Module 26: Atomic Force Microscopy

Lecture 39: Atomic Force Microscopy – 2
39.1 Components of an AFM

In the previous lesson we have discussed about the procedures of alignment and approach. Now we will discuss the functioning of an Atomic Force Microscope, and particularly concentrate on different components and modes of the instrument. The key components of an AFM are shown schematically in figure 39.1.

Figure 39.1: Key Components of an Atomic Force Microscope

First we briefly discuss the key aspects related to operation of the instrument. In an AFM, the mechanical force interactions acting between a sharp probe and a sample are used for surface imaging. We now understand (from Lecture 21) that the probe, which is a micro machined cantilever with a sharp tip at one end, is brought into interaction with the sample surface. The interaction level between the tip apex and the sample is determined through precise measurements of the cantilever displacements. An optical level detection appeared invaluable for precise measurements of the cantilever deflection in most commercial atomic force microscopes.

In this procedure, a laser beam, which is deflected from the backside of the cantilever, is directed to a 4-segment positional photodetector (QPD), which is divided into segments for measurements of normal and lateral deflections of the cantilever. At present the optical level detection is the most reliable way to measure the tip-sample force interactions (figure 21.1). This
method is not completely free of problems related with the use of light such as parasitic interference at the cantilever-sample confinement, heating of a cantilever and a sample by a laser beam. Therefore, the microscope designers are looking for alternative approaches. Among them is the AFM based on a microfabricated piezocantilever, in which the cantilever itself provides not only the deflection sensing but also the actuation.

As a short summary, it becomes clear that the main components of atomic force microscope are probes, optical detection systems, piezo-scanners and electronics for a management of scanning procedures and data acquisition. In the microscope, these components are assembled into a microscope stage, which must satisfy the requirements of minimum vibrational, acoustic and electronic noise as well as small thermal drift. Basic information about these components could be useful for better understanding the performance of AFM instruments, their unique features and limitations.

39.2 The Piezo-Electric Scanner

The scanner which is applied for 3D movement of the sample or probe in AFM is made of piezoelectric materials, which provide the precise positioning and ability to transport the objects in the micron range with sub-angstrom precision. Piezoelectric materials develop electric polarisation on application of stress across them and resultant strain. Piezoelectric materials exhibit intrinsic (spontaneous) polarisation. Most of the piezoelectric materials are ceramic in nature, barium titanate for example, but there are some polymeric materials that are used for specialist applications. Piezoelectric ceramics are usually polycrystalline materials that are divided up into regions of similar polarisation (domains). Once aligned, these domains produce a net polarisation. If an electric field is applied, the dipoles within the domains either contract or expand (resulting in a change in the volume). If a strain is applied, the dipoles are again forced to contract or expand, this time producing a potential difference.

However, due to polycrystalline nature of these materials, the motion of real scanners deviates from linear dependence on applied voltage, especially at voltages generating large translations.
In addition, the motion along the different axes is not completely independent. Therefore, a careful design; precise construction and calibration are important objectives that should be addressed during manufacturing of the scanners and their use. These efforts will allow the real scanners to approach desirable performance, yet an additional electronic control is still needed. In an open-loop scanner, the controller drives the scanner using a non-linear voltage profile that produces a linear motion.

![Figure 39.2: Typical Rastering Arrangement of an AFM](image)

39.3 Imaging by an AFM

The surface imaging is realized by detecting the tip-sample force in different force in different locations while the probe is rastering the sample surface with the help of a piezoelectric actuator. The rastering is performed along two axes, the fast axis and the slow axis, which is shown in figure 39.2.

A feedback control applied during imaging ensures that the tip-sample force is preserved at a constant level. The error signal, which is used for feedback control, is amplified to generate height images, which reflect surface corrugations. The height image, in which brighter contrast is assigned to elevated surface locations, represents the vertical translations of the piezo-scanner needed to eliminate the error signal when the probe is moved from one sample location to the other. The error signal images, which, might be considered as maps of derivatives of height corrugations, emphasize fine surface features that are poor resolved in the height images.

39.3.1 Imaging Modes
There are two main operations modes in AFM: contact mode and tapping or intermitted contact mode. In contact mode which was introduced in practice first, the probe comes in a permanent contact with a sample surface. A product of the cantilever stiffness on the deflection determines the tip-sample force. For many samples, this mode should be applied with caution and the cantilevers with low spring constant are needed for the gentle profiling of the soft surfaces. Imaging with high resolution was demonstrated with the contact mode AFM on many crystalline surfaces. Besides surface imaging, AFM in its force modulation mode has been effectively used for the evaluation of sample mechanical properties by modulating the tip force with an additional actuator. Lateral tip-sample forces accompany scanning of surfaces with the tip being in contact, and these forces can be recorded for evaluation of surface friction. Unfortunately, lateral forces apply to soft samples might induce a strong shearing deformation and sample damage. This limits the contact mode applicability to studies of polymer and biological objects.

In AFM, local tip sample forces can be measured using deflection vs. distance curves. These measurements are also helpful for choosing appropriate set-point deflections for surface imaging with different forces. By immersing the sample and the probe in liquid one can eliminate capillary forces applied to the tip by a liquid contamination layer, which presents on surface in air. Therefore, imaging in liquids can be performed at small forces below one Nano newton. For biological samples, aqueous media is essential and most of AFM studies of these objects are done underwater. For other materials, imaging in liquids is only an optional, not a routine operation.

This situation changed drastically with the introduction of AFM oscillatory mode known as tapping mode. Tapping is performed by the probe, which is driven into oscillatory motion at its resonant frequency by an additional piezoactuator. A drop of the cantilever amplitude when the tip comes into interaction with the sample is used as a measure of these interactions, and the amplitude drop is kept at a pre-set level during scanning. In tapping mode, permanent shearing forces are almost eliminated and intermittent tip contact with the sample surface occurs with a
high frequency (tens and hundreds of KHz) that also restricts material damage. Such operation is gentler than contact mode despite the fact that stiffer probes are used in tapping mode. This mode has revolutionized AFM application because of broad range of samples and materials of industrial importance has become accessible for studies at ambient conditions. For example, the contact mode measurements of Si wafers caused a surface damage that can be avoided by using tapping mode.

The advantages offered by tapping mode for imaging of soft materials are balanced by the complexity of dynamic tip-sample force interactions that in some cases makes the analysis and the interpretation of tapping mode images quite challenging. The main problem is that a change of amplitude of an oscillating cantilever while it interacts with a sample does not solely determine tip sample forces. Alterations of resonant frequency and phase of the cantilever are more sensitive for this purpose. Corrugated surface features as well as contaminated traces make the sensitive phase and frequency measurements less applicable for feedback than the amplitude changes. Therefore the amplitude is used for feedback and vertical adjustments of the piezoscanner needed for keeping the amplitude drop constant are reflected in the height image. The phase changes of the interacting probe during imaging are presented in the phase image. Usually the tapping mode, the height and the phase images are recorded simultaneously. Phase imaging is most valuable for compositional analysis of heterogeneous samples. Differences in adhesive and mechanical properties of different components are responsible for various phase contrast observed on these samples during imaging. The tipping mode with phase or frequency detection also made possible broad applications of electric force microscopy and magnetic force microscopy.
Figure 39.3: Key Components of an Atomic Force Microscope

Qualitative differences of mechanical, adhesive, electric, magnetic and other properties are sufficient for compositional mapping, yet the demand for local quantitative measurements of these properties is increasing with developments of nanoscience and nanotechnology. The local measurements have been a challenge since the introduction of AFM and there are a number of relevant problems. They include preparation of specialised probes, optimisation of instrumentation and a lack of appropriate theoretical analysis of the tip–sample forces at the nanometre scale.

At present, tapping mode is the most common AFM mode. In its applications, researchers are always facing a problem in getting the most valuable information, which can be rationally understood. The crucial issue is a correct choice of instrumental parameters for high resolution surface imaging and compositional mapping of the heterogeneous samples, which are usually quite different to achieve these goals. The principle issue of the AFM is tip sample forces and their control. Minimisation of tip forces allows avoiding surface damage and reducing the tip sample contact area that facilitates high resolution imaging. Compositional mapping will benefit from an increase of tip forces because differences between mechanical properties will be better manifested in this case.