Measurement 45 (2012) 2081–2088

Contents lists available at SciVerse ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Shape effects of micromechanical cantilever sensor

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ARTICLE INFO

Article history:
Received 12 January 2012
Received in revised form 19 April 2012
Accepted 14 May 2012
Available online 1 June 2012

Keywords:
Microsensor
Cantilever
Shape
Resonant frequency
Sensitivity
Aspect ratio

ABSTRACT

Microcantilever has been increasingly used as microsensor thanks to its fast response, low cost and parallel implementation in large quantity. The principle of sensing lies in the positive correlation between the resonant frequency of microcantilever and the target mass loading. The shape of cantilever determines the resonant frequency. Therefore it plays a vital role in microsensing. In the present study three basic geometric shapes (rectangle, triangle and half-ellipse) with innovative inner cut are investigated. The micro-cantilever beams are cut to external aspect ratios of 0.5, 1, and 2, and inner cut at aspect ratios of 0, 0.5, 1, and 2, with equal sensing area. Both numerical and experimental analysis indicates that the low-aspect-ratio cantilever with high-aspect-ratio inner cut achieved high sensitivity. The half-ellipse being the highest followed by the rectangle. The results are useful for optimal shape design of a micromechanical cantilever sensor.

1. Introduction

The cantilever structure has been widely applied to a variety of sensors and actuators in electromagnetics, optics, ambient temperature, and biology [1,2]. For microsensing, improvement in the structure design of the microsensor for higher accuracy and sensitivity is an important factor.

Before 1990, the cantilever was rarely discussed in microsensor application. Mazzola and Fodor [3] used atomic force microscopy (AFM) in protein substrate detection. Later Dammer et al. [4] measured the specific antigen/antibody interactions by detecting the adhesion force from the bending in AFM. Today, the cantilever is mostly used to load the target on the surface and to determine the resonant frequency shift after mass loading. The resonant frequency of cantilevers decreases as the mass increases and has a positive correlation with the specific-binding of an antigen and an antibody [5]. Another application of the cantilever as a microsensor is the fabrication of the laser-assisted deposition of a metallic micropattern through the metabolite of the acidophilic bacteria *Thiobacillus ferrooxidans* [6]. The metal deposition depends on the concentration of the bacteria, which is measured by the microsensor.

Goericke and King [7] investigated the response to surface stress of microsensors. They found that the cantilever sensitivity increased by decreasing the length-to-width ratio. For this experiment they kept the same thickness of the cantilever as in the simulation. They simulated cantilever damping to change the width dependence. The maximum and average sensitivities are compared to the L/W ratio. They showed better result in the low aspect ratio by surface stress loading. The maximum sensitivity of the cantilever is line loading at the free end, and the average sensitivity is surface stress loading. Loui et al. [8] designed five molds of piezo-resistant cantilevers and concluded that the cantilever with low aspect ratio is suitable for microsensor applications. These findings suggest that the low-aspect-ratio cantilevers take higher rigidity and better for surface loading. Therefore, the real experimental result showed the lower deflection response on the wide and short cantilevers when using the same stress loading. Numerical analysis for the optimization of the beam shape was conducted. The sensing area was considered a competing factor against the shape, hence the conclusion was not definite in terms of the shape [9,10]. The geometric designs of cantilevers determine the resonant frequency, which is an essential parameter in microsensing.

This paper proposes a method to explore the effects of the shape of a cantilever subject and an equal probe

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0263-2241/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.measurement.2012.05.007

surface area on the mass binding opportunity. Both numerical and experimental analyses were conducted for a wide range of aspect ratios and for three shapes. The investigated scope of the shapes is the widest among the existing literature. The hollowed structure in the cantilever is suggested due to the improved etching quality for fabricating the cantilever-shaped microsensor.

2. Design and experiment of micro-cantilever beam

2.1. Geometric design of cantilever

The parameters determining the resonant frequency of the cantilever f are the spring constant k and the mass M [11–13].

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{M}} \tag{1}$$

The mass loading on the cantilever to be measured is:

$$\Delta M = \Delta m \times n = \frac{k}{4\pi^2}\left(\frac{1}{f_m^2} - \frac{1}{f_0^2}\right) \tag{2}$$

where f_o and f_m are the resonant frequency before and after mass loading, respectively. ΔM is total mass loading change based on the whole geometric (triangle, rectangle, or half-ellipse) cantilever, detected after sensing. Δm is the total cell mass on the cantilever.

The resonant frequency will decrease with the addition of mass (Δm) during the immobilization reaction. n is a correction factor dependent on the geometry of the cantilevers. From Eq. (2), it can be determined that the higher the base resonance frequency, the higher the sensitivity of the cantilever microsensor. Namely, the same amount of the to-be-detected mass loading will cause a larger frequency shift $f_o - f_m$. Fig. 1 shows the linear correlation between the mass loading (Δm) and the shift in the frequency, or the reciprocal of the square of the frequency ($f_m^{-2} - f_0^{-2}$). The slope of the correlation curve changes with the spring constant divided by the shape factor (k/n). A larger slope leads to a smaller $f_m^{-2} - f_0^{-2}$ at an equal mass loading, causing a higher sensitivity of the measurement.

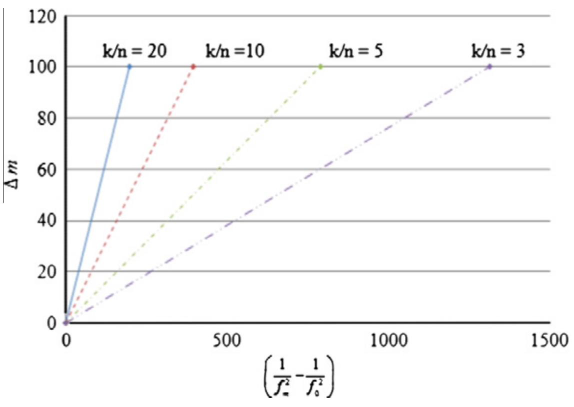

Fig. 1. Correlation between mass loading and the frequency shift in Eq. (2).

The spring constant is affected by the structural dimensions and by Young's Modulus (E), which can be calculated for rectangle cantilevers by:

$$k = 3EI/l^3 \tag{3}$$

where E varies for different cantilever materials. In this paper, Young's Modulus for a silicon dioxide (SiO_2) cantilever is 57–79 GPa [14,15], and I is the moment of inertia, or $wt^3/12$, for the rectangular cross-section of the cantilever. The cantilever dimensions include the length (l), the width (w) and the thickness (t). The length and the thickness have significant effects on the spring constant and rigidity.

The fabrication limitation of the micro-cantilever structure on the line width is approximately 3 μm (based on the information from the facility provider). The laser reflection area for cantilever detection is approximately $20 \times 20\ \mu m^2$. In the current study, the innovative inner cut of the cantilever beam is adopted for the sake of effective fabrication of the beam. The cantilevers have a large suspension to be etched out, often causing a nonuniform thickness of the cantilever beam leading to an inaccurate resonant frequency. On the other hand, a large inner cut reduce the beam rigidity significantly, and hence a compromise is required. In consideration of these factors, three types of cantilevers with the fundamental shapes of a rectangle, triangle, and half-ellipse are selected for analysis. These cantilevers are fabricated in a series of aspect ratios of 0.5, 1, and 2 respectively, with the inner cut at an aspect ratios of 0, 0.5, 1, and 2 respectively, under the same detection surface area of $5000\ \mu m^2$.

2.2. Numerical analysis

The dynamic behavior of the silicon dioxide (SiO_2) cantilever is simulated by ANSYS. A Solid 45 module element type is chosen as the input for the material parameters of a Young's modulus of 73 GPa, a Poisson's ratio of 0.17, and a density of 2200 kg/m^3. Deflection of the free ends occurs by restricting the axial freedom in X, Y, and Z, at the fixed end of cantilever.

The simulation confirms the fact that a low-aspect-ratio cantilever has a high rigidity and sensitivity. Although the aspect ratio of the inner cut will reduce the resonant frequency, the hollowed structure can facilitate the etching process and improve the dimensional accuracy of the designed cantilever. The low-aspect-ratio (0.5) cantilever with an inner cut aspect ratio of 2 slightly changed the resonant frequency compared to the solid one (aspect ratio of 0). As shown in Fig. 3A, the frequency is significantly reduced when the aspect ratio of the hollow cut is changed to 1 or 0.5. For this reason, the shapes of the low-aspect-ratio cantilevers with a high-aspect-ratio inner cut, especially the half-ellipse and rectangle shapes, are considered advantageous for both successful fabrication and agile bio-sensing.

The shape factors and spring constants are the most important parameters in the resonant frequency and the mass loading measurement. With the rectangular cantilever these parameters are readily calculated. The other shapes require an indirect method of gold coating for determining the constant (K/n), defined by the spring constant divided by the shape factor from numerical analysis [16].