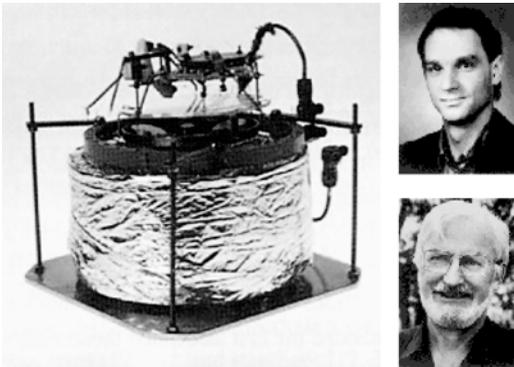


A Brief Introduction to Atomic Force Microscopy

Introduction

In 1986, Gerd Binnig and Heinrich Rohrer won the Nobel Prize in Physics for the invention of the scanning tunnelling microscope (STM) and the fact that it could achieve atomic resolution. They observed that if they held a metallic tip of 10 angstrom above a conductive surface, they could measure a tunnelling current in the order of a nanoampere. When the tip was then scanned over the conducting sample, the topography of the surface could be plotted by measuring the distance-dependent tunnelling current. The STM was a revolution in the field of high resolution microscopy, however, this technique could only be used to image conducting samples.



First STM: First STM (left) invented by Binnig (top) and Rohrer (bottom) in 1981. Image courtesy of IBM.

New scanning probe microscopes (SPM) based on the STM principle have therefore been invented. Among those the most promising is the atomic force microscope (AFM). The success of AFM is due to its capability to achieve atomic resolution and to simultaneously measure topography and other force-related material properties. AFM can also be used to image a huge variety of samples which of course do not need to be electrical conduc-

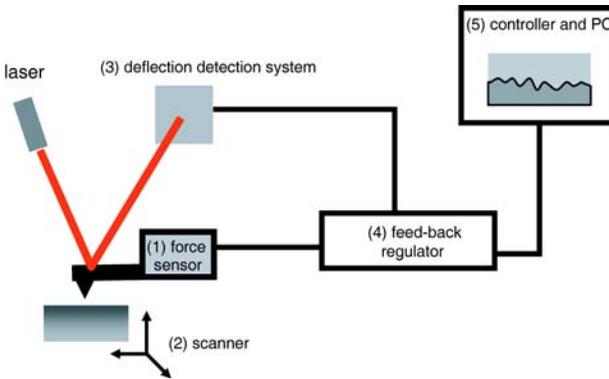
tors and could also be used in different environments like gas, vacuum and liquid.

The basic principle of AFM is very simple. The AFM detects the force interaction between a sample and a very tiny tip ($<10\text{nm}$ radius) mounted on a cantilever. The force interaction between sample and tip is related to the deflection of the cantilever, i.e. the more the tip presses into the sample the greater the deflection of the cantilever and the greater the force exercised on the sample. A regulating feedback system tries to keep the deflection of the cantilever and thus the force interaction constant. Therefore the cantilever is moved away from the surface or towards the surface depending on how the force changes. This movement is then recorded as topography signal when the tip is scanned over a sample. The topography can thus also be interpreted as a map of equal forces. It is thus possible to detect any kind of force as long as the tip is sensitive enough, i.e. as long as the force interaction induces a measurable deflection of the cantilever. Hence not only interatomic forces but also long range forces like magnetic force and electrostatic force can be detected.

The AFM Setup

Independently of the type of tip-sample interaction an AFM basically consist of five major parts shown in figure *AFM Setup* and described in the following sections:

- (1) A force sensor, which is basically a sharp tip ($<10\text{nm}$) mounted on a sensitive cantilever.
- (2) A scanner which moves the sample or the sensor in order to probe the sample surface.
- (3) A sensor which detects the cantilever deflection, for example a laser deflection system or piezoresistive system.
- (4) A feed-back system which regulates the force interaction.
- (5) Controller electronics which records movements, controls the feedback loop and sends the measured data to a personal computer software.



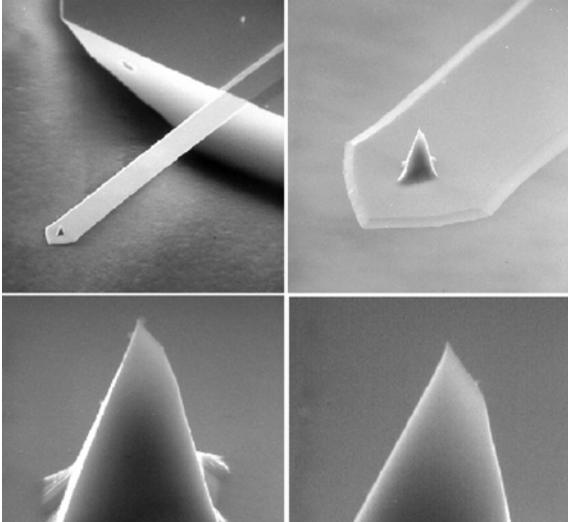
AFM Setup: The five components of an AFM setup

Even if these parts are present in every AFM, their implementation can differ substantially. However a common point to all AFM is the force sensor, also called AFM probe. It is plausible that the results strongly depend on the sharpness of the tip and the spring constant of the cantilever. This will be the subject of *The Force Sensor*. The deflection detection system needs to be very sensitive and can be implemented in different ways which will be discussed in *The Deflection Detector*. The feedback system will be described in *The PID Feedback System*. The AFM can be operated in different modes which will be discussed in *AFM Operation Modes*. Finally *The Scanning System and Data Collection* will deal with the positioning or scanning system which needs to provide nanometer resolution.

The Force Sensor

AFM probes are typically micro-fabricated. The single-leg or V-shaped cantilevers are usually made out of silicon, silicon-dioxide or silicon-nitride. Typical cantilevers are several hundred micrometers long, several tens of micrometers large and on the order of one micrometer thick. For silicon these dimensions will result in spring constants between 0.1 and 1N/m and resonance frequencies between 10 and 100kHz.

Thanks to recent developments in microtechnology it is possible to fabricate cantilevers with integrated sharp tips. It is important to keep in mind that



AFM Probe: Tip and cantilever of an AFM probe. Image courtesy of IBM.

the quality of the tip, i.e. the shape of the tip, determines the quality of the measurement. The critical dimensions of an AFM tip are its aspect ratio (height/width), the radius of curvature (sharpness) and its material. The ideal tip has a high aspect ratio, a small radius of curvature and is made of an extremely hard material. The shape of the tip is of great importance when it comes to the interpretation of the measurement. Due to the fact that not only the very apex of the tip but also its side walls interact with the sample during scanning, the measured image is always a convolution between the tip shape and the sample. Therefore it is important that the feature size of the sample and their aspect ratios are some orders bigger than the radius of curvature and aspect ratio of the tip, respectively.

In AFM the force sensor needs to meet the two following requirements:

- Contact Mode (see *AFM Operation Modes*): The spring constant of the cantilever needs to be small, such that the cantilever can be sufficiently deflected and the deflection can be detected. Ideally the spring constant should be smaller than the interatomic spring constant, which is about 10 N/m.

Dynamic mode (see *AFM Operation Modes*): The portion of perturbation transmitted to the cantilever is given by $a_{trans} = a_0(f_0/f_{ex})^2$, where f_{ex} is the excitor vibration frequency with amplitude a_0 and f_0 is the resonance frequency. It is therefore usual to use cantilevers with high resonance frequency in order to avoid low frequency acoustic or mechanic perturbation such as building vibrations.

The Deflection Detector

Another critical part of the AFM is the deflection measurement system. Ideally, the sensing system must be able to measure the deflection of the cantilever with angstrom resolution and must not perturb the cantilever in any way. The most used detection system is therefore an optical technique based on the reflection of a laser beam on the cantilever. The idea of the technique is shown in figure *AFM Setup*. A laser beam is focused on the very end of the cantilever which reflects it back on a segmented photo diode. The deflection angle of the cantilever is thereby enhanced, i.e. a small displacement of the cantilever results in a bigger displacement of the reflected laser beam on the photo diode. The further away the diode the bigger this mechanical amplification. However the photo diode can't be placed to far away because of external perturbation. One reason for that is that the laser deflection method is sensitive to the ambient light, the light reflected by the sample or the cantilever and other possible sources of light. The optical detection system allows to measure deflections below one angstrom.

There are other detection techniques used for detecting the deflection of the cantilever like

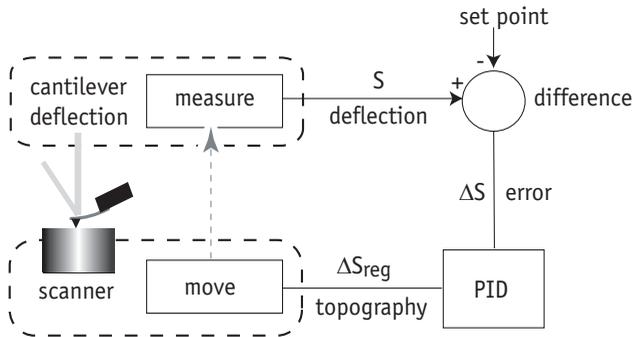
- Interferometric optical system
- Piezoresistive detection

which will not be further discussed here.

The PID Feedback System

Before starting any AFM measurement it is necessary to understand how the feedback regulation system works. This regulation enables the acquisition of

an AFM image. As described previously, the cantilever deflection is detected by a sensor. This position is then compared to a set-point, i.e. a constant value of cantilever deflection chosen by the user. As the deflection of the cantilever is directly related to the tip-sample interaction force, the set point is usually given in Newton (N). Typical forces are in the nN range. The difference between the actual interaction force and the desired force is called the error signal ΔS . This error signal is then used to move the tip or sample to a distance where the cantilever has the desired deflection. This movement is then plotted in function of the lateral position of the tip and is the so-called topography. The goal of the feedback system is to minimize the error in a very fast manner so that the measured topography corresponds to the real topography of the sample. Therefore the error signal must be amplified by a PID controller (Proportional Integral Differential). A schematic representation of the feed-back system is shown in figure *PID controller*.



PID controller

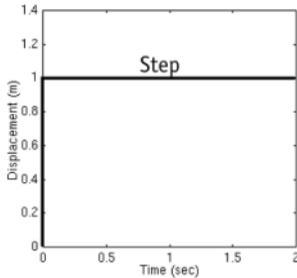
As the name suggests, the PID controller has three domains of action:

- Proportional Gain
- Integral Gain
- Differential Gain

These three gains can be set individually and define how fast and in which manner the error is minimised and the therefore how good the topography

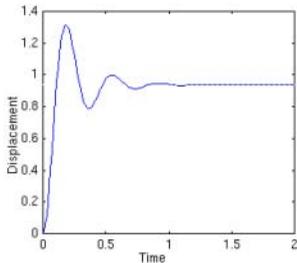
of the sample is reproduced in the measurement. Thus it is important to understand its characteristics. To illustrate the effect of the PID gains consider the following experiment.

A step signal from 0 to 1 will be measured (see figure *Step*). The goal is to



Step

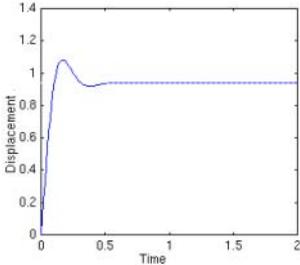
reproduce the rectangular step as precisely as possible. Hence the PID gains must be adjusted. Figure *P-Gain* shows the result when only the proportional gain (P) is turned up. The topography shows a long rise time (slope), an



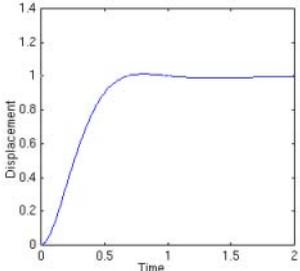
P-Gain

overshoot (peak) and a settling time (wobbles). As next the differential gain (D) will be turned up in addition to P. It can be seen in figure *PD-Gain* that the derivative gain reduces both the overshoot and the settling time, and had little effect on the rise time. In order to see the influence of the Integral gain

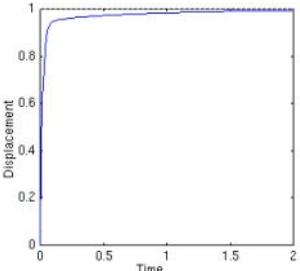
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PD-Gain



PI-Gain



PID-Gain

(I) the D gain is turned down and the I gain up. As can be observed in figure *PI-Gain* the I controller further reduced the overshoot and decreased the settling time.

The response is much smoother now, albeit with an increased rising time. When the P, I and D gains are combined in an appropriate way it is possible to obtain the response shown in figure *PID-Gain* with no overshoot, short rise time, and short settling time. The correct PID settings are sample dependent and have to be determined for each measurement.

AFM Operation Modes

The AFM can be operated in different modes. This depends on the sample and on the information one would like to acquire. Among several modes here only the most common ones are discussed: contact, non contact and dynamic mode.

Static Mode

This mode is the most basic mode which was also the first real mode in which AFMs were operated. The tip is always in contact with the sample while probing the surface. Thereby the deflection of the cantilever and thus the interaction force is set by the user (set-point). The feedback regulator maintains this set-point by moving the scanner in the direction vertical to the sample. This movement generated by the regulation is then plotted as topography of the sample. The major parameter to set in this mode is the interaction force. This must be set to a minimum value, such that the tip is just in contact with the surface. The inconvenience of this method is that the tip might easily be contaminated or broken and that sticky samples can not be imaged correctly.

Dynamic Mode

Dynamic mode is probably the most used mode nowadays. The cantilever is oscillated. Hence the tip is touching the surface periodically. The contact with the surface attenuates the oscillation amplitude. The feedback regulates this attenuation compared to the desired set-point. Ideally the damping of the amplitude is related to the tip-sample interaction force which is therefore defined with the set-point. The set-point of this mode is given by the per-

centage of damped amplitude compared to the undamped amplitude, i.e. a set-point of 100% gives no interaction and a set-point of 60% means that the 40% of the vibration energy is lost in the interaction between tip and sample. As in contact mode, the goal is to keep the interaction as small as possible in order to avoid damage or contamination of the tip. In this case this means that the set-point needs to be as near to 100% as possible.

The oscillation amplitude is also an important parameter. Generally the oscillation amplitude has to be in the order of the features that have to be observed, i.e. large features need large amplitudes and tiny features need a small amplitude. In order to measure tiny features on large features small amplitude and slow scan speeds are recommended.

The achievable resolution of the dynamic mode is comparable to the contact mode. However, due to the fact that the tip is only periodically in contact with the sample, the tip is less damaged and the lateral sticky forces are negligible.

The Scanning System and Data Collection

The scanning system of the AFM must be capable of placing the tip with a subatomic resolution, which is needed in order to image the sample with atomic resolution.

The movement of the tip or sample in the three axes can be realised in several ways. There are different implementations, e.g. piezoelectric, electromagnetic etc. As described in *The PID Feedback System* the topography image is generated by the feedback system which moves the scanner. This motion data is sent to the PC software through the AFM controller, usually line by line. The software combines the lines to a three-dimensional image where the height is usually represented with a colour code.