Study on the progress of piezoelectric microcantilever beam micromass sensor

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Abstract. A variety of excitation modes and signal readout modes of the microcantilever beam are all derived from the deformation characteristics of the cantilever beam, while in the detection of environmental pollutants, deformation of non-quality factors such as environmental vibration, wind, rain and snow will inevitably occur. If we only start from the deformation quantity, the consistency between the obtained results and the actual fouling micro-mass value is more prominent. Therefore, the structure, size, working mode and material properties of the microcantilever beam should be fully considered in simulation and design. The resonant frequency of the microcantilever beam must be large enough to prevent external vibration interference measurement and improve the SNR.

Keywords: micro cantilever beam; piezoelectric materials; vibration mode; Surface microquality detection.

1. Introduction
Microcantilever sensing technology is a new sensing method developed rapidly after the emergence of atomic force microscope and MICRO-electromechanical system [1]. As the simplest micro-mechanical element, it has been the focus of micro-nano sensing technology research. Microbeam sensors are widely used in real-time measurement of specific biochemical response experimental parameters, and their response mechanism is based on the interaction between probe molecules fixed on one side of the microcantilever beam and the target analytes. The selectivity, specificity and, to a lesser extent, sensitivity of the microcantilever sensor depend on the probe molecules deposited on the microcantilever. The interaction between the probe molecules and the target analytes causes different surface stresses on the microcantilever, leading to the deformation of the microcantilever beam, and then a shape variable is generated. The reaction information of this biochemical process can be obtained online in real time through the real-time detection of it by optical or electrical methods [2, 3]. As a real-time, highly sensitive and unlabeled sensing method, this sensing technology has been widely studied in biochemistry and other fields.
The idea of silicon cantilever beam as a sensor to measure deflection or resonant frequency change was first reported back in 1968. Wilfinger et al [4] measured resonant frequency with a 50mm×30mm×8mm silicon cantilever. The cantilever hinge contained piezoelectric resistor. On the other hand, piezoelectric resistors are also used to detect mechanical deflection of the cantilever. This report has covered the basic concepts of cantilever sensing and cantilever actuation.

2. Working principle of piezoelectric microcantilever beam

In 1971, Heng [5] prepared a mechanical fine-tuning gold cantilever which was capacitively coupled to the microstrip line and used for high-frequency oscillator. In 1985, Kolesar [6] proposed a cantilever structure for the detection of electronic nerve agents. Due to the shortage of micromachining, the development of microcantilever sensor has been stagnated in the cantilever stage. In 1986, Gerd Binning of IBM and Calvin F. Quate and Gerber of Stanford University [7] invented the Atomic Force Microscope (AFM) [8]. Because the AFM probe requires a micron size to achieve a relatively high resonance frequency (kHz class) and a low spring constant (N·M⁻¹ class) for atomic level scanning, the AFM cantilever is typically 100 μm×0.5 μm×0.5 μm, and micron cantilever becomes available [9]. In 1990, Tom and his colleagues at Stanford University [10] and IBM's Wolter group [11] first achieved the preparation of a micromechanical cantilever with an integrated cutting-edge. Cleveland et al. [12] then used resonance frequency tracking to detect changes in the mass of small particles deposited at the tip of the AFM probe. In 1994, Itoh et al. [13] reported a cantilever coated with zinc oxide film and proposed a piezoresistive readout mode instead of beam deflection. That same year, the oak ridge national laboratory Thundat Gerber and IBM Zurich, Switzerland, such as laboratory team [14] proposed environmental factors (such as moisture adsorption) will influence the resonance frequencies of the microcantilever beam (MCs) and static bending, thermal effect (double metal effect) also affects the deflection of cantilever metal coating, and use this feature to its development as a new type of sensor is a microcantilever sensors.

Since then, with the development of AFM and the increasing maturity of MEMS [15] manufacturing process, a large number of commercial micro-cantilever beams have appeared, and more and more reports have been published on the sensors built based on them. Gimzewski et al. [16] used the bending of static cantilevers to detect chemical reactions with high sensitivity, which was the first chemical sensing application proposed. Subsequently, Thundat et al. [17] found that the adsorption of the analyte vapor on the cantilever surface can lead to a change in its resonant frequency. In addition, mass loading or adsorption can also lead to a change in resonant frequency, with a pick-level mass resolution. However, the response of a single cantilever as a sensor is susceptible to influences such as thermal drift or non-specific adsorption, especially when the cantilever is detected in liquid. In 1998, Lang et al first reported a cantilever array sensor containing a reference cantilever, and significant progress has been made in the actual response of the cantilever (by calculating the difference between the response of the cantilever and the response of the reference cantilever). In 2000 Fritz [18] modified two DNA strands with only one base and different ones on the microcantilever array to detect single nucleotide polymorphism, providing a data source for the specific identification of DNA and proteins and other macromolecules, demonstrating the potential of microcantilever sensors in the field of diagnosis.
Since the mid-nineteen-eighties of the 20th century, micro cantilever sensors is considered to be a kind of application prospect is very broad superfine quality sensor, because of its small volume, light weight, low power consumption, good durability, low cost, stable performance, outstanding advantages, such as very high quality, together with its tiny resonance frequency and quality factor, is widely used in many fields of science and technology, such as medical, military, industrial control and robot, network and communication, and environmental monitoring, etc. In recent years, with the rapid development of MEMS technology in microelectromechanical systems, many scholars have begun to use microcantilever beams to carry out related biological/chemical molecular detection research [19], including the mass and location identification of the attachment.

### 3. Piezoelectric micro cantilever beam Static mode

In 1906, Josiah Willard Gibbs[20] first proposed the concept of surface stress. From the macroscopic point of view, the surface stress is the change of the surface stress caused by the applied load. From the microscopic point of view, surface stress is the long distance interaction between atoms and the change of surface geometry. The surface stress formed by different surface structures is also different. In other words, the surface stress can be considered as the compressive or tensile forces exerted on both sides by a thin film covering the solid surface, which will eventually appear as the bending phenomenon of the solid surface.

Static mode is the most commonly used mode for microcantilever sensors, which can be used in liquid, air and vacuum environments. It is implemented by changing the surface of the cantilever beam stress, the specific method is: will a can with the material under test can be the combination of specific molecules modified on the surface of the cantilever beam, a side in advance, when cantilever beam are included under test material molecular environment, two molecules binding reaction, the binding
reaction causes the beam surface stress change, change a cantilever beam bending. By detecting the 
amount of bending change, the reaction substance can be quantitatively detected. At present, for during 
the process of cantilever beam in the detection of the mechanism of the change is not yet clear, but one 
of the most affected by cantilever sensors researchers agree that explanation is that these two molecules 
binding reaction after modification on the surface of the cantilever beam, molecular inter-atomic forces 
change, the force transfer to the surface of a cantilever beam surface stress changes, which make the 
cantilever bending change [21]. Micro cantilever tip deflection variation Δ z and surface stress difference 
relationship between Δ sigma as follows:

\[
\Delta z = \frac{3(1-\nu)}{E t^2} L^2 \left( \Delta \sigma_1 - \Delta \sigma_2 \right) = \frac{3L^2(1-\nu)}{E t^2} \Delta \sigma
\]  

Where, E and V are young's modulus and Poisson's ratio of the cantilever beam, l and T (respectively 
are length and thickness of the cantilever beam). Can be seen from the type of the micro beam deflection 
variation Δ z is proportional to the difference of surface stress Δ sigma, when the elastic modulus of 
the beam, the thickness of the beam is small, in the case of the same surface stress difference can acquire a 
greater amount of beam deflection. This can be used as a guide in the manufacturing process of 
microcantilever beam to produce a cantilever beam with high sensitivity, but at the same time it is easy 
to bring more noise signals to the detection results.

4. Dynamic working mode of microcantilever beam

The variation of the mass adsorbed on the surface of the cantilever beam can be accurately determined 
by using the cantilever beam activated with its characteristic frequency. Due to the increase of surface 
mass of the cantilever, its surface stress will change. The eigenfrequency of the cantilever beam will 
turn to a lower value, and the offset value of resonance frequency will be measured to reflect the mass 
of the measured object adsorbed on the surface of the tip of the cantilever beam [22].

Fig. 3 Dynamic working mode of microcantilever beam

Since the eigenfrequency of the cantilever oscillation depends on its mass, the mass variation can be 
accurately determined by tracking the variation of the eigenfrequency, which is the basis of the dynamic 
detection mode. Technically, the resonant frequency of the cantilever is easier to measure than the 
intrinsic frequency. For example, the resonant frequency is measured by actively modulating the 
cantilever with a piezoelectric actuator. The resonant frequency represents the frequency at which the 
oscillation amplitude is maximum. If the elastic properties of the cantilever remain constant and the 
damping effect is not obvious during molecular adsorption, then the eigenfrequency is equal to the 
resonant frequency of the oscillating cantilever [23-25].

The dynamic bending vibration of cantilever beam includes: base resonant frequency, first-order 
vibration mode, multiple high-order vibration mode, high-order resonance frequency [26].

Base resonant frequency: Due to the increase of mass on the cantilever surface, the eigenfrequency 
of the cantilever migrates to lower numerical values. The calculation formula of frequency variation of 
rectangular cantilever with mass on the cantilever is [27-29] :

\[
\Delta z = \frac{3(1-\nu)}{E t^2} L^2 \left( \Delta \sigma_1 - \Delta \sigma_2 \right) = \frac{3L^2(1-\nu)}{E t^2} \Delta \sigma
\]
Where $\Delta m / LWT$ is the mass density of the microcantilever and the deposited molecule and $n_1 = 1$ is the geometric factor. Is derived according to Thunda $\Delta m$ with $\Delta f$ [30] on the relationship between:

$$\frac{\Delta f}{\Delta m} = \frac{1}{4\pi n_1 f_0 \sqrt{\rho}} \sqrt{\frac{E}{\rho}}$$  \hspace{1cm} (2)

Where $n$ is the geometric coefficient ($n = 0.24$ for a rectangular cantilever beam), and $F_0$ and $F_1$ are the initial mass of the cantilever beam and the mass after biochemical reaction respectively [31-33].

$$\Delta m = \frac{k}{4\pi^2 n} \times \left( \frac{1}{f_0^2} - \frac{1}{f_1^2} \right)$$  \hspace{1cm} (3)

Where, $n$ is the geometric coefficient ($n = 0.24$ for a rectangular cantilever beam), and $F_0$ and $F_1$ are the initial mass of the cantilever beam and the mass after biochemical reaction respectively [31-33].

![Fig. 4 Dynamic working mode of microcantilever beam](image)

Generally speaking, the motion of a microcantilever beam can be divided into non-in-plane motion and in-plane motion based on the plane composed of the two largest dimensions of the microcantilever beam (usually the length and width of the microcantilever beam). Non-plane motion includes bending motion and torsional motion, while plane motion includes transverse motion and longitudinal motion. When a microcantilever is excited at a certain characteristic frequency, one of the four modes will show resonance, and the characteristic frequency is called the resonant frequency or natural frequency of the microcantilever. The analytical expressions of resonant frequencies of microcantilever beams in these modes can be obtained by solving the corresponding equations of motion. Of course, the following assumptions must be satisfied before the solution: the aspect ratio of the microcantilever beam is large enough; the deflection of the microcantilever beam is less than the thickness of the microcantilever beam. The microcantilever beam is single layer and has uniform rectangular cross section. The material of the microcantilever beam is isotropic.

5. Conclusion

To sum up, when a microcantilever beam is used for micromass detection, the surface stress of the cantilever beam will change with the increase of surface mass. At this point, it is assumed that the micromechanical cantilever beam has uniform thickness, and the surface stress only exists on the upper surface of the microcantilever beam and uniformly distributes on the top edge along the length direction of the microbeam. Studying the physical meaning of surface stress requires special attention. Some researchers define surface stress as a force per unit length, while others define it as a force per unit width.

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