PROGRESS IN ATOMIC FORCE MICROSCOPY

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Chapter 1

Introduction

The invention of the Scanning Tunneling Microscope (STM) in 1981 [18] has provided a breakthrough in our possibilities to investigate matter on the atomic scale: for the first time, the individual surface atoms of flat samples could be made visible in real space. Only one year after its invention, one of the most intriguing problems in surface science was solved with the help of STM: the structure of the surface reconstruction of silicon (111)-(7×7) [19]. Gerd Binnig and Heinrich Rohrer, the inventors of the STM were rewarded with the physics Nobel prize in 1986, jointly with Ernst Ruska, the inventor of the Scanning Electron Microscope. The spectacular spatial resolution of the STM along with its elegant simplicity has helped to rapidly spread its use across the surface science community. A large number of metals and semiconductors have been investigated on the atomic scale and stunning images of the world of atoms have been created within the first few years after the inception of the STM. Some results have even fascinated the general public, e.g. the work of Eigler et al. where the STM was used to arrange individual atoms into letters only a few nanometers across [33]. In more recent experiments quantum structures have been formed from single atoms with an STM [27, 70].

The STM can only image electrically conductive samples which limits its application to imaging metals and semiconductors. But even conductors – except for a few special materials, like highly oriented pyrolytic graphite (HOPG) – cannot be studied in ambient conditions by STM but have to be investigated in an ultra-high vacuum in order to be able to prepare clean surfaces. This limitation was lifted in 1985 when Binnig, Quate and Gerber introduced the atomic force microscope (AFM) [21]. Like in the STM, a sharp tip is brought close to a sample, but rather than applying a bias
voltage and measuring the tunneling current, the force between tip and sample is measured. Because electrical conductivity of the sample is not required in AFM, the AFM can image virtually any flat solid surface. Consequently, thousands of AFMs are in use in universities, public and industrial research laboratories all over the world. However, the most of these instruments are operated in ambient conditions, where surfaces are covered with contamination layers and the atomic configuration changes constantly with adsorbing and desorbing atoms and molecules. For studying surfaces on the atomic level, an ultra-high vacuum environment is required, where it is more difficult to operate an AFM. While the inventors of AFM have anticipated true atomic resolution capability, it has taken almost a decade to achieve this feat. In addition to the requirements for performing STM with atomic resolution, AFM poses several additional challenges which are summarized in chapter 3. True atomic resolution with static AFM on inert samples was reported in the early nineties [37], [74]. However, imaging reactive surfaces like Si (111) in ultra-high vacuum by static AFM has shown that chemical bonding between the tip and sample and wear on the atomic scale prevents achieving true atomic resolution on silicon by AFM [53, 54].

The topic of this work is the establishment and improvement of AFM as a tool for surface science with a focus on true atomic resolution. Surface science requires experiments to be performed in an ultra-high vacuum. In 1994, true atomic resolution was first achieved on the Si(111)-(7×7) surface by this author [A2] with frequency modulation AFM (FM-AFM) [4]. In this experiment, a cantilever with a spring constant of \( k = 17 \) N/m was oscillating with an amplitude \( A = 340 \) Å, and the frequency shift caused by the tip-sample forces was used as the imaging signal. This result was confirmed soon after by several other groups using similar experimental parameters [61, 48, 69]. Other semiconductors [96], ionic crystals [77, 13, 83], metal oxides [35, 82], metals [68, 76], organic monolayers [44] and even a film of Xenon physisorbed on graphite [6] have been imaged with atomic resolution. In 1998, the “First International Workshop on Non-contact Atomic Force Microscopy (NC-AFM)” was held in Osaka, Japan with about 80 attendants. This meeting was followed by the second meeting in Pontresina, Switzerland in 1999 with roughly 120 participants and the third meeting in Hamburg, Germany in 2000 with more than 200 participants. The forth meeting is scheduled for September 2001 in Kyoto, Japan, and the 2002 conference will take place in Santiago de Compostela, Spain.
While FM-AFM is a well established experimental technique, even more fascinating applications and results are expected in the future. Recently, subatomic resolution was demonstrated by AFM [A9], i.e. the spatial resolution of AFM is now surpassing that of STM. AFM yields information about the strength and geometry of single chemical bonds. Despite substantial progress, the experimental techniques are still improving, and stimulating challenges remain.

This text is structured in the following fashion: Chapter 2 contains a brief review of STM with a discussion of the driving factors which are the basis for the spatial resolution of STM and a comparison with the AFM. Chapter 3 summarizes the extra challenges which are faced by AFM in addition to the conditions for the successful operation of an STM. Chapter 4 describes the experimental implementation of FM-AFM in detail. Chapter 5 shows the calculation of the imaging signal, the frequency shift, as a function of the tip-sample forces and chapter 6 contains a calculation of the vertical noise as a function of the operating parameters. A new force sensor with properties which are close to the optimal sensor properties calculated in chapter 6 is described in chapter 7. A summary and outlook is given in chapter 8 and the bibliography, ordered alphabetically by the last name of the first author, is in chapter 9. A selection of 11 articles written by this author pertinent to the topics presented in chapters 2 - 7 are printed in the appendix. The citations of these articles are marked with a prefix ‘A’.
Chapter 2

Principles of operation

2.1 Scanning Tunneling Microscope (STM)

Even though the principle of STM is explained very well in many excellent books and review articles [20, 22, 24, 45, 95, 108, 109], a brief review about STM is included here because the STM and AFM share many key features, and the additional challenges faced by AFM show up clearly in a direct comparison. Figure 2.1 shows

![Figure 2.1: Schematic setup of a scanning tunneling microscope.](image-url)
the general setup of a scanning tunneling microscope (STM): a sharp tip is mounted on a scanning device ("xyz scanner") which allows 3-dimensional positioning in $x$, $y$ and $z$ with subatomic precision. The tunneling tip is typically a wire that has been sharpened by chemical etching or mechanical grinding. W, Pt-Ir or pure Ir are often chosen as a tip material. A bias voltage $V_t$ is applied to the sample and when the distance between tip and sample is in the range of several Ångstroms, a tunneling current $I_t$ flows between the tip and sample. This current is used as the feedback signal in a $z$-feedback loop. The sample is mounted on a coarse positioning device used to bring the sample within the scanning range of the xyz scanner. Either the probe or sample can be mounted on the xyz scanner: the choice is entirely determined by practical considerations. Usually, the object that is lighter is mounted on the xyz scanner. In some SPMs, the xyz scanner is attached to the coarse positioning device. For obtaining atomic resolution, the mechanical loop consisting of probe, sample, xyz scanner and coarse positioning device needs to be stable enough such that ambient noise and other mechanical vibrations do not cause the relative position of the probe and sample to vary by more than a fraction of the diameter of an atom. This is usually achieved by a mechanically rigid design and a vibration isolation stage, which decouples the microscope from sound and other mechanical vibrations.

The approach of the sample and probe is typically monitored by an optical microscope. When the probe and sample are within a distance of a few micrometers, an automatic approach is engaged which brings the probe and sample into contact. A feedback loop adjusts $z$ such that the magnitude of the imaging signal matches its setpoint. In the "topographic mode", images are created by scanning the surface in the $xy$ plane and recording the $z$ position required to keep the imaging signal at the probe constant. In the "constant height mode", the probe is scanned rapidly such that the feedback cannot follow the atomic corrugations. The atoms are then apparent as modulations of the imaging signal which is recorded as a function of $x$ and $y$. The scanning is usually performed in a raster fashion with a fast scanning direction (sawtooth or sinusoidal signal) and a slow scanning direction (sawtooth signal). A computer controls the scanning of the surface in the $xy$ plane while recording the $z$ position of the tip (topographic mode) or the imaging signal (constant height mode). Thus, a three dimensional image $z(x, y)$ is created.
Instead of the tunneling tip, a force-sensing cantilever, an optical near-field probe, a microthermometer etc. can be mounted to the scanner, giving rise to a whole family of scanning probe microscopes [106].

### 2.1.1 Imaging signal in STM

In an STM, a sharp tip is brought close to an electrically conductive surface that is biased at a voltage $V_t$. When the separation is close enough, a current $I_t$ flows between them. The typical distance between tip and sample under these conditions is a few atomic diameters, and the transport of electrons occurs by tunneling. When $|V_t|$ is small compared to the workfunction $\Phi$, the tunneling barrier is roughly rectangular (see Fig.2.2) with a width $z$ and a height given by the workfunction $\Phi$. According to elementary quantum mechanics, the tunneling current is given by:

$$I_t(z) = I_0 e^{-2 \kappa_t z}. \quad (2.1)$$

$I_0$ is a function of the applied voltage and the density of states in both tip and sample and

$$\kappa_t = \sqrt{2 m \Phi/\hbar} \quad (2.2)$$

where $m$ is the mass of the electron and $\hbar$ is Planck’s constant. For metals, $\Phi \approx 4$ eV, thus $\kappa_t \approx 1 \text{ Å}^{-1}$. When $z$ is increased by one Ångström, the current drops by an order of magnitude. This strong distance dependence is the key reason for atomic resolution with an STM. Most of the tunneling current is carried by the atom that is closest to the sample (“front atom”). If the sample is very flat, this front atom remains the atom that is closest to the sample during scanning in $x$ and $y$ and even relatively blunt tips yield atomic resolution easily.

![Energy diagram of an idealized tunneling gap.](image)
2.1.2 Experimental measurement and noise

The tunneling current is measured with a current-to-voltage converter (see Fig. 2.3), which is usually built with a single operational amplifier (OPA) with low noise and low input bias current, and a feedback resistor with a typical impedance of \( R = 100 \, \text{M}\Omega \). The tunneling current \( I_t \) is used to measure the distance between tip and sample. The noise in the imaging signal (tunneling current in the case of STM, force or some derived quantity in the case of AFM) needs to be small enough such that the corresponding vertical noise \( \delta z \) is considerably smaller than the atomic corrugation of the sample. In the following, the noise levels for imaging signals and vertical positions are described by the root-mean-square (rms) deviation of the mean value and indicated by the prefix \( \delta \), i.e.

\[
\delta \xi \equiv \sqrt{< (\xi - < \xi >)^2 >}.
\]  

(2.3)

For achieving atomic resolution with an STM or AFM, a first necessary condition is that the mechanical vibrations between tip and sample are smaller than the atomic corrugations. This condition is met by a microscope design emphasizing utmost stability and establishing proper vibration isolation, as described in Refs. [24, 95]. In the following, proper mechanical design and vibration isolation will be presumed and not discussed further. The inherent vertical noise in an STM is connected to the noise in the current measurement. Figure 2.4 shows the qualitative dependence of the tunneling current \( I_t \) as a function of vertical distance \( z \). Because the measurement of \( I_t \) is subject to noise, the vertical distance measurement is also subject to a noise
Figure 2.4: Tunneling current as a function of distance and relation between current noise $\delta I_t$ and vertical noise $\delta z$ (arbitrary units).

level $\delta z$:

$$\delta z_t = \frac{\delta I_t}{\frac{\partial I_t}{\partial z}}.$$  \hspace{1cm} (2.4)

It is shown below, that the noise in the current measurement $\delta I_t$ is small and that $\frac{\partial I_t}{\partial z}$ is quite large, consequently the vertical noise in STM is very small.

The dominating noise source in the tunneling current is the Johnson noise of both the feedback resistor $R$ in the current amplifier, the Johnson noise in the tunneling junction, and the input noise of the operational amplifier. The Johnson noise density of a resistor $R$ at temperature $T$ is given by [52]:

$$n_R = \sqrt{4k_BTR}$$  \hspace{1cm} (2.5)

where $k_B$ is the Boltzmann constant. In typical STMs, the tunneling current is of the order of $I_t \approx 100$ pA and measured with an acquisition bandwidth of $B \approx 1$ kHz. With a gain of $V/I = R = 100$ M$\Omega$ and $T = 300$ K, the rms voltage noise is $n_i \sqrt{B} = \sqrt{4k_BTRB} = 40\mu V$ at room temperature, corresponding to a current noise of $\delta I_t = 0.4$ pA. With Eqs. 2.1 and 2.4, the vertical noise is

$$\delta z_t \approx \frac{\sqrt{4k_BTR}}{2n_iI_t}$$  \hspace{1cm} (2.6)

which amounts to a $z$-noise of 0.2 pm in the present example. Thus, in STM the noise in the tunneling current is not a problem, because it is much smaller than the required resolution.
The spectacular spatial resolution and relative ease of obtaining atomic resolution by STM rests on three properties of the tunneling current:

- As a consequence of the strong distance dependence of the tunneling current, even with a relatively blunt tip the chance is high that a single atom protrudes far enough out of the tip such that it carries the main part of the tunneling current;

- Typical tunneling currents are in the nano-ampere range - measuring currents of this magnitude can be done with a very good signal to noise ratio even with a simple experimental setup;

- Because the tunneling current is a monotonic function of the tip-sample distance, it is easy to establish a feedback loop which controls the distance such that the current is constant.

It is shown in the next section, that neither of these conditions is met in the case of the AFM and therefore, substantial hurdles had to be overcome before atomic resolution by AFM became possible.
2.2 Atomic Force Microscope (AFM)

Early on in the development of STM it became evident, that the forces which act between the tip and sample lead to elastic deformations of tip and sample which can cause artifacts like "giant corrugations"[81, 110] or a modified dependence of $I_t(z)$. It was found that these forces could be put to good use in the Atomic Force Microscope (AFM), introduced in 1985 by Binnig, Quate and Gerber [21].

2.2.1 Imaging signal in AFM

![Schematic view of an AFM tip close to a sample.](image)

Figure 2.5: Schematic view of an AFM tip close to a sample.

Figure 2.5 shows a sharp tip close to a sample. The potential energy between the tip and sample $V_{ts}$ causes a $z$ component of the tip-sample force $F_{ts}=-\frac{\partial V_{ts}}{\partial z}$ and a "tip-sample spring constant" $k_{ts}=-\frac{\partial^2 V_{ts}}{\partial z^2}$. Depending on the mode of operation, the AFM uses $F_{ts}$ or some entity derived from $F_{ts}$ as the imaging signal.

Unlike the tunneling current, which has a very strong distance dependence, $F_{ts}$ has long- and short-range contributions. We can classify the contributions by their range and strength. In vacuum, there are van-der-Waals, electrostatic and magnetic forces with a long range (up to 100 nm) and short range chemical forces (fractions of nm). In ambient conditions, also meniscus forces formed by adhesion layers on tip and sample (water or hydrocarbons) can be present.

The van-der-Waals interaction is caused by fluctuations in the electric dipole moment of atoms and their mutual polarization. For two atoms at distance $z$, the energy varies as $1/\!z^6$ [15]. Assuming additivity and disregarding the discrete nature of matter by replacing the sum over individual atoms by an integration over a volume with
a continuous number density of atoms, the van-der-Waals interaction between macroscopic bodies can be calculated ("Hamaker approach") [49]. This approach does not account for retardation effects due to the finite speed of light and is therefore only appropriate for distances up to several hundred Ångströms. For a spherical tip with radius $R$ next to a flat surface ($z$ is the distance between the plane connecting the centers of the surface atoms and the center of the closest tip atom) the van-der-Waals potential is given by [55]:

$$V_{LL} = -\frac{A_H R}{6z}. \quad (2.7)$$

The "Hamaker constant" $A_H$ depends on the type of materials (atomic polarizability and density) of the tip and sample. For most solids and interactions across vacuum, $A_H$ is of the order of 1 eV. For a list of $A_H$ for various materials, see [63]. The van-der-Waals interaction can be quite large – the typical radius of an etched metal tip is 100 nm and with $z = 0.5$ nm, the van-der-Waals energy is $\approx -30$ eV, and the corresponding force is $\approx -10$ nN.

A more modern approach to the calculation of van-der-Waals forces is described in [50], and other tip shapes are treated in [A4].

When the tip and sample are both conductive and have an electrostatic potential difference $U \neq 0$, electrostatic forces are important. For a spherical tip with radius $R$, the potential energy is given by [88]

$$V_{electrostatic}(z) = 2\pi \epsilon_0 R \sum_{\alpha=2}^{\infty} \frac{\sinh(\alpha)}{\sinh(n\alpha)} U^2 \quad (2.8)$$

with

$$\alpha = \ln\left(1 + \frac{z}{R} \left(1 + \sqrt{1 + 2\frac{R}{z}}\right)\right). \quad (2.9)$$

Like the van-der-Waals interaction, the electrostatic interaction can also cause large forces - for a tip radius of 100 nm, $U = 1$ V and $z = 0.5$ nm, the electrostatic energy is $\approx -89$ eV, and the corresponding force is $\approx -5.5$ nN.

Electrostatic forces also arise in the imaging of ionic crystals, where the envelope of the electrostatic field has an exponential distance dependence [38].

Chemical forces are more difficult to describe. Empirical model potentials for chemical bonds are the Morse Potential (see e.g. [55]).

$$V_{Morse} = -E_{\text{bond}} \left( 2e^{-\alpha(z-\sigma)} - e^{-2\alpha(z-\sigma)} \right) \quad (2.10)$$
and the Lennard-Jones potential [12, 55]:

\[ V_{\text{Lennard-Jones}} = -E_{\text{bond}}(2 \frac{z^6}{\sigma^6} - \frac{z^{12}}{\sigma^{12}}). \]  

(2.11)

These potentials describe a chemical bond with bonding energy \( E_{\text{bond}} \) and equilibrium distance \( \sigma \). The Morse potential has an additional parameter – a decay length \( \kappa \). While the Morse potential can be used for a qualitative description of chemical forces, it lacks an important property of chemical bonds: chemical bonds, especially covalent bonds show an inherent angular dependence of the bonding strength [26, 78]. Therefore, more sophisticated models like the Stillinger-Weber potential [94] are used in a more detailed description of the chemical interaction [A9].

More information about tip-sample forces can be found in Refs. [25, 55, 79, 80, 88, A4, A7] and references therein.

### 2.2.2 Experimental measurement and noise

Forces between the tip and sample are typically measured by recording the deflection of a cantilever beam that has a tip mounted to its end (see Fig. 2.6). While simple cantilevers can be cut from household tin foil [86], high-quality cantilevers are mainly built by micromachining silicon, where pioneering work was done in the group of Calvin F. Quate [2, 3, 100] and at IBM [111].

The cantilever bends in response to the forces between tip and sample. The cantilever is characterized by its spring constant \( k \), eigenfrequency \( f_0 \) and quality factor \( Q \). For

![Figure 2.6: Top view and side view of a microfabricated silicon cantilever (schematic).](image-url)
a rectangular cantilever with dimensions $w, t$ and $L$ (see Fig. 2.6), the spring constant $k$ is given by [24]:

$$k = \frac{E_Y wt^3}{4L^3}.$$  \hfill (2.12)

where $E_Y$ is Young’s modulus. The eigenfrequency $f_0$ is given by [24]:

$$f_0 = 0.162 \frac{t}{L^2} \sqrt{\frac{E_Y}{\rho}}$$  \hfill (2.13)

where $\rho$ is the mass density of the cantilever material. The $Q$-factor depends on the damping mechanisms present in the cantilever. For micromachined cantilevers operated in air, $Q$ is typically a few hundred while in vacuum, $Q$ can reach hundreds of thousands.

In the first AFM, the deflection of the cantilever was measured with an STM - the backside of the cantilever was metalized, and a tunneling tip was brought close to it to measure the deflection [21]. While the tunneling effect is very sensitive to distance variations, this method has a number of drawbacks. The tunneling tip also exerts forces on the cantilever, and it is quite difficult to position a tunneling tip close to a cantilever. Subsequent designs used optical (interferometer, beam-bounce) or electrical methods (piezoresistive, piezoelectric) for measuring the cantilever deflection. A discussion of the various techniques can be found in [88], and the appendix contains descriptions of piezoresistive [A1, A3] and piezoelectric [A5, A8] methods.

The deflection of the cantilever is subject to thermal drift and other noise factors. This can be expressed in a plot of the deflection noise density versus frequency. A typical noise density is plotted in Fig. 2.7. The noise density has a $1/f$ dependence for low frequency and merges into a constant noise density (“white noise”) above the “$1/f$ corner frequency”. This $1/f$ noise is also apparent in other force sensing devices, such as scales. Typically, scales have a reset or zero button, which allows the user to reset the effects of long-term drift. Machining AFMs from materials with low thermal expansion coefficients like Invar or operation at low temperatures helps to minimize $1/f$ noise.

In the dynamic operating modes (see next section), drifts in $f_0$ also add to the vertical noise. This is discussed in detail on page 45.
2.3 Operating Modes of AFMs

2.3.1 Static AFM

In the case of the AFM, the force $F_{ls}$ which acts between the tip and sample is used as the imaging signal. In the static mode of operation, the force translates into a deflection $q = F_{ls}/k$ of the cantilever. Because the deflection of the cantilever should be significantly larger than the deformation of the tip and sample, restrictions on the useful range of $k$ apply. In the static mode, the cantilever should be much softer than the bonds between the bulk atoms in tip and sample. Interatomic force constants in solids are in a range from 10 N/m to about 100 N/m - in biological samples, they can be as small as 0.1 N/m. Thus, typical values for $k$ in the static mode are $0.01 - 5$ N/m.

The eigenfrequency $f_0$ should be significantly higher than the desired detection bandwidth, i.e., if 10 lines per second are recorded during imaging a width of say 100 atoms, $f_0$ should be at least $10 \times 2 \times 100 \text{ s}^{-1} = 2 \text{ kHz}$ in order to prevent resonant excitation of the cantilever.

Even though it has been demonstrated that atomic resolution is possible with static AFM, the method can only be applied in certain cases. The detrimental effects of $1/f$-noise can be limited by working at low temperatures [38], where the coefficients of thermal expansion are very small or by building the AFM of a material with a
low thermal expansion coefficient [74]. The long-range attractive forces have to be
cancelled by immersing tip and sample in a liquid [74] or by partly compensating
the attractive force by pulling at the cantilever after jump-to-contact has occurred
[37, 38, 39]. Jarvis et al. have cancelled the long-range attractive force with an elec-
tromagnetic force applied to the cantilever [57, 58]. Even with these restrictions,
static AFM does not produce atomic resolution on reactive surfaces like silicon, as
the chemical bonding of AFM tip and sample pose an unsurmountable problem [53].
While the experimental implication of static AFM is difficult, the physical interpre-
tation of static AFM images is simple: The image is a map $z(x, y, F_{ts} = \text{const.})$.

2.3.2 Dynamic AFM

In the dynamic operation modes, the cantilever is deliberately vibrated. The can-
tilever is mounted onto an actuator to allow an external excitation of an oscillation.
There are two basic methods of dynamic operation: amplitude modulation (AM) -
and frequency modulation (FM) operation. In AM-AFM [71], the actuator is driven
by a fixed amplitude $A_{drive}$ at a fixed frequency $f_{drive}$ where $f_{exc}$ is close to but differ-
ent from $f_0$. When the tip approaches the sample, elastic and inelastic interactions
cause a change in both the amplitude and the phase (relative to the driving signal)
of the cantilever. These changes are used as the feedback signal. The change in am-
plitude in AM mode does not occur instantaneously with a change in the tip-sample
interaction, but on a timescale of $\tau_{AM} \approx 2Q/f_0$. With $Q$-factors reaching 100000 in
vacuum, this means that the AM mode is very slow. Albrecht and coworkers found a
way around this problem by introducing the frequency modulation (FM) mode [4],
where the change in the eigenfrequency settles on a timescale of $\tau_{FM} \approx 1/f_0$.

Both AM and FM modes were initially meant to be “non-contact” modes, i.e. the
cantilever was far away from the surface and the net force between the front atom
of the tip and the sample was clearly attractive. The AM mode was later used very
successfully at a closer distance range in ambient conditions involving repulsive tip-
sample interactions (“Tapping Mode”[112]) and Erlandsson et al. obtained atomic
resolution on Si in vacuum with an etched tungsten cantilever operated in AM mode
in 1996 [34]. Using the FM mode, the resolution was improved dramatically [A1, 40]
and finally atomic resolution [A2] was obtained by reducing the tip sample distance and working in vacuum. While it was believed initially that the net force between the front atom of the tip and the sample has to be attractive when atomic resolution is desired, this view has been challenged recently [93]. Nevertheless, the dynamic modes are commonly still called “non-contact” modes and the conference series which covers AFM with atomic resolution in vacuum is named “International Conference on Non-contact Atomic Force Microscopy”. It is noted, that the definition of “contact” between two objects (tip and sample) is difficult when looking on atomic length scales – even though on a macroscopic scale the definition of “contact” between two objects is perfectly clear. What is commonly understood by ‘Non-contact AFM’ is that neither tip nor sample suffer permanent deformations or wear during the imaging process – no matter whether the force between tip and sample or the force between the front atom of the tip and the sample is attractive or repulsive. For atomic studies in vacuum, the FM-mode is now the preferred AFM technique. A detailed description of the FM-mode is given in chapter 4.
Chapter 3

The four additional challenges faced by AFM

In a scanning tunneling microscope, a tip has to be scanned across a surface with a precision of fractions of an Ångström while a feedback mechanism adjusts the $z$-position such that the tunneling current is constant. This task seems daunting and the successful realization of STM is an amazing accomplishment. Yet, implementing an AFM capable of atomic resolution poses even more obstacles than the operation of an STM. Some of the additional challenges faced by AFM are apparent by comparing the tunneling current and tip sample force as a function of distance (Fig. 3.1). The

![Graph showing tunneling current and force as a function of distance](image)

Figure 3.1: Plot of tunneling current $I_t$ and force $F_{ts}$ (typical values) as a function of distance $z$ between front atom and surface atom layer.
tunneling current is a monotonic function of the tip-sample distance and has a very sharp distance dependence. In contrast, the tip-sample force has long- and short-range components and is not monotonic.

3.1 Jump-to-contact problem

Van-der-Waals forces in vacuum are always attractive, and if chemical bonding between tip and sample can occur the chemical forces are also attractive for distances larger than the equilibrium distance. Because the tip is mounted on a spring, approaching the tip can cause a sudden “jump to contact” when the stiffness of the cantilever is smaller than a certain value.

This instability occurs in the quasistatic mode if [98, 23]

\[ k > \max\left(-\frac{\partial^2 V_{ts}}{\partial z^2}\right) = k_{ts}^{\text{max}}. \] (3.1)

The jump to contact can be avoided even for soft cantilevers by oscillating it at a large enough amplitude \( A \) [A3]:

\[ kA > \max(-F_{ts}) = F_{ts}^{\text{max}}. \] (3.2)

It has been found empirically (see column 5 in table 4.1), that \( kA \approx 200 \) nN for avoiding this instability. With typical spring constants of \( k \approx 20 \) N/m, amplitudes in the range of \( A \approx 10 \) nm are required. However, using large amplitudes has critical disadvantages, which are discussed in chapter 6.

3.2 Non-monotonic imaging signal

The magnitude of the tunneling current increases continuously as the tip-sample distance decreases, i.e. the tunneling current is a strictly monotonic decreasing function of the distance (see Fig. 2.4 on page 11). This property allows a simple implementation of a feedback loop: the tunneling current is fed into a logarithmic amplifier to produce an error signal that is linear with the tip-sample distance.

In contrast, the tip-sample force is not monotonic. In general, the force is attractive for large distances and upon decreasing the distance between tip and sample, the
force turns repulsive (see Fig. 3.1). Stable feedback is only possible on a branch of the force curve, where it is monotonic.

Because the tunneling current is monotonic for the whole distance range and the tip-sample force is not monotonic, it is much easier to establish a $z-$ distance feedback loop for STMs than for AFMs.

### 3.3 Contribution of long-range forces

The force between tip and sample is composed of many contributions: electrostatic, magnetic, van-der-Waals and chemical forces in vacuum. In ambient conditions there are also meniscus forces. While electrostatic-, magnetic- and meniscus forces can be eliminated by working in vacuum with nonmagnetic tips and equalizing the electrostatic potential between tip and sample, the van-der-Waals forces cannot be switched off. For imaging by AFM with atomic resolution, it is desirable to filter out the long-range force contributions and only measure the force components which vary at the atomic scale. In STM, the strong distance dependence of the tunneling current naturally enables high resolution. While there is no way to discriminate between long- and short-range forces in static AFM, it is shown in section 5.2 that it is possible to enhance the short-range contributions in dynamic AFM by proper choice of the oscillation amplitude $A$ of the cantilever.

### 3.4 Noise in the imaging signal

Forces can be measured by the deflection of a spring. However, measuring the deflection is not a trivial task and is subject to noise, especially at low frequencies ($1/f$ noise). In static AFM, the imaging signal is given by the dc deflection of the cantilever, which is subject to $1/f$ noise. In dynamic AFM, the low-frequency noise is discriminated if the eigenfrequency $f_0$ is larger than the $1/f$ corner frequency. With a bandpass filter with a center frequency around $f_0$ only the white noise density is integrated across the bandwidth $B$ of the bandpass filter.

Frequency modulation AFM, described in detail in chapter 4, helps to overcome three
of these four challenges. The non-monotonic imaging signal in AFM is a remaining complication for FM-AFM.
Chapter 9

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