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Oscillation of Cantilever through In-plane Interdigitated Comb-drive Actuators Driving

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Key Words : Cantilever, Comb-drive actuator, Scanning force microscopy

Abstract

We present the concept of scanning force microscopy cantilevers with large deflection and ultra slope at the free end of the lever arm and pure single crystal silicon property exclusion of any types of surface deposition, which are realized through the new actuation mode. This novel cantilever bending actuation mode is firstly proposed totally differing from all of the conventional modes, the out of plane motion of the cantilever is achieved by integrated pre-bent cantilever with in-plane interdigitated comb-drive actuators, the horizontal comb-drive actuator actuation could be transferred to the pre-bent cantilever as a bend moment hence the in-plane actuation of the actuators offer the out of plane actuation for the cantilever.

1. Introduction

Scanning probe microscope (SPM) family has been well researched to obtain topography and various physical or chemical properties of surface on the nano-scale, to measure the multiple interaction force between the sample and probe, to serve data storage and nanolithography. There are significant advantages of SPM as an imaging tool in biology and physics when compared with complementary techniques such as electron microscopy. A SPM system mainly consists of three important components: cantilever with a sharp tip (or cantilever array), piezoelectric scanners and feedback control. It provides a 3D profile of the surface on a nanoscale by measuring the forces between a sharp probe and a surface within short distance. The probe is supported on the flexible cantilever, during scanning, the SPM tip gently touches or taps the surface and records the small surface force between probe and the surface. The cantilever in SPM system is a beam or lever carrying loads to a strong mounting point with one end of the beam anchored, and the other end suspended in the air, which typically is made of silicon or silicon nitride with tip sizes on the order of nanometers. The resolution of SPM depends mainly on the sharpness of the tip which may be coated with diamond or metals, while the spring constant (stiffness) and the resonant frequency of the cantilever decide the sensitivity and the scanning rate.

With the further development and the wide applications of the scanning probe microscope, it is endowed with more functions such as chemical identification [1, 2], and two–pass measure techniques (topography during the first pass and another selected electric property of the sample using topographical information to track the tip at a constant distance above the surface during the second pass [3]. Thereby, a powerful and versatile cantilever is strongly required in SPM system to meet various environments and applications. Different characteristics of cantilevers are desired in different applications, some common factors are favored in most cases i.e. relatively low spring constant, high resonant frequency and big deflection. However, it is pretty difficult to compromise all of the above desired factors in a single versatile or switchable cantilever simultaneously for several applications. In terms of conventional cantilever for contact AFM mode, the spring constant is around 0.2 N/m, which is suitable for big deflection in atom manipulation or sample extraction for chemical analysis, but the resonant frequency is limited and it suffers from the cantilever tip abrasion and fragile sample's surface damage. In noncontact and intermittent contact modes, high resonant frequency and intact sample surface can be satisfied, but the high stiffness of the beam leads to small deflection to

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the order of several nanometers that is not able to be extended to universal applications.

In this article we propose a new concept of cantilever actuation mode that is capable to meet various applications at the same time due to its advantages as relatively low spring constant, high resonant frequency and huge free end deflection.

2. Principal Mechanism

Most common cantilevers as actuation are driven by the deformation of bilayer structure, the transverse force exerted through the deposited material or smooth beam surface. The structure of these cantilevers tends to be simple where a standard cantilever with or without deposited film bends under vertical load. The actuation methods for them can be generally divided into electrostatic, piezoelectric, thermal and magnetic, shown in Fig.1.

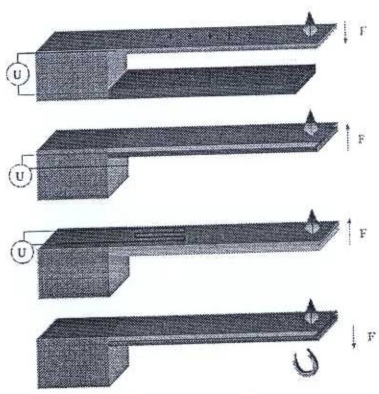

Fig. 1 Schematic diagrams of cantilever actuation mechanism as electrostatic, piezoelectric, thermal and magnetic respectively.

Above cantilevers actuations can be categorized as internal actuation or active actuation, in which cantilevers with those actuation mechanisms serve to transduce the input signal or power into load hence realize self-bending or self-oscillation. However, these common cantilever structures are halted to our desired versatile functions. Firstly, the most serious drawback is the deposited film, which results in non-single crystal silicon property for the beam thereby residual stress, low quality factor will be consequently aroused and the composite materials beam structure instead of single crystal silicon beam increases the numerical analysis complexity, additionally the deposited film is quite difficult to fabricate and precisely pattern; secondly, for a big displacement, a very high driving voltage and thick piezoelectric film are needed for piezoelectric actuation, which is against the unimorph beam principle. Regarding the thermal actuation, a big deflection is available, but a small amount of heat actuation way is favored for applications such as chemical identification of single molecules [4]. No deposited film on the surface of the electrostatic actuation, but the driving force is too small to be employed for big deflection. Another means to drive the cantilever is by outside actuation, which is categorized as external or passive actuation; cantilever is driven by outside medium rather than itself, as illustrated in Fig.2.

Thereby, cantilevers with conventional actuation means can not be hoped to implement various applications at the same time.

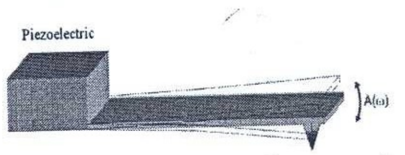

Fig. 2 Schematic diagram of external cantilever actuation mechanism by piezoelectric.

Special cantilevers satisfying general requirements have been researching and developing for meeting the aforementioned diverse applications and working environments.

Wetzel *et al.* [5] reported a system where cantilever is mounted onto a rotatory tip holder driven by piezoelectric tube, a switching between SPM mode and huge displacement of the cantilever for chemical analysis due to tip holder rotation could be realized, however the manual assembly and conventional macromachining mechanism give rise to long switching time on the order of seconds between two working modes, in addition, it is not able to be fabricated through microfabrication. Spence *et al.* [6] also encountered the same issue in their device. Kawai *et al.* [7] demonstrated a novel cantilever for a high frequency silicon resonator combined with integrated piezoelectric actuation for large displacement, which could be used in both dynamic SPM system and chemical analysis, while the deposited film issue still exists, and excellent capability as huge displacement and big bending slope is not obvious there.

In order to solve those problems and develop a versatile cantilever, in this paper, we firstly propose a novel actuation mode which is totally different from all the conventional cantilever driving ways. In contrast to the conventional cantilever bending actuation, where the beam is exerted by an external vertical load (either attractive or repulsive) to bend up or down the beam with standard cantilever mode that is one end fixed while the other end free, the deflection simply depends on the load and the same direction corresponding efficient spring constant, given by

$$D = \frac{F}{k} \tag{1}$$

where F is the load, k is the spring constant and D is the cantilever deflection. Form this equation, it shows that in conventional cantilever actuation mode, the load which is responsible for the deflection should own the same direction with the deflection, a new actuation mode should be employed to break the conventional one to avoid the undesired deposited film which is usually a source of external vertical load or out of plane force; in our new mode, the load direction is perpendicular to the cantilever deflection, thanks to the new system the out of plane motion of the cantilever is achieved by integrating pre-bent cantilever with in-plane interdigitated comb-drive actuators, as demonstrated in Fig. 3. The horizontal comb-drive actuator actuation could be transferred to the pre-bent cantilever as a bending moment hence the in-plane actuation of the actuators offers the out of plane actuation for the cantilever. In this mode, the big deflection could be achieved by increasing the force of the in-plane comb-drive actuators, therefore no influence on the surface of the cantilever arm, here the vertical force is not responsible to drive the vertical deflection, which decrease the complexity and the compromise of the cantilever that in conventional works as both actuator and efficient spring system.

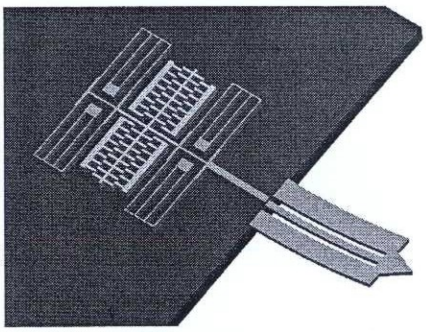

Fig. 3 The schematic diagram of novel cantilever actuation mode.

3. Design

3.1 Cantilever Configuration

Fig. 4 shows a schematic diagram of the proposed cantilever system structure. As shown, the cantilever structure consists of three pre-bent beams arranged perpendicular to each other. The middle beam works as a supporting beam, one end of it connects with the comb-drive actuators while the other end links the cantilever system, which enables to transfer the in-plane driving force to the cantilever system, then transducer the in-plane drive force to bending moment due to the pre-bent beam structure. Two other beams are located at two sides of supporting beam with one end fixed and the other one free, suffering the bending moment and deflect as two passive beams. According to the working mechanism of this cantilever system that free end deflection is attributed to transduced bending moment instead of conventional direction vertical force mode, the Eq.1 is not suitable for deriving the deflection here, the mechanics formulation of this system can be concluded based on successive integration of the beam, expressed as

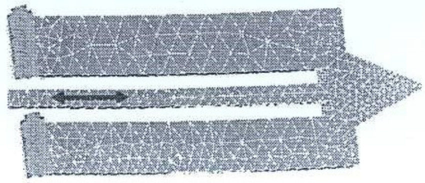

Fig. 4 The schematic diagram of cantilever system.

$$V = \frac{ML^2}{2EI} \tag{2}$$

where M is the bending moment exerted at the free end of cantilever system, L is the effective length, E is the Young's modulus, I is the moment of inertia and EI is flexural rigidity.

3.2 Comb-drive Actuators System

As shown in Fig.5, this comb-drive actuators system consists of two comb-drive actuators [8], one supporting beam which connects with the supporting beam of the cantilever system to transfer the driving force, two spring-like folded flexures and a substrate. Both the supporting beam and the movable comb drives are suspended above the substrate by the folded flexures through the anchors which connect the folded flexures with the substrate.

Comb–drive actuators which mainly use the fringe field of capacitors can generate electrostatic force when a voltage difference is formed between movable comb drives and fixed comb drives. Mechanical spring beams structure is incorporated into the comb–drive actuators to support the suspended structure. The force balance between the spring restoring force and the electrostatic force determines the position of movable comb drives, accordingly the desired displacement of actuators can be obtained.

The new arrangements of the comb–drive actuators in our research are composed of one set of movable comb drives and two sets of fixed ones which are located at each side of the movable comb drives differing from the conventional arrangement consisting of one set of movable comb drives and one set of fixed

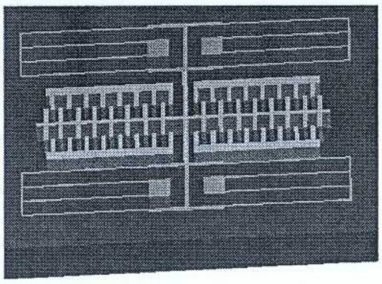

Fig. 5 The basic structure of the comb-drive actuators system.

comb drives next to the moving parts, thereby both of the fixed comb drives can give the movable comb drives electrostatic force from either left or right direction, so this novel arrangement allows single comb-drive actuator to possess two-sided actuation mechanism for both pulling and pushing the supporting beam. During SPM dynamic scanning, one fixed comb drives is given certain DC voltage for a big deflection of the cantilever system to approach the tip to the sample surface, while the other fixed one is input AC voltage working as a mechanical resonator to oscillate the free end of cantilever in order to dynamically scan the surface, as illustrated in Fi.6.

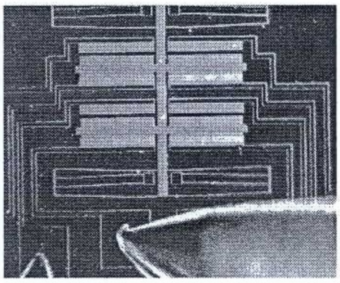

Fig. 6 The actuation of the comb-drive actuators.

Thereby, the deflection and the slope of the cantilever depends on the DC voltage, the AC voltage is responsible for the amplitude and the frequency of the cantilever oscillation.

The driving force and the spring constant of the folded flexures can be express as

$$F_x = \frac{N\varepsilon t}{g} V^2 \tag{3}$$

$$K = \frac{2Etw^3}{L^3} \tag{4}$$

where E is the Young's modulus, t is the thickness of comb drive fingers and folded flexure beam, N is the number of comb drive fingers, ε is the permittivity constant of air, g is the fingers gap spacing, V is the driving voltage and L is the folded flexure length. With the know parameters of the system, the spring constant and resonant frequency could be calculated. By controlling the voltage, we can precisely determine the cantilever deflection and oscillation amplitude.

4. Fabrication and Numerical Analysis

The fabrication of this device is based on the MEMS fabrication methods by operating Deep Reactive Ion Etching (DRIE) on a SOI (silicon on insulator) wafer. The cantilever system is released by the backside etching. In the fabrication process, the most key process is to control the pre-bent deflection and the bending slope of the cantilever, which is realized by metal deposition onto the supporting beam. The intrinsic or residual stress induced by the metal deposition is usually prevented in most MEMS devices, but it is desired here for providing a pre-bent deflection. A metal deposition is sputtered by controlling the sputtering chamber pressure, deposition rate, substrate bias voltage and RF power to obtain a desired intrinsic stress, thereby the pre-bent moment caused by metal deposition could be determined as (9)

$$M = \Sigma_i \, wt_i \sigma_i (h_i - h_j) \tag{5}$$

where w is the width of the cantilever, t_i the thickness and σ_i the residual stress of the ith layer, h_i-h_j is the distance between the ith layer and neutral plane. Consequent deflection is then calculated by substituting Eq. 5 into Eq. 2, the efficient Young's modulus of the bilayer composite materials is equivalent to (10)

$$E_{bi} = \frac{E_1 h_1 + E_2 h_2}{h_1 + h_2} \tag{6}$$

$$\sigma_{bi} = \frac{\sigma_1 h_1 + \sigma_2 h_2}{h_1 + h_2} \tag{7}$$

where h, E and σ denote the thickness, Young's modulus and the residual stress, respectively, and the subscripts "1", "2" and "bi" stand for silicon layer, deposited metal layer and the bilayer severally. The simulation of the residual stress effect on the cantilever deflection is demonstrated in Fig. 6.

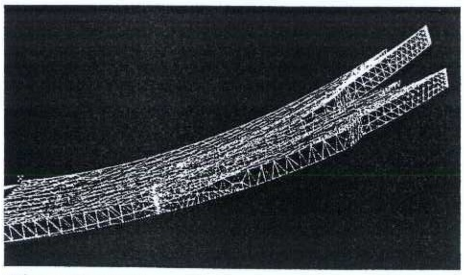

Fig. 7 The simulation of the pre-bent deflection from the horizontal plane due to residual stress.

Based on the mechanics theory, the magnitude of pre-bent deflection decides the bending moment of the cantilever system hence determines the total deflection of the cantilever. Due to the bending moment influence on the cantilever deflection, the deflection length of the cantilever system depends on the pre-bent length which suffers the bending moment when it is under an in-plane driving force, as shown in Fig. 8. The slope of the cantilever is expressed as

$$\theta = -\frac{ML}{EI} \tag{8}$$

From the mathematical calculation and the simulation results, the deflection slope could reach nearly 90°, which is recorded biggest one from the literature, as shown in Fig. 9.

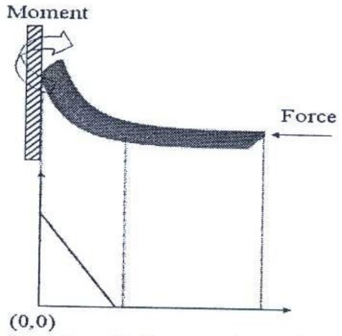

Fig. 8 The principle of the pre-bent beam bending under in-plane force and its bending moment diagram.

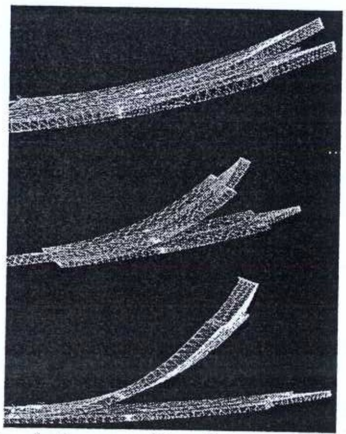

Fig. 9 The simulation results of the cantilever system deflection from releasing to 90° bending slope deflection.

The metal deposition for creating residual stress is only conducted onto the supporting beam surface in order to keep the other two passive beams free from composite materials bilayer, the cantilever system is able to pre-bend only relying on the residual stress induced on supporting beam, thereby the single crystal silicon property is kept in those two beams for the sequent integrated sensor fabrication, the piezoresistive sensor which is located at the fixed end of the cantilever to increase the deflection sensitivity, sensing the deflection of the single crystal silicon cantilever, it enables a high sensitivity and precision for sensing compared with the conventional cantilever with metal or piezoelectric layer which performs as the complex composite materials mode or experience the physical property change under heat. Another sensing way may depends on the force feedback from the free end of the cantilever to the comb-drive actuators, where the comb-drive actuators could also be employed as a sensor to measure the in-plane displacement change by sensing the capacitance change, this new sensing way is under research.

5. Conclusions

A novel concept of cantilever system with potential for versatile application is proposed. The system consists of pre-bent cantilevers and in-plane interdigitated comb-drive actuators, which enable to offer relatively low spring constant, big deflection, high resonant frequency and high quality factor, in addition, no surface deposition eases the fabrication complexity. The theoretical model and simulation model are constructed to analyze the feasibility of the new system and find out the basic principle of this novel actuation mode which is totally different from the conventional modes. Now the fabrication is underway, more results will be shown in the near future.

Acknowledgments

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