AFM Theory

The basic principle of AFM is very simple. The AFM detects the force interaction between a sample and a very tiny tip (<10 nm radius) mounted on a cantilever, which is generally described by the Lennard-Jones potential (*Figure 12*). 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 tip sample interaction then results as the superposition of the single interaction

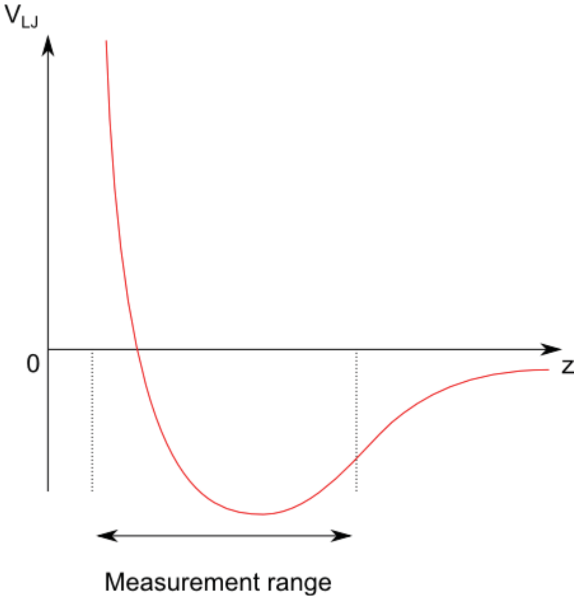

Figure 12: Lennard-Jones potential resulting in long range attraction and short range repulsion. The measurement range of the AFM is indicated.

AFM setup

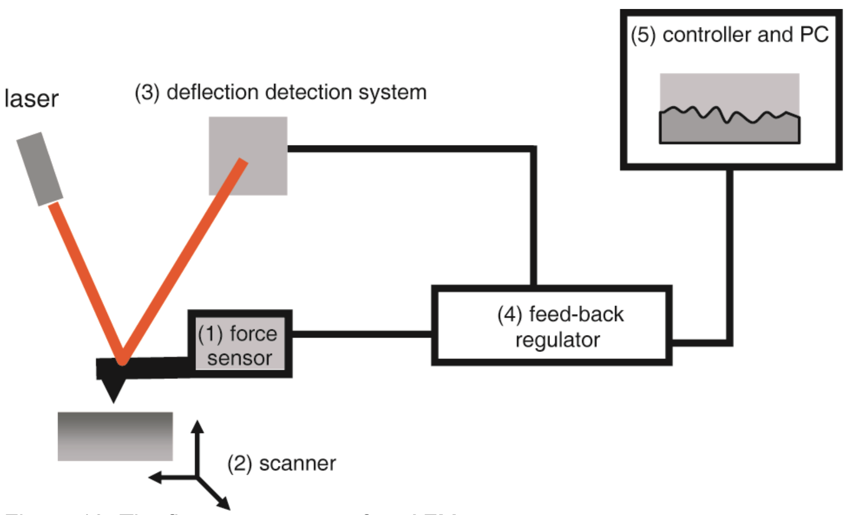

Figure 13: The five components of an AFM setup.

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Independently of the type of tip-sample interaction an AFM basically consist of five major parts shown in *Figure 13* and described in the following sections:

1. A force sensor, which is basically a sharp tip (< 10 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 piezo-resistive 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 ta personal computer software.

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 Section *The Force Sensor*. The deflection detection system needs to be very sensitive and can be implemented in different ways which will be discussed in Section *The Deflection Detector*. The feedback system will be described in Section *The PID Feedback System*. The AFM can be operated in different modes which will be discussed in Section *AFM Operating Mode*. Finally, Section *The Scanning System and Data Collection* will deal with the positioning or scanning system which needs to provide nanometer resolution.

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 wide and around one micrometer thick. For silicon these dimensions will

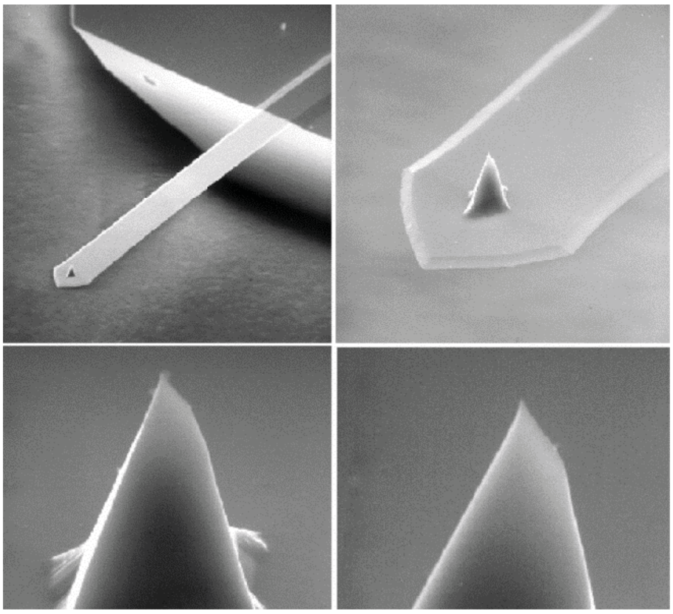

Figure 14: Tip and cantilever of an AFM probe.

result in spring constants between 0.1 and 1 N/m and resonance frequencies between 10 and 100 kHz.
Thanks to recent developments in microtechnology it is possible to fabricate cantilevers with integrated sharp tips. It is important to keep in mind that 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

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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:

1. Contact Mode (see Section *AFM Operating 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.
2. Dynamic mode (see Section *AFM Operating Modes*): The portion of perturbation transmitted to the cantilever is given by $a_{trans} = a_0 \left(\frac{f_0}{f_{ex}}\right)^2$, where f_{ex} is the excitation 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.

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 13: 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 too 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 measurement of deflections below one angstrom.
Other cantilever deflection detection techniques, which will not be discussed here, are:

- Interferometric optical systems
- Piezoresistive detection

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 15: PID controller.*

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

1. Proportional Gain
2. Integral Gain
3. Differential Gain

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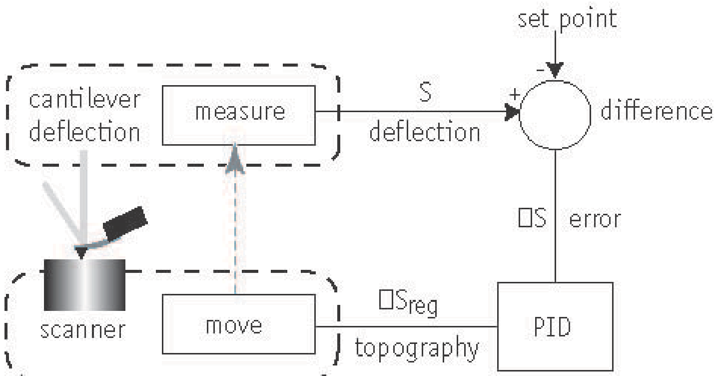

Figure 15: PID controller

These three gains can be set individually and define how fast and in which manner the error is minimized 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 16: Step*). The goal is to reproduce the rectangular step as precisely as possible. Hence the PID gains must be adjusted. *Figure 17: P-Gain* shows the result when only the proportional gain (P) is turned up. The topography shows a long rise time (slope), an 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 18: 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 (I) the D gain is turned down and the I gain up. As can be observed in *Figure 19: 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 20: 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.

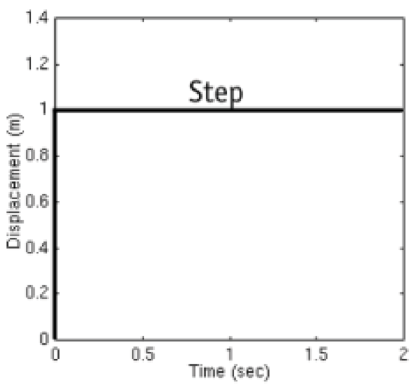

Figure 16: Step

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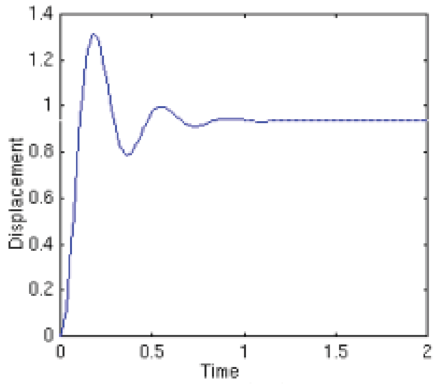

Figure 17: P-Gain

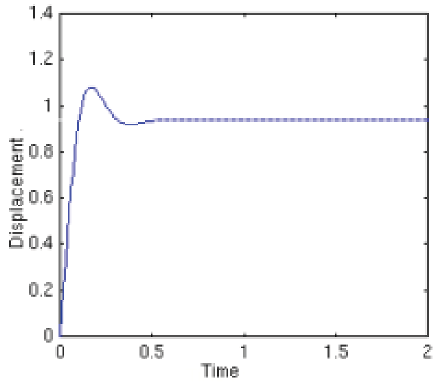

Figure 18: PD-Gain

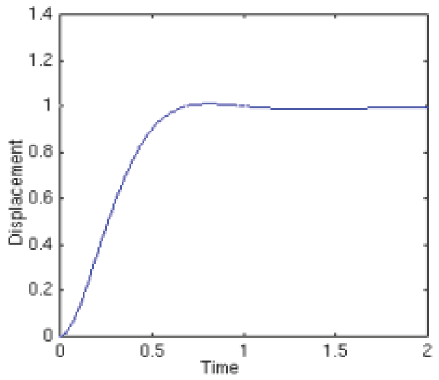

Figure 19: PI-Gain

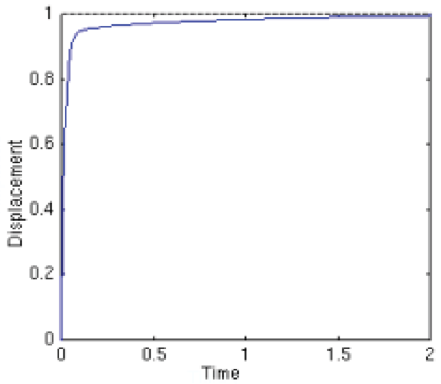

Figure 20: PID-Gain

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AFM Operating 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: static (contact) and dynamic (tapping) mode.

Static Mode

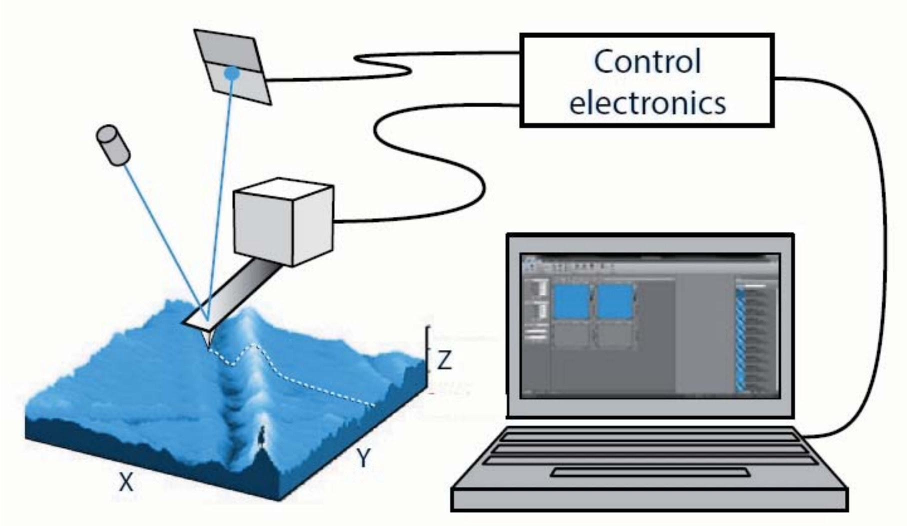

Figure 21: AFM setup in static mode.

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 and samples might easily be damaged 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 percentage 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.

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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 realized in several ways. There are different implementations, e.g. piezoelectric, electromagnetic etc. As described in Section *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 color code.

Task 2: Investigate the influence of the scanning parameters on the imaging quality and performance, e.g. PID gain, setpoint (force), vibrational amplitude, and scanning speed. Use both static and dynamic force mode.

In the following the optimization of the most important measurement parameters is shown. By applying the shown steps basically any sample can be imaged, as long as its height variation across the scan is in the operating range of the device.

Influence of PID-gain
Since the chip structures are so well defined, this sample is conducive to testing the effects of your instrument's gain settings. The gain settings play an important role regarding image quality for all measurement modes of the AFM.

Image acquisition
1. Set a large scan range, somewhere between 10 and 80 µm. The chip structure can be clearly seen at this size.
2. Approach the reflective part at the center of the sample. This is the section that contains the most interesting structures of the chip. Note the well-ordered, repeating pattern. The height of the structures (or rather: the depth of the trench) is approximately 1.6 µm.

CAUTION
Excessively high or low gains can result in damaged to the tip. Monitor your system carefully when adjusting the gains.

Optimize your gain settings
- If you have not already done so, make sure your gains are set to levels that produce reasonable images. The line trace in *Figure 24: Optimized Gain* represents well optimized gain settings; the tip is accurately tracking the topography of the SCA sample.

Lowering the gain
- Lower the integral gain well below the optimal setting. As you lower the gain, the feedback loop will not work quickly enough to provide high resolution. Note the poorly defined edges in *Figure 25: Low Gain*. At a lowered gain, the feedback loop is not responding quickly enough to respond to changes in height.

Raising the gain
- Gradually raise the gain to well above the optimal settings. At some point, the Z-controller will start to overcompensate for feedback errors when the tip encounters steps in the sample. This overcompensation is also called overshoot.

Overshoot and Undershoot
When the gain settings are increased further, the controller will react to this overshoot by undershooting; the undershoot will be less than the overshoot. These overreactions initiate an oscillation that eventually subsides. The frequency of this oscillation is either the mechanical resonance frequency of the

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scanner or the resonance frequency of the cantilever itself.

At even higher gains, the oscillation will no longer subside. Instead, it will steadily increase, most likely resulting in damage to the cantilever tip. The oscillation should be visible in both the topography and the error signal (deflection or amplitude, depending on the measurement mode) images. Be sure to monitor your system for indications that the controller is becoming unstable. First it will overshoot, and then it will “ring”, which is represented by a vibration with decreasing amplitude at the step edges. Additionally, the error signal (in this case the cantilever deflection) will start to increase again.
The following scans are performed in dynamic mode using a corresponding cantilever. Remember selecting the right cantilever in the *Acquisition* tab, too. The obervations are basically the same when measuring in contact mode. However, in contact mode the tip or sample might get damaged easier if the gain values are not set correctly.

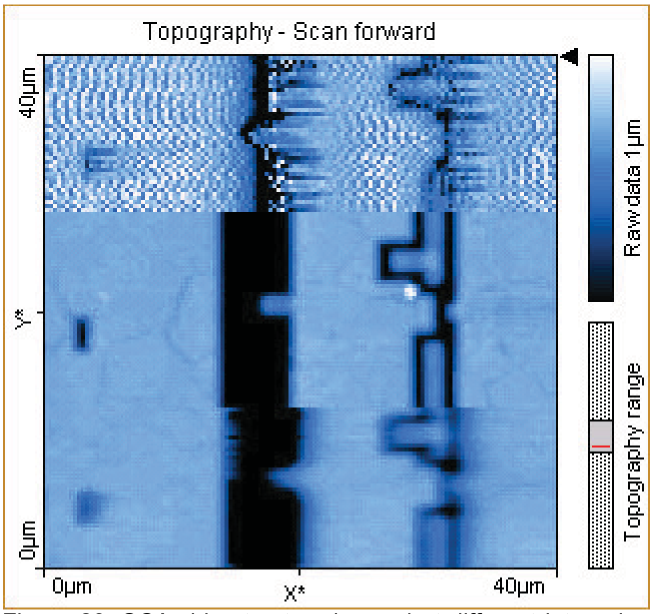

Figure 23: SCA chip structure imaged at different integral gain settings. In the lowest region of the image, the gain is too low; at the center, it is optimized; at the top, it is too high.

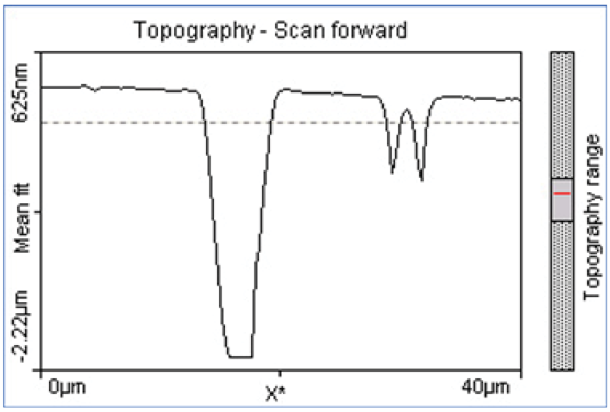

Figure 24: Optimized Gain. Optimized gain setting for SCA chip structure

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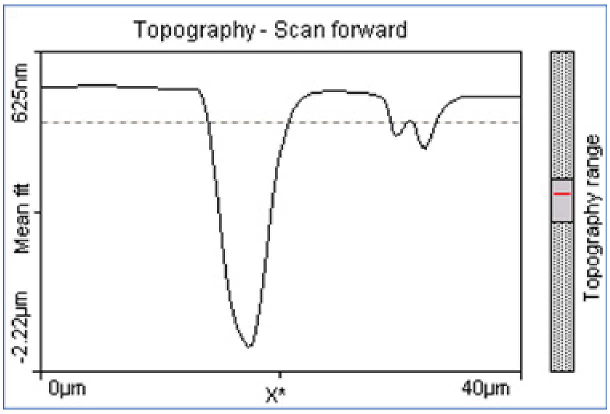

Figure 25: Low Gain. The feedback loop is not responding quickly enough.

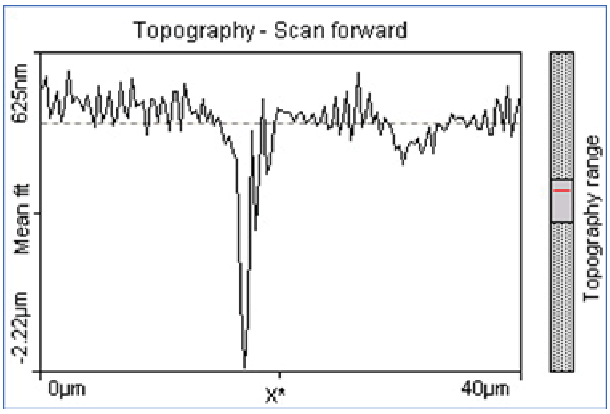

Figure 26: High Gain. Oscillating signal when gain is set too high.

As seen in the scans too low gain settings result in blurry images of the measured structures and too high gain will result in oscillations. Either extreme might damage the tip. Therefore, it is recommended to use the *Auto Set* function which will provide reasonable gain settings to start with. However, in general further optimization of the gain is necessary to get the best possible results.

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CD stamper

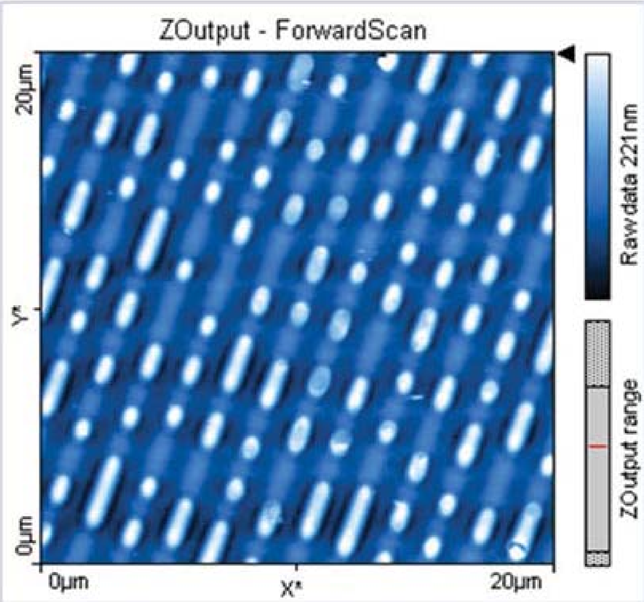

Figure 33: 20-µm Image of CD Stamper. Note that the curvature of the tracks is not discernible at this scan size.

Image acquisition

1. Set a large scan range, approximately 50 µm. At this size, you can see many bumps, and it is even possible to make out the curvature of the rows (tracks). Each bump is approximately 200 nm high.
2. Practice zooming in on individual bumps. This sample is good for practicing zooming in on individual surface features, as bumps are visible at a variety of scan sizes.
3. Take an image of well-ordered bumps at least 5 or 6 tracks wide. Try to get an image similar to *Figure 33: 20-µm Image of CD Stamper*, which is suitable for measuring the bump length (*Figure 34: Bump length*). Furthermore, you can determine the track distance if interested.

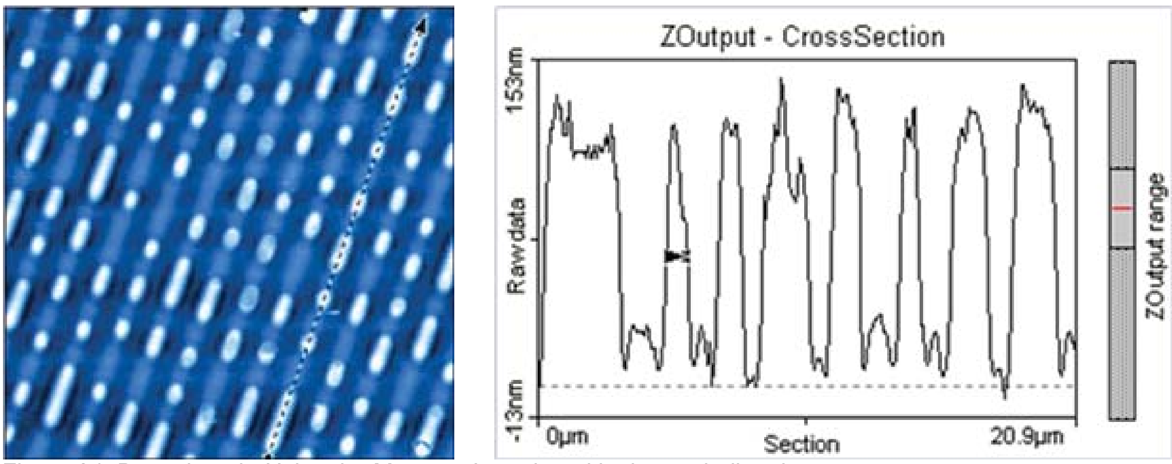

Figure 34: Bump length. Using the Measure Length tool in the track direction.

The size of CD and DVD structures must be very well-defined, and this requirement is well served by the measurement evaluation tools in AFM software, which is demonstrated in this measurement.

The CD stamper sample contains a piece of the master copy of a CD. This is the original that creates the imprint in the pressed CD that you listen to. A CD has small indentations, called pits, whereas the stamper has bumps in the corresponding places.

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