MEMS Microcantilevers Sensor Modes of Operation and Transduction Principles

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Abstract

MEMS based microcantilever is a microfabricated mostly rectangular bar shaped structure, longer as compared to width, and has a thickness much smaller than its length or width. Microfabricated silicon cantilever sensor arrays represent a powerful platform for sensing applications in physics, chemistry, material science, biology and medicine. Microcantielver senses even a few molecules or atoms. A small change in mass causes a greater displacement. It is important that due to micron size of cantilever, the cantilevers bend or displacement is due to small amount of mass but not weight. For application in biomedical diagnostics this device plays an important role in the identification of disease detection particles. In this paper we review the cantilever principle, modes of operation, transduction principle and application of cantilever as sensor. MEMS applications operate the cantilever in either a static mode of operation or a dynamic mode of operation. The concept of stress concentration region (SCR) is used to increase stress occurred in the cantilever.

Keywords : Microcantilevers, Modes of operation, Transduction principle, Sensors, MEMS

1 INTRODUCTION

Brugger et al. (1999) and Thundat et al. (1995) have pointed out that cantilever based sensors are the simplest devices among MEMS devices that offer a very promising future for the development

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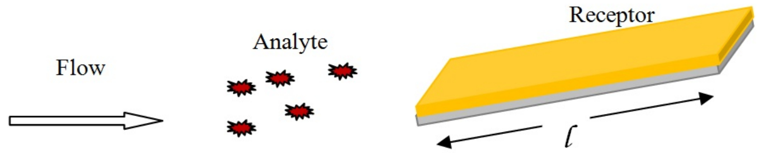

Figure 1: Schematic illustration of an ordinary microcantilever sensor in which receptor attracts analyte

of novel physical, chemical and biological sensors. A cantilever is a simplest mechanical structure, which is clamped at one end and free at the other end. MEMS cantilever sensor works based on the mechanical deformation of the structure, or in other words the deflection of membrane or beam structure. When the cantilever is loaded, its stressed elements deform and the MEMS cantilever will bend. As this deformation occur, the structure changes shape, and points on the structure displace. The concept is that deflection occurs when a disturbance or loading is applied to the cantilever is free end or along the MEMS cantilever surface. To serve as a sensor, cantilever has to be coated with a sensing layer, which should be specific, i.e. able to recognize target molecules in key-lock processes. Microcantilever sensors can be operated in air, vacuum or in a liquid. One of their major limitations is that the measurement of cantilever displacement typically involves elaborate off-chip setups with free-space optics. [1]. Microcantilevers can transduce a chemical signal into a mechanical motion with high sensitivity. [2].

Two commonly used approaches for the operation of cantilever for sensing applications are the adsorption-induced deflection and the resonant frequency shift. The continuous bending of a cantilever as a function of molecular coverage with the molecules is referred to as an operation in a static mode, Adsorption of the molecules onto the functional layer generates stress at the interface between the functional and the forming molecular layer. The bending and resonant frequency shift of the microcantilever can be measured with high precision using optical reflection, piezoresistive, capacitance and piezoelectric methods [3]

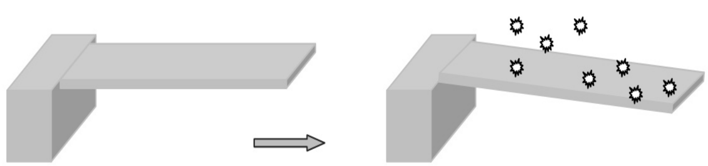

Figure 2: (a) Stress-free cantilever and (b) bending of the cantilever due to the generated surface stress by interaction with analyte

2 CANTILEVER MODES OF OPERATION

The sensing modes of cantilever could be broadly classified based on their principles in translating the recognition event into micro or nano mechanical motion. Typically there are three modes of operation as static mode, dynamic mode and heat mode. In static mode, the bending of microcantilever upon the molecular adsorption is measured. In dynaic mode, the dependence of resonant frequency of microcantilever on the mass of the microcantilever is exploited. The heat mode, takes advantage of the bimettalic effect that leads to a bending of a biomaterial microcantilever with change in temperature. [4]

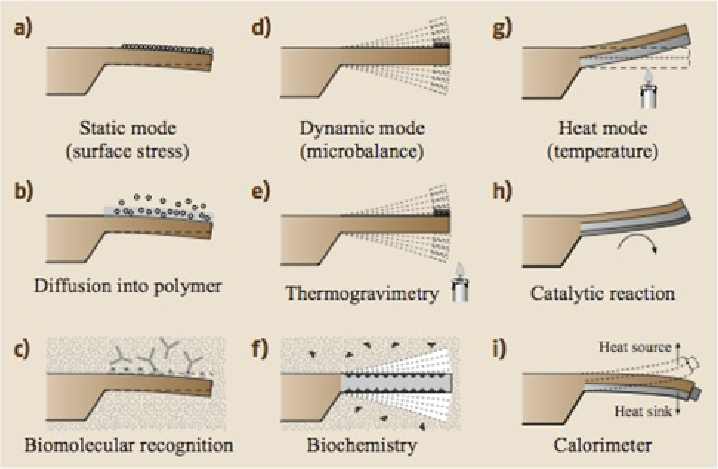

Figure 3: Basic cantilever operation modes (a)Static bending of a cantilever on adsorption of a molecular layer (b) Diffusion of molecules into a polymer layer leads to swelling of the polymer and eventually to a bending of the cantilever (c) Highly specific molecular recognition of biomolecules by receptors changes the surface stress on the upper surface of the cantilever and results in bending. (d) Oscillation of a cantilever at its resonance frequency (dynamic mode) allows information on mass changes taking place on the cantilever surface to be obtained (application as microbalance) (e) Changing the temperature while a sample is attached to the apex of the cantilever allows information to be gathered on decomposition or oxidation process. (f) Dynamic mode measurements in liquids yield details on mass changes during biochemical processes. (g) In the heat mode, a bimetallic cantilever is employed. Here bending is due to the difference in the thermal expansion coefficients of the two materials. (h) A bimetallic cantilever with a catalytically active surface bends due to heat production during a catalytic reaction. (i) A tiny sample attached to the apex of the cantilever is investigated, taking advantage of the bimetallic effect. Tracking the deflection as a function of temperature allows the observation of phase transitions in the sample in a calorimeter mode

2.1 Static mode The static deflection of a microcantilever is related to the difference in surface stress of the two faces of microcantilever. When one of the surfaces of the microcantilever is functionalized with a receptor layer, the adsorption or binding of target molecule or material to the receptor layer leads to a differential surface stress between top and bottom of the micro cantilever. Uniform compressive or tensile stress acting on an isotropic material tends to increase or decrease the surface area. The radius of curvature due to differential stress was developed by Stoney in 1909 for measuring surface stress is given by [5]

$$\frac{1}{R} = 6\left(\frac{1-V}{E\,t^2}\right)(\Delta\sigma_1 - \Delta\sigma_2) \qquad (1)$$

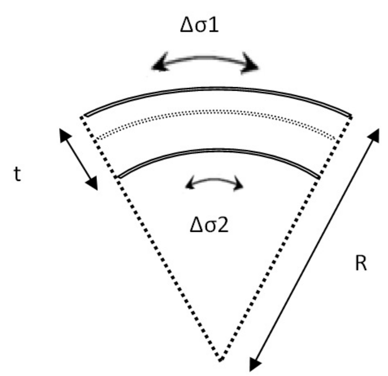

Figure 4: Lateral view of cantilever subject to surface stress

Where R is radius of curvature, E is Youngs modulus, t is thickness of the film, V is Poissons ratio, (1-2) is differential stress.

These stoneys equation was further modified for a simply supported microcantilever. The Z end point displacement of the microcantilever is given by [5]

$$\Delta Z = \cong \frac{L^2}{2R} = \frac{3(1-V)L^2}{Et^2}(\Delta\sigma_1 - \Delta\sigma_2) \qquad (2)$$

2.2 Dynamic mode In dynamic mode does not require the functionalization of only one cantilever surface, as the cantilever resonance frequency change depends on the total mass adsorbed on both sides. In this mode, the microcantilever is used as a microbalance and extremely high

$$\Delta m = \frac{K}{4\pi^2}\left(\frac{1}{f_1^2} - \frac{1}{f_0^2}\right) \qquad (3)$$

sensitivities can be obtained. The mass change on a rectangular cantilever will produce a reduction on the resonance frequency, which can be estimated[4] from

The sensitivity of the cantilever response will depend on its mechanical properties, which are determined mainly by their spring constant and resonance frequency. Both parameters depend on the cantilever material and its geometry. The spring constant, k, and resonance frequency, f, for a rectangular cantilever clamped at one end are given by

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{m}} \qquad (4)$$

$$K = \frac{Ewt^3}{4L^3} \qquad (5)$$

where E is Youngs modulus, L,w,t are length, width and thickness of cantilever

2.3 Heat mode If a cantilever is coated with metal layers, thermal expansion differences in the cantilever and the coating layer will further influence cantilever bending as a function of temperature. This mode of operation is referred as heat mode causing cantilever bending because of different thermal expansion coefficients in the sensor layer [4]. Intermolecular forces that result from adsorption of bio-molecules can bend a micromachined cantilever and enable detection of nucleic acids and proteins without any prior labeling of target molecules [6]

3 TRANSDUCTION PRINCIPLES OF MICROCANTILEVER

In order to detect small deflection of cantilevers and related structures different sensitive displacement sensors are used. Some methods are robust and well established but rather bulky, whereas other techniques are a bit more immature but with the promise of becoming miniaturized. The important transduction principle of microcantilever is as follows [7]

3.1 Optical read-out Optical leverage is the commonly used method of read-out system. A laser is focused on the back of the cantilever which acts as a mirror. The reflected laser light is detected by a PSD (position sensitive photodetector). The technique routinely gives a resolution of 1 nm deflection and even sub-angstrom resolution can be achieved. However, this set-up does not facilitate the simultaneous read-out from a reference cantilever. To allow for the detection of multiple cantilever deflections simultaneously new optical read-out schemes have been developed.

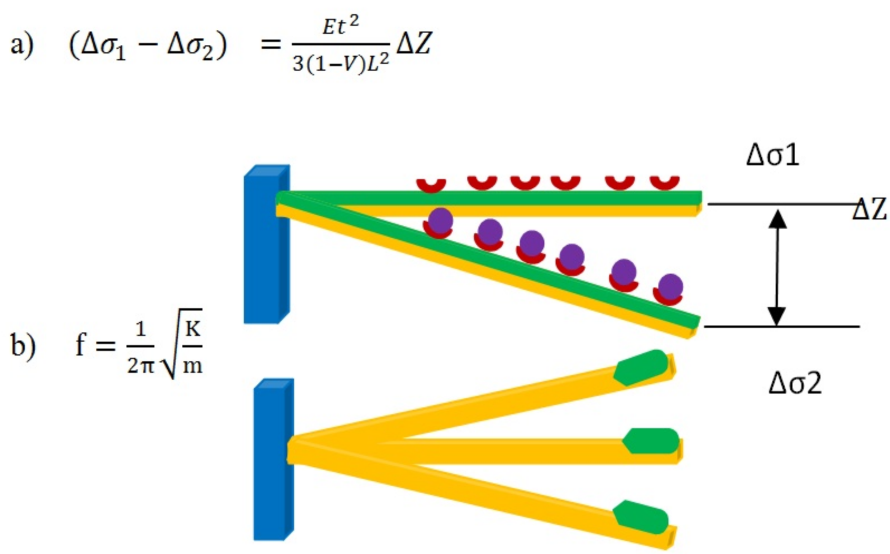

Figure 5: Microcantilever working principles, a) static mode and, b) dynamic mode

The reflected light is collected by a single photodetector. The photodetector can track the individual movement of the spots reflected from each respective cantilever. There, a two-dimensional array of cantilevers is illuminated simultaneously with an expanded and collimated laser beam. Each cantilever only reflects the light from a mirror placed at the apex. The resulting two dimensional arrays of reflected spots are captured by a high resolution CCD camera . The movement of the individual spots can be registered with a resolution of 1 nm and read out from two-dimensional cantilever arrays with about 720 cantilevers has been reported using this technique.

3.2 Capacitive read-out Two electrodes separated by any material have a capacitance and this capacitance changes when the distance between the electrodes changes. If a cantilever is placed close to a parallel electrode, the deflection of the cantilever will cause a change in capacitance. Capacitive read-out is mainly explored for mass detection in non-liquids. The sensor elements can be achieved by defining the cantilever in the top layer of an SOI wafer and using the buried oxide as a sacrificial layer to define the separation between cantilever and counter electrode. Capacitive read-out has the advantage of offering an integratable read-out which does not influence the cantilever itself. No additional layer needs to be added with the risk of degrading the cantilever mechanical performance.

3.3 Piezoelectric read-out Piezoelectricity is widely used for both cantilever actuation and for detection of cantilever deflection. A mechanical stress generates an electrical potential across a piezoelectric material and vice versa. For high resolution detection of the deflection it is necessary to operate the cantilever in the dynamic mode since the voltage produced by a static force cannot be maintained by the thin film piezoelectric material. Thus, the piezoelectric read-out is primarily utilized in resonance mode. The challenge of this technique is that most piezoelectric materials are difficult to work with and they are not all clean room compatible. The read-out has the advantage of being easily scalable and with low power consumption. Clean room compatible materials such as aluminium nitride with a high stiffness and with interesting electrical properties will probably be further explored.

3.4 Piezoresistive read-out In piezoresistive cantilever sensing, cantilever has an integrated resistor which has piezoresistive properties. Due to the piezoresistive property, the resistance value get changes when the cantilever bends. Thus, by an electrical measurement of a resistance change the deflection of the cantilever can be determined. The benefits of this method are that the principle works well in both liquid and gas phase and large arrays can be realized and read-out. Also, the technique is applicable for static as well as dynamic mode measurements.

3.5 Hard-contact/tunneling One of the important parameters of a read-out system in cantilever system is the signal-to-noise ratio. One way to obtain a large signal-to-noise ratio is to use a system with a highly non-linear response to changes in deflection. In tunneling read-out the cantilever is placed in close proximity to a counter electrode and the tunneling current between the electrode and the cantilever is measured. Here the fabrication and operation are complicated since very small electrode cantilever gaps need to be realized. The gap spacing needs to be adjustable and the measured tunneling current is in the pA range which requires high-quality signal amplification. In hard contact read-out the cantilever is allowed to touch the electrode and the current (10 nA) running through the system is measured. The large current at resonance makes the read-out nearly digital and the quality of the signal amplification is not as important.

3.6 Autonomous devices Coloured marker molecules are loaded in a small volume closed by a flexible lid. The lid is coated with specific detector molecules, which bind the molecules under investigation. The binding of molecules causes the lid (just like a cantilever) to deflect and the marker molecules are released and can be detected by the naked eye. The complete sensor is approximately 1 cm 1 cm in size and is fabricated in polymer. The deflection of the lid can also be caused by removal of a material on the top surface of the lid. The deflection of the lid can also be caused by removal of a material on the top surface of the lid.

4 MICRO CANTILEVER BASED SENSOR

Cantilever-based sensors can be operated by the working principle is presented based on bio-sensing experiments which have been performed recently in the study of biotinstreptavidin and antigenantibody interactions, and specific surface charge development of organic molecules[2]. The primary deflection due to the chemical reaction between the analyte molecules and the receptor coating, which produces surface stresses on the receptor side is analyzed. Novel microcantilever assemblies are presented to increase the deflection due to chemical reaction while decreasing those due to flow dynamical effects[23] Analyte gases are absorbed by a sensitive layer deposited on cantilever, resulting mass change of the system implies the cantilever resonant frequency decrease. The measurement, piezoelectric and electromagnetic excitations are investigated and for the detection of microcantilever vibrations, piezoresistive measurement is performed. Then, the polymer choice and the spray coating system are detailed using various geometrical microcantilevers[8]. On chip microelectromechanical system based on an array of cantilevers for mass detection also been designed. The sensor transducer, using polysilicon as structural layer, has been integrated monolithically with the CMOS circuitry. Arrays of four and eight resonant cantilevers excited and detected electrically through the integrated circuit have been fabricated[9]. A finite element modeling of V-shaped silicon micro-cantilevers aiming at high sensitivity for chemical sensors applications developed [10]. A novel nanofabrication method that develops from the traditional micro electro mechanical system technology of anisotropic etching, deep reaction ion etching, and sacrificial layer process has been reviewed[11]. SU-8 is an interesting polymer for fabrication of cantilevers for bio/chemical sensing due to its simple processing and low Youngs modulus, examples of different integrated read-out methods and their characterization shows that SU-8 cantilevers have a reduced sensitivity to changes in the environmental temperature and pH of the buffer solution. Moreover, SU-8 cantilever surface can be functionalised directly with receptor molecules for analyte detection, thereby avoiding gold-thiol chemistry[12].The sensor response is mechanical bending due to absorption of molecules. In gaseous environment, polymer-coated microcantilevers are used as electronic nose for characterization of vapors, resulting in cantilever bending due to polymer swelling upon exposure. Medical applications involve fast characterization of exhaled patient's breath samples for detection of diseases, based on the presence of certain chemicals in breath-[13].MEMS cantilever oscillators under electrostatic actuation is the hope to estimate the influence of the geometrical dimensions and operating conditions on the frequency response of mechanical paddle cantilevers fabricated from polysilicon. Theoretical approach and finite element analysis are developed considering the multiphysics coupling between the electrical field and the mechanical structure[14]

Piezoelectric materials are used in a in micro electro mechanical systems for the construction of cantilever. These materials offer characteristics that provide unique advantages for both sensing and actuating. Common implementations of piezoelectric transduction involve the use of a cantilever with several layers, some of which are piezoelectric[15].A technique to calibrate the sensitivity of sensor-integrated atomic force microscope cantilevers using pseudo-gratings control signal which modulates the cantilever position over a flat surface, driving the cantilever toward and away from the surface in a controlled way. The relationship between the cantilever sensor signal and displacement provides the cantilever calibration[16]. The design and fabrication of smart reservoir integrated with MEMS cantilevers for bio medical application is used. A reservoir is a kind of trap where fluid can be collected for biological sensing purposes. These smart reservoir is integrated with the cantilevers of desired shapes of well defined length, width, thickness and hence spring constant[17].The design simulations of MEMS based micro-cantilever made up of single crystal silicon can be simulated using COMSOL Multiphysics. The cantilever structure on silicon substrate with optimized silicon dioxide film has been simulated. The simulations results into the stress, displacement, Eigen frequency and

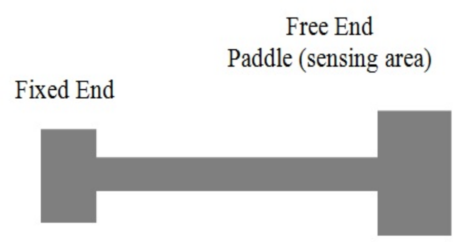

Fig.6 Schematic of a paddle cantilever

Figure 6: Schematic of a paddle cantilever

C-V characteristics measurements of the cantilever can be performed[18]. The development of MEMS force sensors constructed using paper as the structural material. The working principle on which these paper-based sensors are based is the piezoresistive effect generated by conductive materials patterned on a paper substrate[19]. The finite element method to obtain the optimal performance of SiO2 based microcantilevers sensors by rearranging the dimensions of the cantilever beam to improve the efficiency of the output (sensitivity) of the micro cantilever for the given input is demonstrated [20].The concept of Stress concentration region (SCR) is used to increase stress occurred in the cantilever. SCR is an approach where defects or holes are made to increase stress to increase sensitivity. The mass of the particle with area and pressure induced is explained using the simulated results from ANSYS [21]

5 CONCLUSION

Microcantilever is an important device in the field of engineering and it can used to transduce mechanical motion into electrical output with high sensitivity. In this review, cantilever structure, characteristics, modes of operation and transduction principle along with biomedical applications presented, Hence microcantilever provides main application in sensors platform for identifying various chemical and biological analytes. we have presented the main developments achieved during the last few years in the microcantilever based biosensing field. It is definitely a fast emerging technology, which has already demonstrated its sensitivity for advanced and complex biological problems.

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