博　士　論　文

Photothermally induced vibration of an optically driven atomic force microscope cantilever

（光駆動ＡＦＭカンチレバーの光熱誘起振動に関する研究）

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List of acronyms

AFM	Atomic Force Microscope
STM	Scanning Tunneling Microscope
SPM	Scanning Probe Microscope
SEM	Scanning Electron Microscope
MEMS	Micro-Electro-Mechanical System

CHAPTER 1

INTRODUCTION

1.1 Cantilever in Scanning Probe Microscopy (SPM) and Micro-electro-mechanical System (MEMS)

The first working atomic force microscopy (AFM) was demonstrated in 1986 by G. Binnig, C.F. Quate, and Ch. Gerber (1). The invention was based on its predecessor, a scanning tunneling microscope (STM), which led to the recognition award of the Novel Prize (Physics) in 1986 (2). The STM operation lies on the electron tunneling effect trough the potential barrier between electrically conductive probe and sample surface. Meanwhile, force interaction (e.g. van der Walls forces, electrostatic forces, magnetic forces) between sample surface and probe is the operation principle for AFM. Compared to the STM, samples studied under the AFM do not need to be electrically conductive or metal-coated. The AFM invention solves the problem to image a surface beyond the diffraction limit (resolution in nm order) of common optical microscopy in both electrically conductive and non-conductive samples, as well as in various condition of sample environment (e.g. liquid). Since the invention of the STM and AFM, various probe based-microscopes have been developed, for example friction force microscope (FFM) and near-field scanning optical microscope (NSOM). These kinds of microscopes are grouped under the family of scanning probe microscope (SPM).

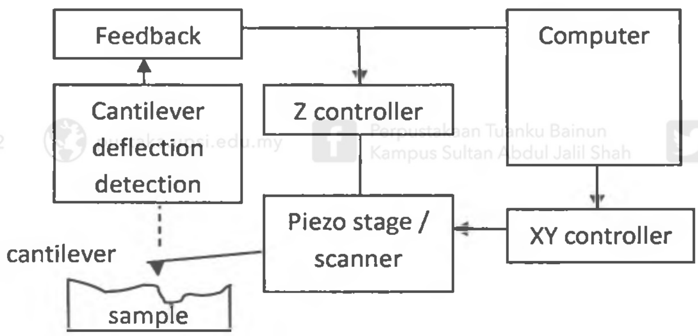

Figure 1.1: Working block diagram of the AFM.

The basic schematic of the AFM is shown in Fig. 1.1. The main element is a cantilever with tip, which acts as a probe and senses the change in mechanical property of the sample surface being studied. The change at the point of "contact" on the surface is translated into measurable quantity in the form of cantilever deflection. A suitable detection system measures this cantilever deflection. During the surface imaging, distance of the vertical tip-surface is controlled by z-controller through a feedback line. XY-controller brings the cantilever into a raster scan. The resulted image provides topographic image of the quantity being measured.

The first demonstrated AFM modifies the STM function, which measures tunneling current due to the deflection of AFM cantilever (2). The most popular detection method is by using a laser beam deflection method. A laser beam is directed on the cantilever surface and reflected to position sensitive detector (PSD) (3). For this purpose, an additional reflective coating such as aluminium or gold is necessary on one side of the cantilever surface. The laser beam deflection requires more space for laser source, PSD and optical path. To overcome this issue, compact AFM utilizes alternative detection methods such as piezoresistive or capacitance method (4).

The AFM can be operated in static mode and dynamic mode. In static mode or so-called contact mode, the probe tip is in physical contact to the sample surface. As the tip scans on the sample surface, the cantilever will deflect due to the variation in topographic structure. The amount of exerted force by the tip to the cantilever can be calculated from Hooke's law ($F = kx$), where x is the tip cantilever deflection and k is the cantilever stiffness. In dynamic mode, the cantilever is excited into mechanical vibration, usually at its resonance frequency. During the scan, the cantilever periodically taps the sample surface. As the tip approaches the sample surface, the gradient change of the interaction force causes a shift in the resonance amplitude or the resonance frequency of the vibrating cantilever. Since the tip briefly touches the sample surface during imaging, the dynamics mode has an advantage of being gentle on soft surfaces such as polymers and biological samples.

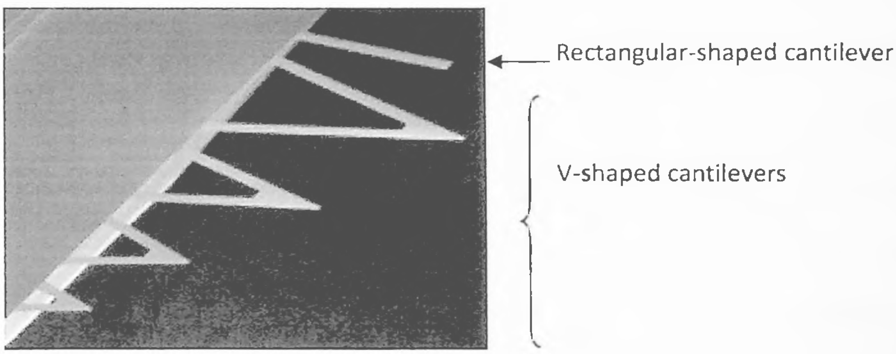

Figure 1.2: Rectangular- and V-shaped AFM cantilevers.[1]

Others than surface scanning for topographic image, AFM can also be utilized as a lithographic pen and manipulator. For instance, carbon nanotubes which is attached to the AFM tip is able to fabricate 10 nm wide oxide lines on silicon oxide substrate (5). The same AFM tip is used again to scan the topographic image of the fabricated line. As a nanomanipulator, an AFM in non-contact mode has been demonstrated to control the movement of the nanoparticles of size 10-100nm on silicon oxide substrate (6). These examples show that AFM can be expanded in various possible applications.

The cantilever and tip design is important in AFM. Generally, there are two type of AFM cantilever shape as shown in Fig. 1.2; rectangular or

[1] http://www.brukerafmprobes.com/images/product/cantilever/detailed/MLCT.jpg

bar shaped and triangular or V-shaped. The geometry and the material of the cantilever determine its mechanical properties such as resonance frequency, stiffness and flexural mode. Due to the small in size and mechanically sensitive to the environment change, the AFM cantilever has been widely used in microsensor technology. A bi-material V-shaped AFM cantilever has a potential to detect photothermal radiation with resolution 40 pW at room temperature (7). In cantilever-based photothermal absorption spectroscopy, a V-shaped AFM cantilever is coated with nanograms of biological sample (*e.i.* Bacillus anthraicis) and the absorbance spectrum of the sample against infrared irradiation is investigated (8). In another spectroscopic technique, an AFM cantilever is placed several micrometers above the infrared-irradiated sample and the cantilever mechanical response due to local heating is analyzed (9).

The versatility of the AFM cantilever leads to the practical attention in the field of cantilever based micro-electro-mechanical-systems (MEMS). Some designs of MEMS employs arrays of cantilevers for actuating or sensing applications. For example, millipede design of thermomechanical cantilevers with nano-heater for data-storage application has been demonstrated (10).

For AFM in dynamic mode and microresonator MEMS, the cantilever must be excited into mechanical vibration. Among the common methods of excitation are by means of electrostatic, piezoelectric and magnetic excitation (11), (12). Figure 3.3 shows a vibrating cantilever under an electrostatic excitation for gas sensor application (13). Photothermal excitation is an alternative method in AFM and microresonator MEMS, and it offers three advantages. First, the cantilever can be remotely excited especially when the space around the cantilever is very limited. Second, it is very simple to setup compared to piezoelectric and electrostatic actuation. Photothermal excitation requires irradiation beam from a remote laser source which is directed onto the cantilever surface. For the third advantage, the excited cantilever shows clean vibration spectrum since the cantilever is locally heated. These advantages are useful in specific application such as in liquid AFM (14) (15). Furthermore, photothermal excitation has been also shown to amplify the weak light detection in a bimaterial silicon cantilever (16).

In general, the photothermally induced vibration in optically driven cantilever can be explained in three intermediate stages. At first, local heating at the spot-position occurs when the excitation laser is absorbed on the cantilever surface. Second, the temperature gradient, which is highest at the excitation spot, is established along the cantilever due to the local heating. Lastly, the cantilever experiences thermal expansion depending on the expansion coefficient and the specific geometry of the cantilever. For bimaterial cantilever, the difference in expansion rate produces structural bending (17). The bending is detected as a transversal translation if a read-out probe is positioned above the cantilever horizontal surface.

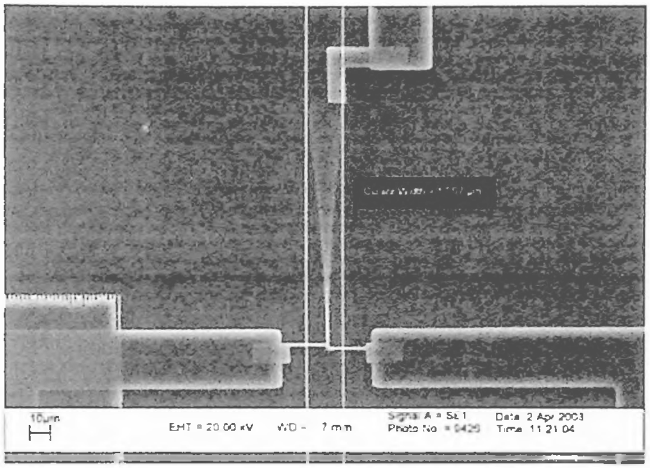

Figure 3.3: Vibrating cantilever (between vertically parallel lines) under electrostatic excitation in a gas sensor MEMS.[2]

1.2 Fano Resonance

1961, U. Fano suggested a theoretical description to the anomalous characteristic at the resonance in an absorption spectrum of atoms (18). Credited to his contribution, the resonance is later called as the Fano resonance. The Fano resonance can be characterized as an asymmetric resonance in the absorption spectra of atoms, molecules, and single quantum dots (19) (20). The existence of two scattering channels, one from a discrete state and the other from a continuum state, modifies the resonance profile of the universal Lorentzian shape into a peak-and-trough resonance curve.

This phenomenon is not limited to the field of atomic physics, but also extends to optical microcavity systems where the discrete state in

[2] http://en.wikipedia.org/wiki/File:MEMS_Microcantilever_in_Resonance.png

the microcavity interferes with continuous uncoupled light (21). It has been demonstrated that a resonance analogous to Fano resonance can be appeared in a pair of classical oscillators coupled by a weak spring (22). These show that Fano's theoretical approach can be applied and generalized into various systems which exhibit asymmetric resonance. In this thesis, Fano's idea of interference is applied to analyze the vibration spectrum of an AFM cantilever.

1.3 Motivation and Research Objective

Even though the dynamics of optically driven both-fixed and free-end typed cantilevers are well described elsewhere, the dynamics for V-shaped cantilever remains difficult (23) (24). Since the flexural mode of a free-end rectangular cantilever is close to the flexural mode of V-shaped cantilever, the photothermal effect is predicted to behave similarly for the first flexural flexural mode. V-shaped is favorable in AFM applications compared to the rectangular shape because of the sensitivity of the flexural modes is high for imaging soft surface (25). Furthermore, the V-shaped cantilevers have a higher torsional spring constant in comparison to rectangular cantilevers (26). Using cantilever with high torsional spring constant is beneficial for avoiding torsional cantilever bending to achieve stability during scanning operation. Large surface area of the V-shaped AFM cantilevers is suitable for coating active substances or samples for chemical and biological sensors applications.

Another researcher studies the localized fields in nanogaps between metal particles using scattering-type NSOM in parallel with my study (27). We are using the same AFM and optical path. He employs evanescent field illumination on his samples and scans by the AFM operation of tapping mode. In the tapping mode AFM, the change in the resonance frequency of the cantilever is critical for producing high-resolution topography and clean scattered near-filed images. Leaked illumination due to imperfections in setting up the evanescent field and far-filed scattered light from the scanning may influence the performance of NSOM by mean of local heating. It is our interest to see whether such problem may occur. It has been reported that the local temperature variation shifts the resonance frequency of a microresonator beam (28) (29) (30).

In this study, the researcher focuses on the optically driven AFM cantilever using point-like excitation. The AFM cantilever is V-shaped cantilever with stiffness below 1 N/m which is suitable for imaging soft sample surface. The main purpose of this study is to analyze the dynamic response of the AFM cantilever against an external optical excitation. The effect of thin metal coating on the observed dynamics response will be reported. In addition, the researcher observed the phenomenon of Fano-like resonance in the vibration spectrum of the cantilever. The Fano-like resonance is found to be dependent on the excitation spot-position along the central axis of the cantilever.

CHAPTER 1

This thesis is divided into 6 chapters including the current Chapter 1 as the introduction to the research. The theoretical foundation of the cantilever dynamics, photothermal effect and Fano resonance are discussed in Chapter 2.

In Chapter 2, theoretical description of cantilever mechanics is explained. Brief discussion about Fano resonance and its manifestation in oscillation analysis will be treated.

In Chapter 3, I will describe the experimental setup and procedures to study the dynamics response of the cantilever.

In Chapter 4, the analysis of dynamics of the metal-coated AFM cantilever is presented. The front side of the cantilever, which faces against the laser excitation, is coated with gold layer. The difference in dynamics response of the coated and uncoated cantilever will be discussed.

In Chapter 5, I report the observation of Fano-like resonance in the vibration spectrum of the optically driven AFM cantilever. Instead of showing Lorentzian profile, the vibration resonance shows asymmetric profile, which is analogous to famous Fano resonance. The analysis of the dynamics response will be discussed.

Finally, Chapter 6 summarizes the study results.