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Characteristics of a dynamic atomic force microscopy based on a higher-order resonant silicon cantilever and experiments

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ABSTRACT

In order to improve the sensitivity and scanning speed of the dynamic AFM, a surface scanning method using higher-order resonant cantilever is adopted and investigated based on the higher-order resonance characteristics of the silicon cantilever, and the theoretical analysis and experimental verification on the higher-order resonance characteristics of the corresponding dynamic AFM cantilever are given. In this method, the cantilever is excited to oscillate near to its higher-order resonant frequency which is several times higher than that of the fundamental mode. Then the characteristic changes a lot compared with the first-order resonant cantilever. Because of the changes of the quality factor, amplitude and the mode shape of the cantilever, the higher-order resonant AFM gets higher sensitivity and scanning speed. Based on the home-built tapping-mode AFM experiment system, the resolution and the response time of the first and second order resonance measured by experiment are respectively: 0.83 nm, 0.42 nm; 1265 μs, 573 μs. The higher-order resonance cantilever has higher sensitivity and the dynamic measurement performance of the cantilever is significantly improved from the experimental results. This can be a useful method to develop AFM with high speed and high sensitivity. Besides above, the surface profile of a grating sample and its three-dimensional topography are obtained by the higher-order resonant mode AFM.

0. Introduction

A micro silicon cantilever is used in the atomic force microscope (AFM) to sense the atomic force between the tip on the cantilever and atoms on the sample surface, and then to realize surface scanning by the detected force signals. AFM is one of the instruments with highest spatial resolution by now. It has a sub-nanometer or even higher spatial resolution, which has been widely used in various field [1–4], such as nano-measurement, nano-manipulation, nano-machining and nano-etching [5–8].

The AFM is divided into two categories according to the operation mode of the cantilever: static mode AFM and dynamic mode AFM [9]. Nowadays, many versions of dynamic AFM have been proposed and developed [10–12]. All of these versions rely on the cantilever's dynamic characteristic that the resonant parameters (amplitude or frequency/phase) of the cantilever are sensitive to the atomic interactions to make the measurement. Compared with the static mode AFM, the dynamic mode AFM has become the main working mode of the AFM because of its small lateral force, fast scanning speed, strong anti-interference ability and other advantages. In fact, the cantilever used in AFM has many resonant modes. The minimum detectable force gradient and dynamic response characteristics of these AFMs are restricted by the geometric parameters of the cantilever itself and cannot be further improved.

Currently, efforts are still done to make the dynamic AFM more sensitive and more repaid. It is believed that increasing resonant frequency is good to lower the minimum detectable force gradient and improve the scanning speed of the cantilever in dynamic AFM [13]. In order to obtain a higher operating frequency, fabrication of nanometric-scale cantilevers of small mass has been already reported [14]. Due to the small size of the cantilever, this kind of cantilever which requires more complicated detection systems, should be prepared specially and is difficult to be commercialized. Another alternative is to use conventional AFM silicon cantilevers vibrating at higher-order resonant modes. In earlier years, Rabe and Minne had done some research on the higher-order resonant mode AFM, and gave detailed analysis of cantilever vibration mechanisms [15,16]. Girard P concluded that the stabilization time of the second resonant mode cantilever is smaller than that of the first resonant mode cantilever in vacuum and ambient conditions

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[17]. Recently, the research on the higher-order resonance has gone further with some new theories applied to the vibrating model analysis of cantilever [18], and multifrequency AFM [19–21] and subsurface AFM emerged [22,23].

Since the commercial silicon cantilever has many resonant modes and the cantilever in higher-order resonant mode is more sensitive to the micro external force, a scanning method based on the higher-order resonance mode of the cantilever is proposed. The higher-order resonant characteristics of the silicon cantilever will be analyzed and validated both theoretically and experimentally, and so does the feasibility and superiority of the profile measuring by using this method.

1. The flexural vibration model of the cantilever

In dynamic AFM here, the cantilever is assumed to be a uniform, homogenous beam with constant, rectangular cross section. One end of the cantilever is fixed and the other is hung up for free vibrating, and a tip with a small radius (the mass of the tip is assumed to be zero) is attached to the free end. The flexural vibration schematic diagram of the resonant cantilever is shown in Fig. 1. Assuming that the deflection of any arbitrary point in the cantilever relative to its equilibrium position is defined by $y(x, t)$, x is the horizontal distance between the point observed and fixed end of the cantilever, t is the time, the Young modulus, the inertia moment of the cantilever are defined by E and I respectively, EI is uniform over the length of the cantilever. L is the length of the cantilever. When the dynamic AFM's cantilever vibrates in atmosphere environment, the air damping exists inevitably and must be considered. Damping is modeled by parameter c which describes the additional damping coefficient caused by air when the cantilever vibrates and m is the mass density of the material. $f(x, t)$ is the interaction force and it is the tip-sample interaction force at the point $x = L$. Then the equation of motion for transversal cantilever vibrations is:

$$EI\frac{\partial^4}{\partial x^4}y(x,t)+m\frac{\partial^2 y(x,t)}{\partial t^2}+cm\frac{\partial y(x,t)}{\partial t}=f(x,t) \tag{1}$$

The transformation rule is $y(x,t)=\sum_{i=1}^{\infty}\phi_i(x)Y_i(t)$. Here, $\phi_i(t)$ and $Y_i(t)$ are defined as the eigenfunction and the corresponding generalized coordinates of the i-th order resonant cantilever. After been integrated in the range $[0–L]$ and been applied the orthogonal properties of the vibration mode, Eq. (1) can be transformed into a set of decoupled ordinary differential equations in generalized coordinates:

$$Y_i''(t)+2\gamma_i\omega_i Y_i'(t)+\omega_i^2 Y_i(t)=\frac{F_i(t)}{M_i} \tag{2}$$

where the apostrophes denote the corresponding derivatives with respect to time $\partial/\partial t$. In Eq. (2), the generalized mass of the i-th order resonant cantilever is $M_i=\int_0^L m(x)\varphi_i^2(x)dx$, the generalized force of the i-th order resonant cantilever is $F_i(t)=\int_0^L f(x,t)\varphi_i(x)dx$. $Y_i(t)$ is defined as the corresponding generalized coordinates. ω_i and γ_i is the resonant frequency and the damping ratio of the i-th order resonant cantilever. The form of formula (2) is same as that of standard single-degree-freedom systems, so the frequency response characteristics of high-order resonant cantilever can be solved as the form of Lorentzian curve [24]:

$$A=\frac{A_{0i}(\omega_i/\omega)}{\sqrt{1+Q_i^2(\omega/\omega_i-\omega_i/\omega)^2}} \tag{3}$$

A_{0i}, Q_i, ω_i is defined as the vibration amplitude, quality factor and resonant angular frequency of the i-th order resonant respectively. Fig. 2 shows the curve of the frequency response characteristic of the resonant cantilever.

The change of the tip-sample interaction forces drives shift of the vibration amplitude and the resonant angular frequency of cantilever. In this paper, the detection of changes in the tip-sample interaction forces was achieved by detecting the deformation in the vibration amplitude of the cantilever. Clearly, in order to get the biggest change in cantilever vibration for a given change in resonant angular frequency, one would work on the steepest portion of the A vs ω. This is not at the peak point but occurs at $\omega_{mi}\approx\omega_i(1\pm 1/\sqrt{8}Q_i)$. At this point on the curve, the maximum slope of the A vs ω given by

$$\frac{dA}{d\omega}=\frac{4A_{0i}Q_i}{3\sqrt{3}\omega_i} \tag{4}$$

Two main factors that affect the amplitude deformation of resonant cantilever are vibration amplitude and quality factor of the cantilever. The experimental results show that the Q of the second order is much higher than the first order under the same experimental conditions. These are favorable factors for improving the detection sensitivity.

In a dynamic AFM system in which the vibrating amplitude of the cantilever is detected by optical lever method, the deflection angle of the cantilever can produce a corresponding optical power change $\Delta p(x, t)$ on position sensitive detector (PSD) [25] as

$$\Delta p(x,t)=\sqrt{2\pi}\frac{p_i d_0}{\lambda}\theta(x,t) \tag{5}$$

where p_i defines the incident optical power, λ is the wavelength of laser and d_0 defines the beam diameter projected on the cantilever. The power change $\Delta p(x, t)$ on PSD is proportional to the deflection angle θ. The deflection angle in the free end of the first, second, and third order resonant cantilevers are θ_1, θ_2, θ_3 respectively. It can be seen from Fig. 3 that the deflection angle in the free end of the

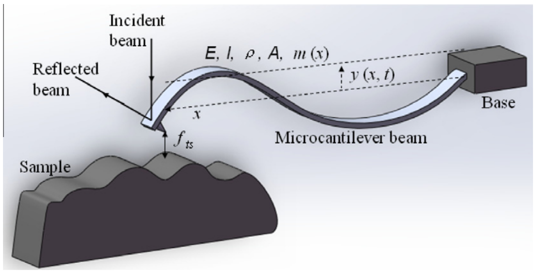

Fig. 1. Schematic view of a rectangular cantilever at the higher-order resonant frequency interacting with sample.

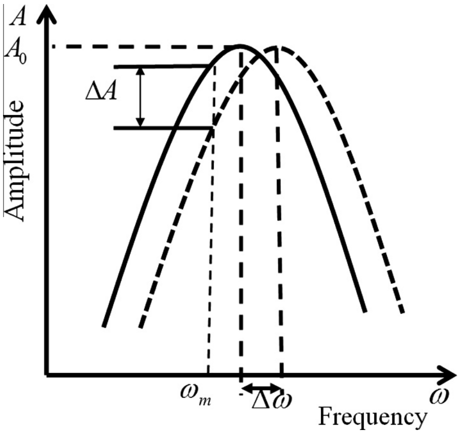

Fig. 2. Curve of amplitude-frequency characteristic.