Novel cantilever for biosensing applications

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ABSTRACT

Chemomechanical actuation of a microcantilever beam induced by biomolecular binding such as DNA hybridization and antibody-antigen binding is an important principle useful in biosensing applications. As the magnitude of the forces involved is very small, increasing the sensitivity of the microcantilever beams involved is a priority. In this paper we are considering to achieve this by structural variation of the cantilevers. Merely decreasing the thickness of the microcantilever may improve the sensitivity, but it gives rise to the disadvantages of 'arching' and lesser reliability due to greater probability of defects during fabrication. We consider a 'ribbed' cantilever that eliminates the disadvantages while improving the sensitivity simultaneously. Simulations for validation have been performed using the finite element analysis software ANSYS 8.0. The simulations reveal that a ribbed microcantilever is almost as sensitive as a thin cantilever and has relatively very low arching effect. Simulations also reveal that higher the arching lower is the sensitivity.

Key Words: microcantilever, ribbed microcantilever, notched microcantilever, biomolecular assay, biosensor, transducer, MEMS.

1. INTRODUCTION

1.1 Biosensing

Biosensing technology is being applied in a wide variety of analytical problems in medicine, the environment, food, process industries, security and defense. The key part of a biosensor is the transducer. The transducer detects a physical change accompanying the reaction on which the biosensing is based and converts it into a measurable parameter. This physical change may be[1]: (1) absorption or evolution of heat (thermometric or calorimetric biosensors[2]), (2) changes in the distribution of charges causing an electrical potential to be produced (potentiometric biosensors[3]), (3) movement of electrons produced in a redox reaction (amperometric biosensors[4]), (4) light radiation or difference in optical properties between the reactants and products (optical biosensors[5]) and (5) effects due to the mass or intermolecular interaction of the reactants or products (piezo-electric biosensors[6]). Based on our requirements and constraints we need to choose from amongst these sensors. Micro-cantilevers have been extensively used for piezo-electric biosensing. In the clinical field in particular, critical diagnostic and therapeutic monitoring situations require frequent testing with ideally low turnaround times. For applications like early and rapid diagnosis of acute myocardial infarction, microcantilever-based biosensors have been found to be very effective[7].

1.2 Microcantilever-based Biosensing

Microcantilevers can be used in two ways for bio-sensing. It could be used as a microbalance, where the mass of the bio-material bound on the surface induces some measurable change. The resonant frequency of the microcantilever, for example, will change when the bio-material which we want to sense attaches to the microcantilever[6]. The change in the resonance frequency depends on the mass of the bio-material attached to the microcantilever and the mass attached in turn depends on the concentration of the bio-material in the sample. However, this method is not very efficient in liquid phase due to the damping effect of the liquid. Alternatively, micro-cantilevers can be employed as surface stress

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sensors. This is useful in liquid phase environments. Most of the biomolecules are available in liquid phase environments hence this method turns out to be more effective method of monitoring the binding of biomolecules[8].

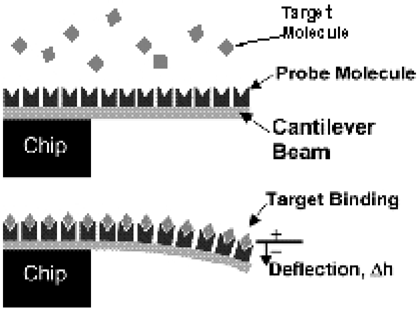

Figure 1[9]: Principle of microcantilever-based biosensing involving the measurement of effects of surface-stress changes.

In this method, the two surfaces of the cantilever have different characteristics because of which the target molecules preferentially get adsorbed to one of the surfaces (Fig. 1). This difference in characteristics can be achieved by depositing probe molecules preferentially on one of the surfaces. The intermolecular interaction of the biomaterial on this surface generates surface stresses on one side of the cantilever which are good enough to bend the cantilever by a detectable magnitude. The deflection of the cantilever can be measured by sensing the change in resistance of a piezo-electric material embedded on the surface of the microcantilever or sensing the deflection of a laser beam reflected from the microcantilever surface. Arrays of microcantilevers have also been used in bio-applications for greater reliability and accuracy. Here the net differential signal from the array of microcantilevers is the sensor signal[11].

The deflection of the microcantilever depends on the distribution and number of target molecules adsorbed on the surface. This in turn depends on the concentration of target molecules in the sample solution. Hence, the deflection of the cantilever represents the concentration of the molecules in the sample solution.

The popularity of microcantilevers as transducers in biosensing can be attributed to two reasons. First, they render measurable mechanical responses directly. Secondly, the sensitivity of these cantilevers to small quantities of analytes is superior to that of many other transducers.[12]

1.3 Improving the sensitivity

The magnitude of surface-stresses involved in microcantilever-based biosensing is very small. Consequently, it is of great importance to find out ways of enhancing the sensitivity of the microcantilever. This can be achieved by adjusting various parameters like choice of the materials (which in turn changes the Young's Modulus), surface properties (it is shown that the sensitivity can be improved by modifying the surface roughness by introducing metal nano-clusters[10]) and geometric parameters. It is desirable to have sensitive microcantilevers made of commonly and commercially available material. Hence we need to consider factors like shape of the cantilever, incorporation of stress concentration regions, grooves and notches[12], which offer sensitivity improvement ways of a microcantilever of given material and surface characteristics.

In this paper, we are considering the method of structural variation to enhance the sensitivity. By simply reducing the thickness of the microcantilevers sensitivity can be improved. However, the thinner cantilevers have the following disadvantages in comparison with the thicker cantilevers (1) the thinner cantilevers are more susceptible to breakage during fabrication and transportation; the probability of surface cracks getting introduced during fabrication is greater for the thinner cantilevers (2) since the widths of these cantilevers are comparable to the lengths, there is bending even in the lateral direction (arching effect, as shown in Fig. 2). This is undesirable because the section modulus 'S' of the cross-section of the cantilever increases thereby making the longitudinal bending more difficult. Also, measuring the change in piezo-resistance may also become complicated.

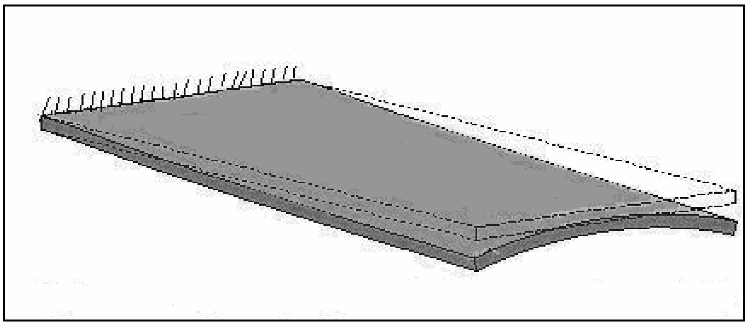

Figure 2: The arching effect.

1.4 The ribbed micro-cantilever

We consider a design in the form of a ribbed cantilever, which has alternate thick and thin sections (Fig. 3). The aim of this paper is to show that the ribbed cantilever indeed has the advantages of both the thin and thick micro-cantilevers viz., (1) it has better sensitivity than that of the thick microcantilever (2) the arching effect also reduces substantially. We expect that the ribbed cantilever has sensitivity comparable to that of the thin microcantilever and arching effect similar to that of the thick microcantilever. Also, a ribbed cantilever is likely to have less probability of breakage and the fabrication appears to be more robust when compared to that of thinner microcantilevers. This is because the probability of surface cracks getting introduced during fabrication is decreased when the thickness is higher.

In actual practice, the shape of the ribbed cantilever could be achieved by introducing notches in a thick microcantilever by using a focused ion beam (FIB) mill.

2. SIMULATIONS AND RESULTS

Simulations have been performed in order to validate the claim that a ribbed microcantilever is better than both the thin and the thick microcantilevers. For simulation purposes, we have considered a thick microcantilever diaphragm of 100μm long x 50μm wide x 4μm thick dimensions; a thin microcantilever of thickness 2μm; four ribbed microcantilevers with 2, 3, 5 and 10 segments. The following data was used for simulations using ANSYS: material - polysilicon; Young's Modulus 169GPa; Poisson's ratio 0.22 and surface stress due to biomolecules 48μN/μm.

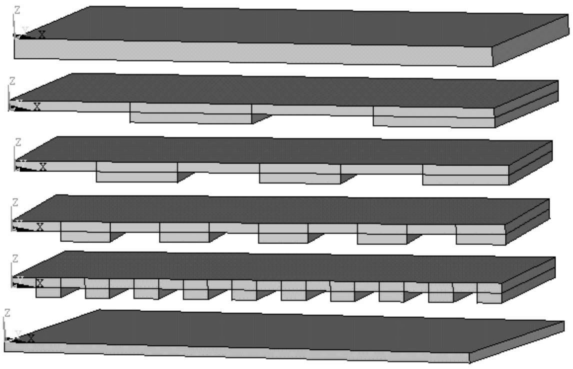

Figure 3: The microcantilever diaphragms used in simulations (thickness exaggerated for clarity).

For the finite element meshing of the structures, the structural solid element SOLID45 has been used. SOLID45 is used for the 3-D modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions; it suits well for our simulations.

The effect of the surface stress created by the biomolecular interactions on the surface of the cantilever can be effectively simulated by substituting it with a line force (amounting to 48µN/µm) on the edges of the cantilever surface. We have done this by applying an appropriate amount of force at each node on the edge (Fig. 3).

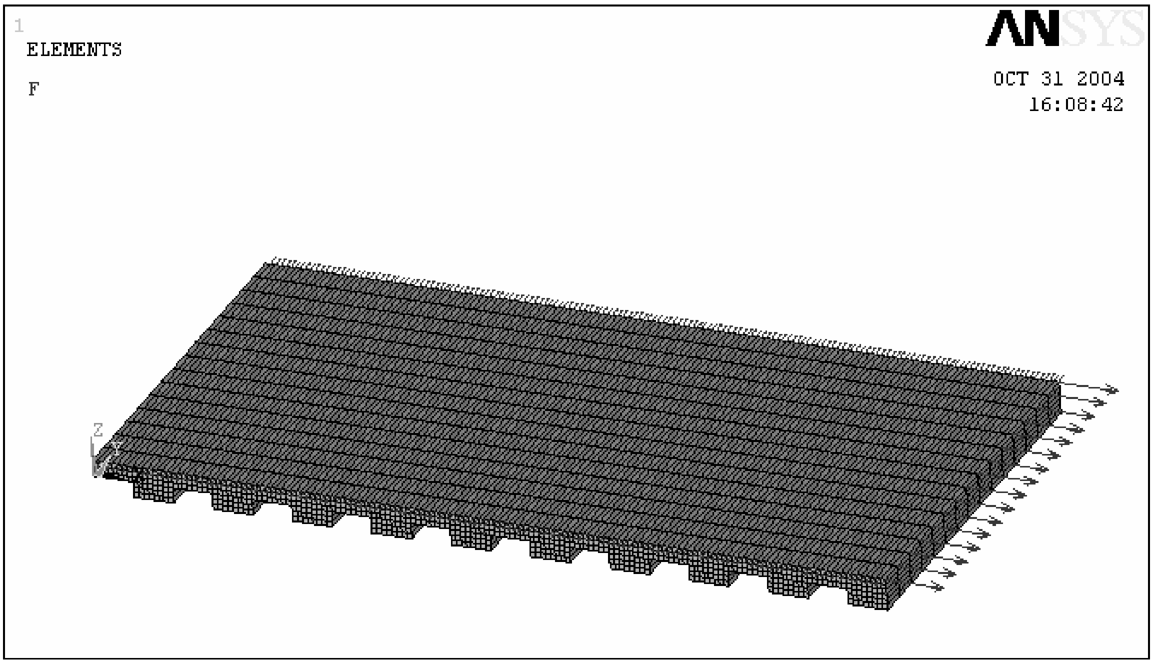

Figure 4: A meshed microcantilever. The arrows indicate forces applied on the nodes on the three edges of the top surface. The surface stress has been modeled as line forces on the edges. The force on the free-end causes deflection where as the forces on the side edges cause the arching effect, which in turn reduces deformation.

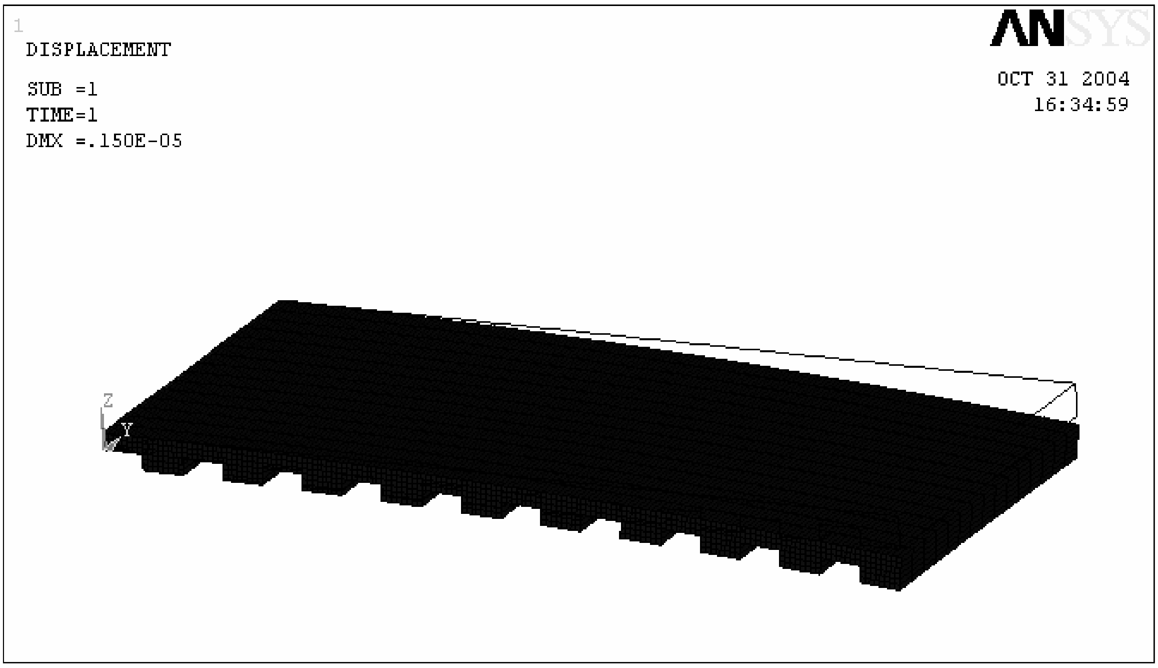

Figure 5: Result of ANSYS simulation of a ribbed microcantilever with ten segments. Only the outline of the initial position of the cantilever is shown.

The results obtained from ANSYS simulations are as follows:

Table 1: Results of ANSYS simulations

	Thick cantilever	Cantilever with 2 segments	Cantilever with 3 segments	Cantilever with 5 segments	Cantilever with 10 segments	Thin cantilever
Sensitivity	0.4636 µm	1.4005 µm	1.3592 µm	1.3896 µm	1.4978 µm	1.8883 µm
Arching	0.0324 µm	0.0317 µm	0.0369 µm	0.0318 µm	0.0326 µm	0.1603 µm
Relative sensitivity	1	3.17	3.06	3.15	3.4	4.0
Relative arching effect	1	0.97	1.14	0.98	1.01	4.95

Sensitivity has been measured in terms of the maximum displacement undergone by any point on the cantilever (in this case, the points will be the corners of the free-edge). Arching effect has been quantified as the difference in the displacements of the mid point of the free-end of the cantilever and its corners, which undergo maximum displacement. The relative sensitivity and relative arching effect parameters are with respect to the thick microcantilever.

3. ANALYSIS AND CONCLUSIONS

The simulations suggest that, roughly, the sensitivity of the ribbed microcantilevers is comparable to the thinner microcantilever where as the arching is almost same as that of the thicker microcantilever. This validates our claim that the ribbed cantilevers have the positive aspects of both the thinner and thicker microcantilevers. Among the different ribbed cantilevers, as expected, the relative sensitivity is observed to be proportional to relative arching effect.

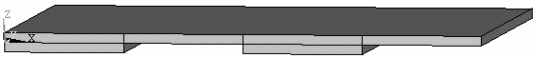

Figure 6: A microcantilever with a thicker segment at the fixed-end

A simulation has been carried out with a thicker segment towards the fixed end of the microcantilever (as in Fig. 6). For this microcantilever, the relative sensitivity is 2.31 and relative arching effect is 2.24. These values are not as favorable as those for the earlier two-segment microcantilever. Hence it is desirable to have a thin segment towards the fixed end of the microcantilever.

REFERENCES

1. http://www.lsbu.ac.uk/biology/enztech/biosensors.html, as on November1, 2004.
2. Yuyan Zhang and Srinivas Tadigadapa, *Calorimetric biosensors with integrated microfluidic channels, Biosensors and Bioelectronics*, Volume 19, Issue 12, 15 July 2004, Pages 1733-1743.
3. N. Tinkilic, O. Cubuk and I. Isildak, *Glucose and urea biosensors based on all solid-state PVC–NH2 membrane electrodes*, Analytica Chimica Acta, Volume 452, Issue 1, 31 January 2002, Pages 29-34.
4. D. G. Pijanowska, A. J. Sprenkels, W. Olthuis and P. Bergveld, A flow-through amperometric sensor for micro-analytical systems, Sensors and Actuators B: Chemical, Volume 91, Issues 1-3, 1 June 2003, Pages 98-102.

5. Brian Cunningham, Jean Qiu, Peter Li and Bo Lin, *Enhancing the surface sensitivity of colorimetric resonant optical biosensors*, Sensors and Actuators B: Chemical, Volume 87, Issue 2, 10 December 2002, Pages 365-370.
6. Roberto Raiteri, Massimo Grattarola, Hans-Jürgen Butt and Petr Skládal, *Micromechanical cantilever-based biosensors*, Sensors and Actuators B: Chemical, Volume 79, Issues 2-3 , 15 October 2001, Pages 115-126.
7. Y. Arntz, JD Seelig, HP Lang, J Zhang, P Hunziker, JP Ramseyer, E Meyer, M Hegner, and Ch Gerber, *Label-Free Protein Assay based on a Nanomechanical Cantilever Array*, Institute of Physics Publishing, Nanotechnology, December 20, 2002.
8. S. J. O'Shea, M. E. Welland, T. A. Brunt, A. R. Ramadan, and T. Rayment, *Atomic force microscopy stress sensors for studies in liquids*, Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures, Volume 14, Issue 2, March 1996, Pages 1383-1385.
9. http://www.nano.me.berkeley.edu/research/nano-bio/biocom.htm, as on 1st November, 2004.
10. Lavrik, N.V., *Enhanced chemi-mechanical transduction at nanostructured interfaces*, Chemical Physics Letters, Volume 336, Issue 5, March 23, 2001, Pages 371–376.
11. Fritz J, Baller MK, Lang HP, Rothuizen H, Vettiger P, Meyer E, Guntherodt H, Gerber C, Gimzewski JK, *Translating biomolecular recognition into nanomechanics*, Science, Volume 288, April 14, 2000, Pages 316-318.
12. Justin Clay Harris, Doe Erulf, *Enhanced sensitivity of micro mechanical chemical sensors through structural variation*, The Ohio state university, Oak ridge national laboratory, December 06, 2000.