chamber) is considered.

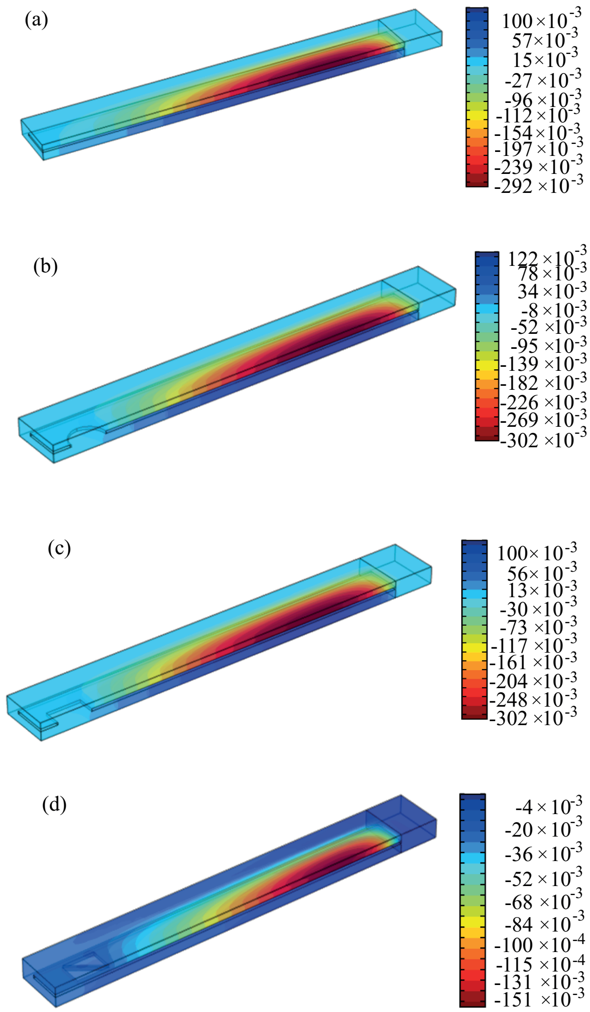

Figure 3. Maximum stress of (a) conventional MCL, (b) MCL with a circular hole, (c) MCL with a rectangular hole, (d) truss design of MCL.

For the conventional MCL, the maximum pressure is related to $t = 2.6 \times 10^{-5}$ s and its range is within [–0.02–1.37 $\times$ 10^{-2}] and for the cantilever with a circular hole; this factor is in [–0.02–1.27 $\times$ 10^{-2}] for $t = 3 \times 10^{-5}$. Furthermore, the pressure for cantilever with a circular hole is maximized in $t = 3.2 \times 10^{-5}$ and its amounts are in the range of [–0.3–0.13] and in the truss structure for $t = 3.6 \times 10^{-5}$ it belongs to [–0.02–6.97 $\times$ 10^{-4}]. It can be seen that the minimum pressure is applied on the truss structure, which shows that this sensor is strong enough to undergo the pressure arising from bioelements

3.3. Quality factor

To investigate the quality factor of the proposed design for the MCL and to test truss effects on its performance, some factors such as quality factor and sensitivity are considered and this factor is calculated by Eqs. (1)–(7) and boundary conditions. In this section, two different sizes of thickness are taken into account by applying prementioned air damping effects. As shown in Figure 4, it is obvious that the holes on MCLs lead to improvement in their quality factor, which finally makes the quality factor of the truss MCL better than the others do. The last point to mention is that the displacement amplitude of the truss MCL is two times greater than the conventional one. The Q factor for the conventional MCL, with a circular hole MCL, with a square hole MCL, and truss structure with $b = 3\,\mu m$ are equal to 11.09, 11.32, 12.3, and 16.82, respectively. In addition, the amounts of these factors for $b = 4\,\mu m$ are 13.13, 12.54, 13.72, and 15.81, respectively. As known, higher Q factor causes the resonance frequency to be measured more easily and more accurately.

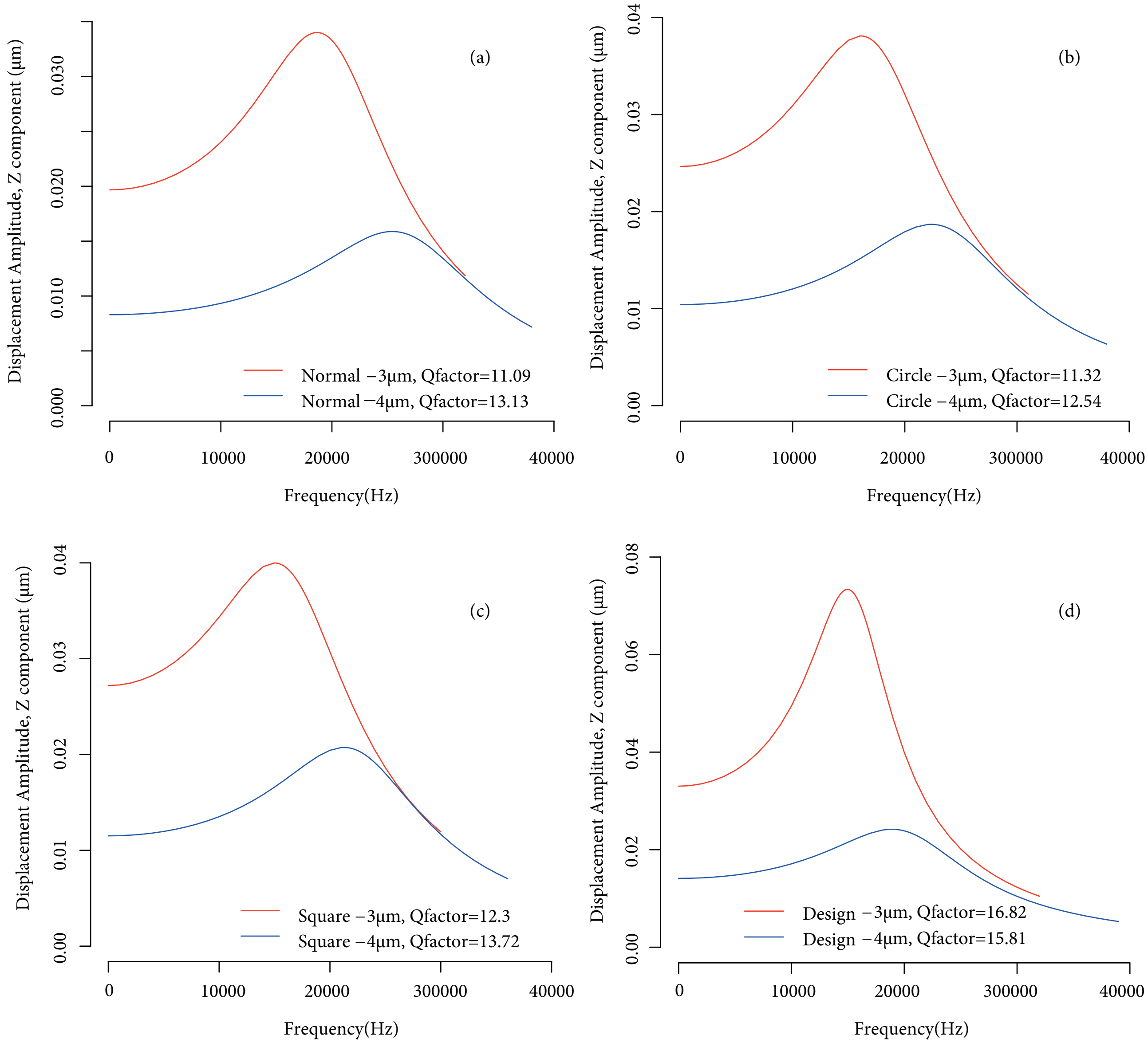

Figure 4. The quality factor of (a) conventional MCL, (b) MCL with a circular hole, (c) MCL with a rectangular hole, (d) truss design of MCL for $b = 3\ \mu m$ and $b = 4\ \mu m$.

3.4. Sensitivity

Various masses are attached on the desired MCL designs with $l = 450\,\mu m w = 80\,\mu m$, and $h = 3.4\,\mu m$. Then the resonance frequency for each of them is calculated. For better representation, normalized sensitivity is chosen here, which is defined as the ratio of resonance frequency difference between before and after absorption and undamped resonance frequency. Figure 5 depicts the calculated normalized sensitivity for different designs, which are calculated by Eqs. (9) and (10) and boundary condition. To calculate sensitivity of MCLs, different masses are placed on them, helping to evaluate their resonance frequency. The sensitivity of designs with $3\,\mu m$ thickness was better than those of $4\,\mu m$ thickness. Additionally, truss structure sensitivity was the highest among its counterparts, indicating its sufficient potential for diagnosis applications.

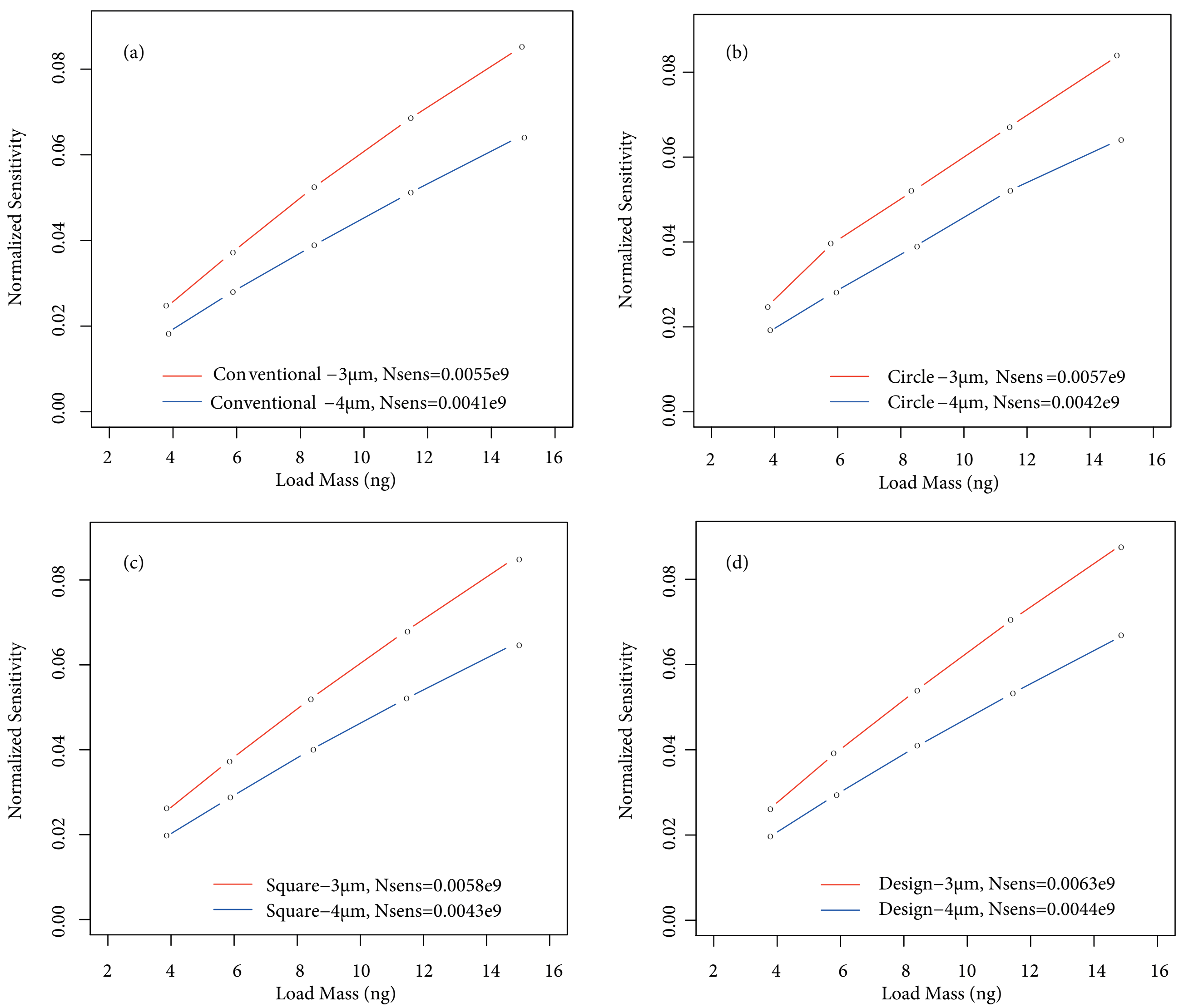

Figure 5. Sensitivity of (a) conventional MCL, (b) MCL with a circular hole, (c) MCL with a rectangular hole, (d) truss design of MCL for $b = 3\ \mu m$ and $b = 4\ \mu m$.

4. Conclusion

This paper compared some conventional MCL designs examining the most striking factors of a biosensor within an air medium, and finally proposed a novel design of MCL with high sensitivity and quality factor. The novel cantilevers are considered as cantilever arrays for detecting multibiomarkers with truss structure near the end of the structure. These structural features of MCLs led to some benefits such as high sensitivity, high quality factor, and linear relationship between resonance frequency shift and the masses on MCLs compared to the conventional ones. It is obvious from the previous sections that quality factor was increased from 11.09 to 16.82 and sensitivity amplitude in the proposed design was the best obtained. These biosensors are potentially applicable in early disease diagnosis.

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