Atomic Force Microscopy: its development and applications

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Abstract

This paper reviews the invention and developments of atomic force microscopy (AFM). It starts with structure and the basic principles, then its applications and limitations are discussed. Some recent experiments using AFM are reviewed.

I. Introduction

The invention of scanning tunneling microscope (STM) [1] overcame the diffraction limit of conventional optical microscopes and increased the resolution to atomic scale. STM has a sharp tip that measures the tunneling current from the sample to the tip, which has a good resolution investigating the surface of conductors and semiconductors. Four years later, an equivalent technique, atomic force microscope, was developed to study insulators [2]. The first atomic resolution was obtained one year after the introduction of AFM [3]. In the same year, the atomic resolution of insulators was achieved for the first time [4]. Because AFM does not require the conductivity of the sample surface, this technique are widely used in all kinds of sciences over the world. Advances in AFM also allow us to visualize the inner structure of covalent bond [5], which will be discussed in section.

II. Basic Principles

The microscope consists of a cantilever with a sharp tip [2, 6]. When the tip is brought to the vicinity of the sample, it will interact with the sample surface and deflect the cantilever. The tip-sample force F and the deflection z is described by the Hooke's law

$$F = kz \tag{1}$$

For a rectangular cantilever, the spring constant k of the cantilever is calculated by [7]

$$k = \frac{Ywd^3}{4L^3} \tag{2}$$

where Y is the Young's modulus, w is the width, d is the thickness, L is the length as shown in Fig. 1

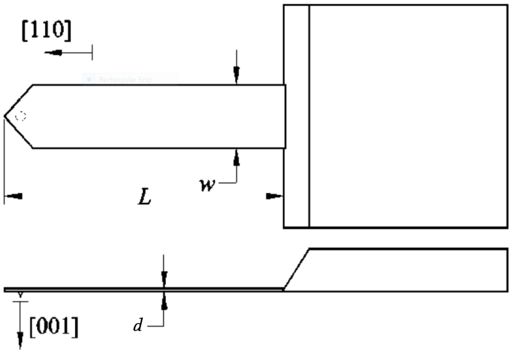

Figure 1: *Cantilevel viewed from top and side. (Fig. 7 of [8])*

The deflection is monitored by a deflection sensor which generates a electrical signal that can be controlled by a feedback loop to keep the deflection constant.

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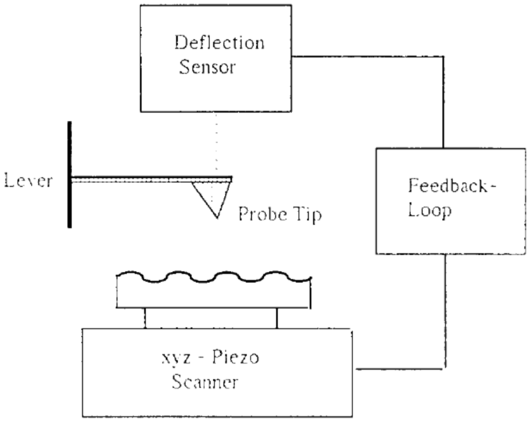

Figure 2: *Basic structure of AFM. (Fig. 1 of [9])*

Tip-sample forces

There are many publications on the calculations of tip-sample forces [10, 11, 12, 13]. The tip-sample force F_{ts} has contributions from many fundamental forces, like van der Waals, electrostatic, magnetic, ionic repulsion and frictional forces [9].

Van der Waals force arises from the fluctuating polarizations of nearby particles. The interaction energy for two atoms is derived by London [14]

$$V(z) = -\frac{3}{4}\frac{\alpha^2 h\nu}{(4\pi\varepsilon_0)^2 z^6} \tag{3}$$

Hamaker gave the result for the interactions between macroscopic atoms [15]. For a spherical tip, the van der Waals potential is [16]

$$V = -\frac{A_H R}{6z} \tag{4}$$

and hence the force is proportional to $1/z^2$, where R is the radius of the tip, A_H is the Hamaker constant which is provided by Krupp and French [17, 18]. For pyramidal and conical tips, the force is proportional to $1/z$ [19]. Electrostatic forces can be detected by AFM with a very high resolution. For a spherical tip, the force is calculated to be [20, 21]

$$F = -\frac{\pi\varepsilon_0 R U^2}{z_{effective}} \tag{5}$$

This becomes very important when the tip is conductive and a bias voltage is applied between the tip and the sample.

The theoretical models for other forces will not be discussed in detail here.

Cantilevers

The cantilever is a key element in AFM. The spring constant k of the cantilever should as small as possible in static mode in order to detect small interatomic forces [22], while in dynamic mode, k must be very large to reduce noise [23].

The first cantilever was made from gold foil with a diamond probing tip, with the ability to measure a force that is as small as $10^{-18}N$ [2]. Other simple cantilevers are made from aluminum foil [22] and etched tungsten wires [24]. Later, the advances in microfabrication enables us to produce cantilevers with well-defined properties. The most popular ones in use today were developed by Wolter *et al.* using silicon with integrated tips [25].

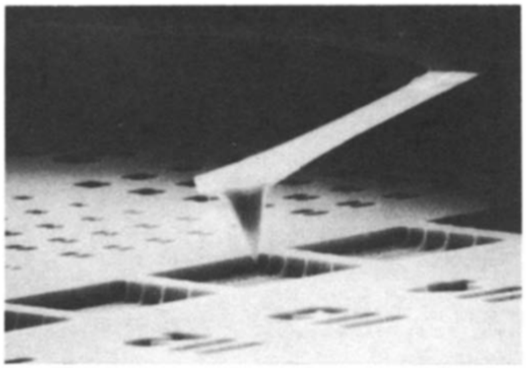

Figure 3: *Micromachined Si-cantilever [25]*

Tips

To achieve atomic resolution, there should be only one atom interacting strongly with the sample. Si and SiO_2 can be used to build vary sharp apex [26]. The spatial arrangement of the tip's front atoms is also crucial for AFM. As shown in Fig. 4, the front atom in [111]-oriented Silicon tips has more connecting bonds than in [001]-oriented tips, and hence the [111] tip is more stable.

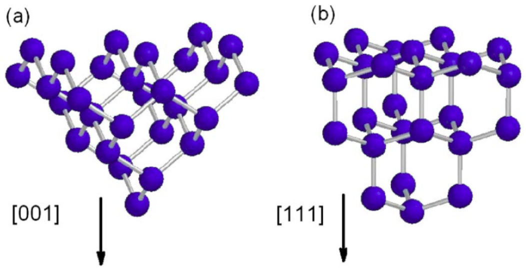

Figure 4: *Silicon tips pointing in (a) [001] direction and (b) [111] direction (Fig. 14 of [8])*

Deflection Sensors

There are many types of sensors to measure the deflection of cantilevers, such as beam deflection, piezoelectric detection, laser Doppler vibrometry, STM, optical interferometry, and capacitive detection.

STM is used in the first microscope [2]. The relative variations of the tunneling current are given by [9]

$$\Delta I/I \approx \sqrt{U}z \tag{6}$$

which indicates that this method is very sensitive to distance changes as small as 0.01Å. Despite of the high sensitivity, STM method has lots of drawbacks. The tunneling tip will exert an significant force on the cantilever and it is very difficult to distinguish this force from the cantilever-sample force. During preparation, it takes a lot of time to align the STM tip with the thin cantilever.

Beam deflection was designed two years after the introduction of AFM [27] and it is the most common method today. A positive sensitive detector (PSD), a photodiode, is used to monitor the reflected beam. The relationship between the photocurrent and the cantilever deflection is given by [9]

$$\frac{\Delta I}{I} = \frac{6\Delta z}{l}\frac{1}{\delta} \approx \frac{\Delta z}{\lambda} \tag{7}$$

where l is the length of the cantilever. In static mode, the typical resolution is 0.1Å. The lateral force can also be measured by using a four-segment photodiode [28, 29]

Operation Modes

In static mode, which is also called contact mode, the cantilever is deflected and kept at a constant position using a feedback loop. The deflection of the cantilever must be significantly larger than the deformation of the tip and sample, so the spring constant k should be small. In order to avoid resonance of the cantilever, the fundamental eigenfrequency must be significantly larger than the detection bandwidth. The eigenfrequency is given by [7]

$$f_0 = 0.162\frac{d}{L^2}\sqrt{\frac{Y}{\rho}} \tag{8}$$

where ρ is the mass density of the cantilever. These two restrictions make static mode experimentally difficult.

In dynamic mode, the cantilever is mounted on an actuator and oscillates close to its resonance frequency. The amplitude-modulation operation (AM-AFM) was developed by Martin *etal*. that drives the actuator at fixed amplitude and fixed frequency f_{drive} which is different from f_0 but very close to f_0 [30]. When the tip is brought to proximity of the sample, interactions will change the cantilever's oscillation amplitude and phase. However, this method is very slow due to the slow change in amplitude. To solve this problem, frequency-modulation mode (FM-AFM) was introduced [31]. Later, tapping mode was introduced to bring the tip close enough to the sample to detect short-range interactions [32].

III. Applications and recent discoveries

Shortly after the introduction of AFM, it revealed its amazing imaging and spectroscopy power around the world. Many materials were studied by AFM, like insulators [33], ionic crystals [34], metal oxide [35], organic monolayers

[36], etc. Last year, the covalent bond was visualized for the first time [5], that provides a lot of information on chemical reactions.

IV. Conclusion

AFM is a very powerful imaging tool that can map a 3D surface profile. Unlike STM, AFM does not requie any special sample treatment, which avoids irreversible damage to the sample. However, AFM also has limitations. Due to its design, the scanning size is small compared to other microscopes, and the scanning speed is also very slow. Thanks to AFM, imaging material surfaces is standard practice today, and this technique will continue facilitating scientific research in the future.

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