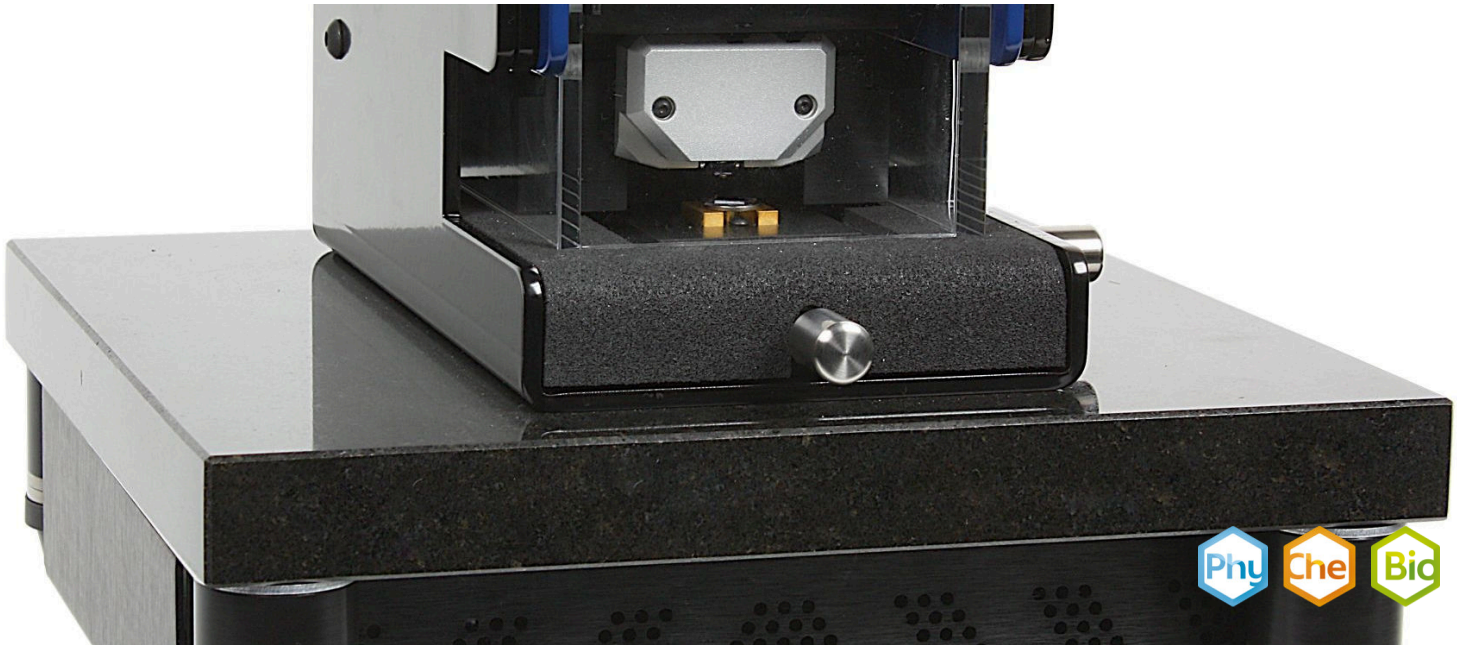
Basic methods in imaging of micro and nanostructures with AFM (Atomic Force Microscopy)



Biology > Modern Imaging Methods in Biology

Applied Science > Medicine > Histology & Medical Microbiology

Difficulty level	Group size	Preparation time	Execution time
hard	2	10 minutes	45+ minutes

This content can also be found online at:

http://localhost:1337/c/5fdb8e275098f00003f1ed42

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General information

Application

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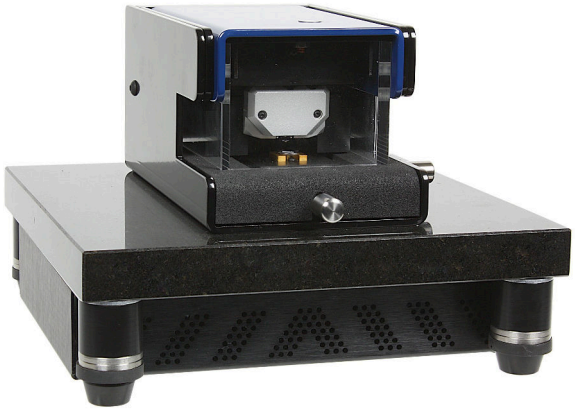

PHYWE Atomic Force Microscope

An Atomic Force Microscope (AFM) is a type of high-resolution microscope that uses a mechanical probe to map the surface of a sample at the nanometer scale. It works by moving a sharp tip attached to a cantilever very close to the sample surface. As the tip scans the surface, it experiences forces from the sample, causing the cantilever to deflect. These deflections are measured and used to create detailed, three-dimensional images of the surface.

AFMs are used in various fields such as materials science, biology, and nanotechnology to observe surface characteristics, measure mechanical properties, and manipulate nanoscale features of materials.

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Other information (1/2)

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Prior knowledge

The prior knowlege required for this experiment is found in the theory section.

Main principle

Approaching a sharp silicon tip mounted on a cantilever to a sample surface leads to an atomic scale interaction. The results is a bend of the cantilever which is detected by a Laser. In static mode the resulting deflection is used to investigate the topography of the sample surface line-by-line using a feedback loop. In dynamic mode the cantilever is oscillated at fixed frequency resulting in a damped amplitude near the surface. The measurement parameters (setpoint, feedback gain,…) play a crucial role for image quality. The dependence on the imaging quality is investigated for different nano structured samples.

Other information (2/2)

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Learning objective

The goal of this experiment is to learn the usage of a AFM.

Tasks

1. Set up the microscope and start up the software. Mount a cantilever (with tip) and approach the tip towards a sample.
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
3. Image 7 different samples (microstructures, carbon nano tubes, skin cross-section, bacteria, CD stamper, chip structure, glass beads) by optimizing the parameters respectively.

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Theory (1/17)

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AFM

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 1). 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 interactions.

Theory (2/17)

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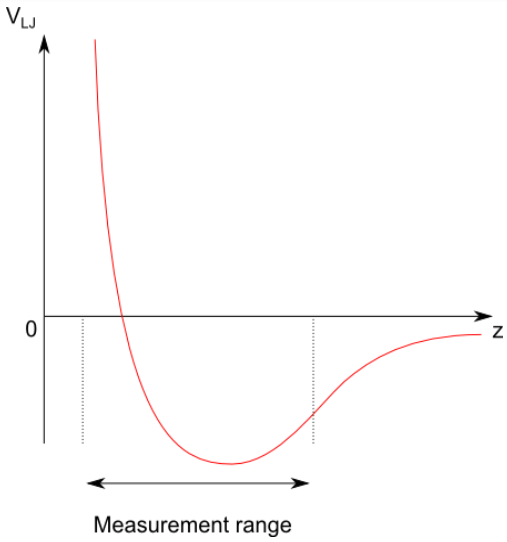

Figure 1: Lennard-Jones potential resulting in long range attraction and short range repulsion. The measurement range of the AFM is

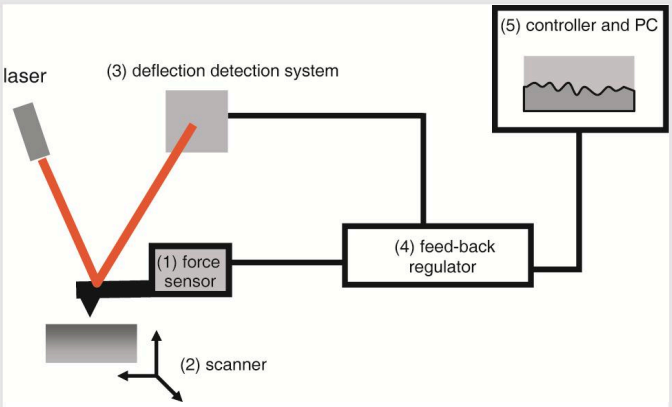

Figure 2: The five components of an AFM setup.

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Theory (3/17)

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Independently of the type of tip-sample interaction an AFM basically consist of five major parts shown in Figure 2 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 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 ta personal computer software.

Theory (4/17)

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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.

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Theory (5/17)

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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 result in spring constants between 0.1 and 1 N/m and resonance frequencies between 10 and 100 kHz.

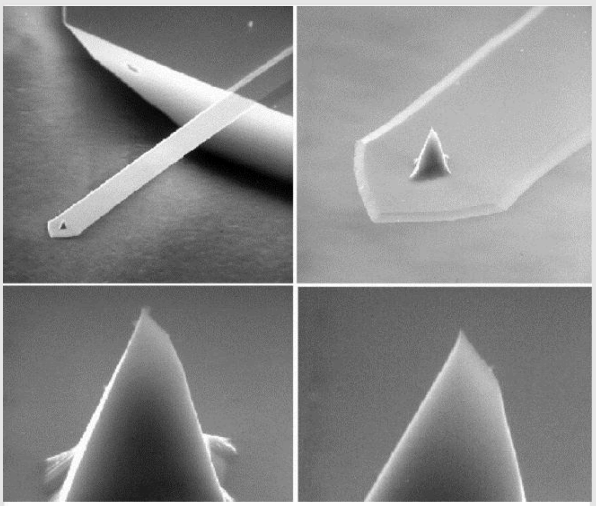

Fig 3: Tip and cantilever of an AFM probe.

Theory (6/17)

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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 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.

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Theory (7/17)

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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 , where is the excitation vibration frequency with amplitude and 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.

Theory (8/17)

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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 and Piezoresistive detection

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Theory (9/17)

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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 . 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 4: PID controller.

Theory (10/17)

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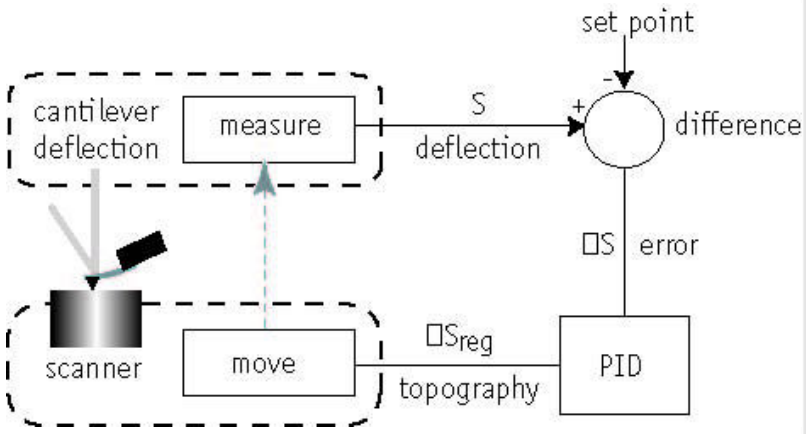

Figure 4: PID controller

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 5: Step).

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Theory (11/17)

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The goal is to reproduce the rectangular step as precisely as possible. Hence the PID gains must be adjusted. Figure 6: 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 7: 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 8: PI-Gain the I controller further reduced the overshoot and decreased the settling time.

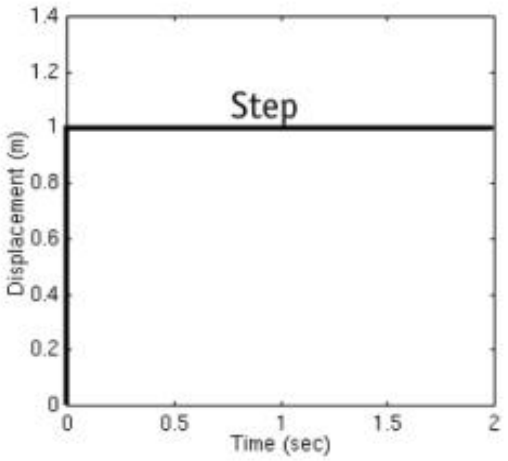

Figure 5: Step

Theory (12/17)

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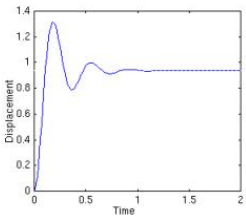


Fig 6: P-Gain

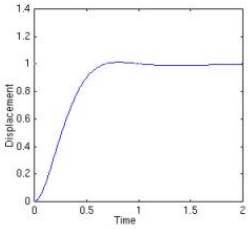


Fig 8: PI-Gain

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 9: 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.

Fig 7: PD-Gain

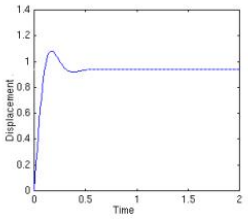
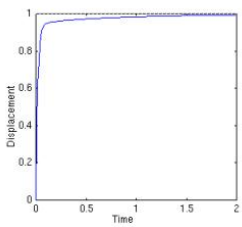


Fig 9: PID-Gain



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Theory (13/17)

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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: 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 setpoint 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.

Theory (13/17)

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Theory (14/17)

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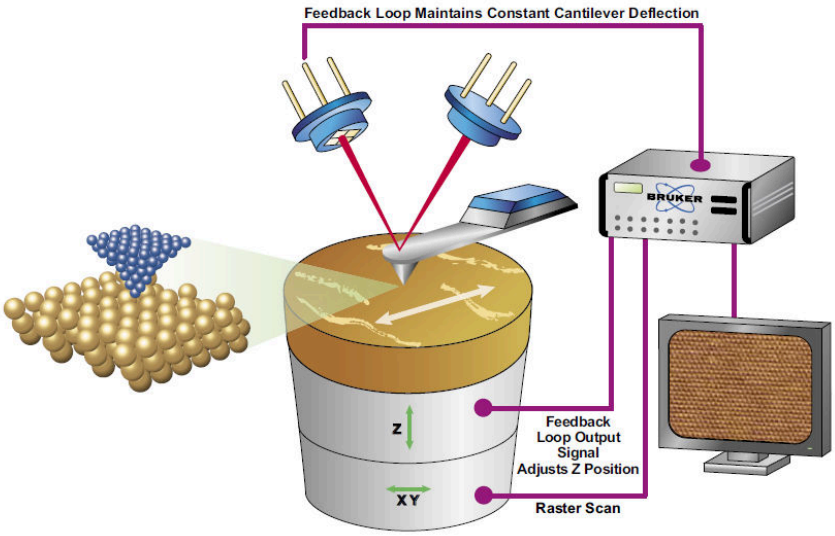

Figure 10: AFM setup in static mode.

Theory (15/17)

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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.

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Theory (16/17)

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.

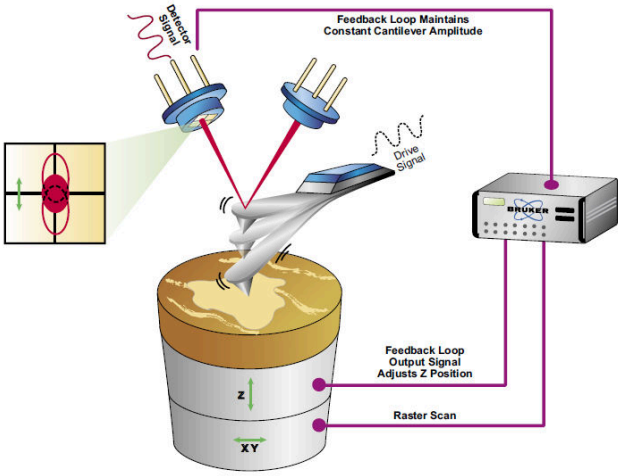

Figure 11: AFM setup in dynamic mode.

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Equipment

Position	Material	Item No.	Quantity
1	Compact AFM, Atomic Force Microscope	09700-99	1

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Equipment

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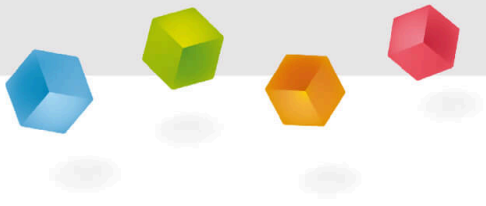

Setup and Procedure

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Setup (1/2)

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Setting-up the Microscope

Place the instrument on a stable support (a very steady table or bench) in a location that has a low level of building vibrations (perhaps in the basement), acoustic noise (you should close the door and inform everybody around you to be as quiet as possible when they pass your set-up), electrical fields (set up your system several meters away from power switches or high powered machines), and air currents (don't set up under your air conditioning or near radiators).

Make sure that the mains power connection is protected against excess voltage surges (a power connection with built in security circuits is recommended). If you notice very high noise signals in your measurements later on you can try to protect your microscope by placing it under a plexiglass or cardboard box.

Setup (2/2)

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Connecting the Microscope

To initiate the automatic hardware recognition, follow these steps:

1. Log on to your computer with Administrator privileges.
2. Connect your computer with the supplied USB cable to the microscope control unit.
3. Press the power button on the side of your microscope next to the USB connection. A blue LED will light up.

A popup balloon appears in the Windows notification area, stating that a new hardware device has been found and drivers are being installed.

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Procedure (1/30)

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Start the PHYWE Measure Nano software and make sure the correct calibration files are loaded:

1. Open the menu item “File” >> “Parameters” >> “Load...”, and load the file “Default_AFM.par” from the directory that holds the default Measure Nano configurations. Usually this is “C:\Program Files (x86)\PHYWE\measure nano\Config”.
2. Open the menu item “File” >> “Chart Arrangement” >> “Load...”, and load the file “Default_AFM.chart” from the directory that holds the default Measure Nano configurations.

Procedure (2/30)

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Software interface

The software provides all functions to operate the microscope during imaging of surfaces and more advanced operating modes. It also provides data analysis functions for post-processing of measurement data.

The main STM Control Software window (also referred to as workspace) consists of five major areas (Figure 12):
(1) The Measurement pane on the left. This area contains the so-called Operating windows, which are used to acquire and display ongoing measurement data
(2) The Document space in the middle. This area is used for displaying and analyzing previously stored measurement documents.
(3) The Info pane on the right. This area contains several stacked Panels and is used to group a diverse array of functionality and information.
(4) The Ribbon at the top. This area is used to access all action functions.
(5) The Status bar at the bottom. This area is used to display additional information.

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Procedure (3/30)

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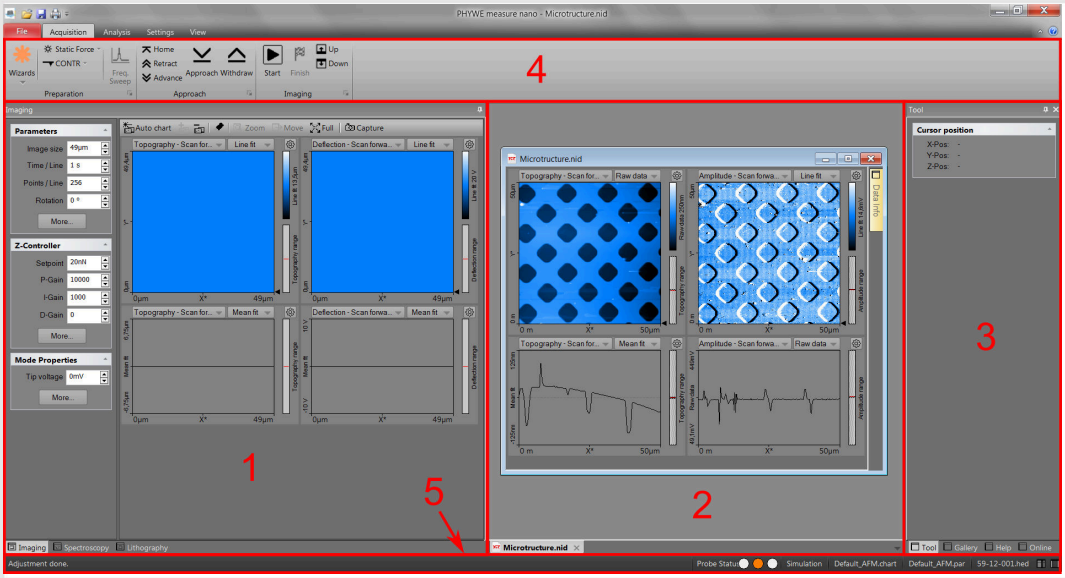

Fig 12: The Software Interface in “Normal” workspace mode

Procedure (4/30)

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Changing parameters in any panel

- Activate the parameter by clicking it with the mouse pointer, or by selecting it with the “Tab” key.

In case of a drop-down menu selection, change the selection with the mouse, or the “Up” and “Down” arrows on the keyboard. In case of a numerical value, use one of the following methods:

- Use the “Up” and “Down” arrow keys of your keyboard to increase or decrease the value of a parameter. The new value is automatically used after one second.
- Click the arrow buttons next to the parameter’s value with the mouse pointer. The new value is automatically used after one second.

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Procedure (5/30)

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Enter the new value using the keyboard. The entered value is applied by pressing the “Enter”/“Return” key, or by activating another input.
The entered value is discarded by pressing the “Esc” key. The unit prefix can be changed by typing one of the following keyboard keys:

Example: If the basic unit is volts, type “m” to change to millivolts, or type “u” for microvolts. Sometimes the program changes an entered parameter value to a slightly different value. This happens when the desired value is outside the digitization range of the Measure Nano Controller, for example due to resolution or timing limits. In such cases, the desired value is automatically changed to the nearest possible value.

Shortcut	Prefix
f	femto
p	pico
n	nano
u	micro
m	mlli
k	kilo
M	mega
G	giga
T	terra
space-bar	none

Procedure (6/30)

PHYWE

Mounting the cantilever (incl. tip)

To maximize ease of use, the PHYWE AFM is designed in such a way that the cantilever can quickly be installed and removed without having to re-adjust the cantilever deflection detection system (Figure 13: Cantilever deflection detection system). The quick cantilever installation is possible because the Scan Head contains a self-alignment system. The alignment system consists of a structure in the alignment chip and matching grooves in the back side of the cantilever chip. The alignment system positions the cantilever with micrometer accuracy (see Figure 14). This accuracy is only guaranteed when the cantilever and the mounting chip are absolutely clean. Installation of the cantilever should therefore still be carried out with great care. The quality of measurements depends strongly on the accuracy of the installation.

It is very important that the cantilever type is suitable for the operating mode that is used. Stiffer and shorter cantilevers (e.g. NCLR, Nanoworld or Tap190Al-G, BudgetSensors) are generally used for the dynamic operating mode. More flexible and longer cantilevers (e.g. CONTR, Nanoworld or ContAl-G, BudgetSensors) are generally used for the static operating mode.

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Procedure (7/30)

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To change to a different cantilever type:

- In the Preparation group of the Acquisition tab (in the Ribbon), select the desired cantilever type from the “Mounted cantilever” drop-down menu by clicking the currently selected cantilever type.

Figure 13: Cantilever deflection detection system.

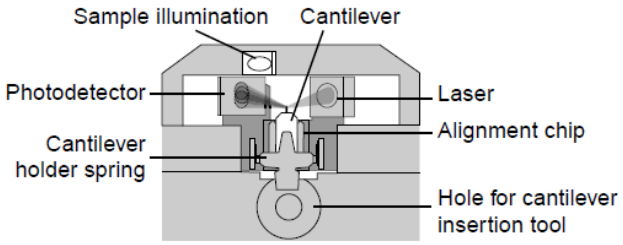
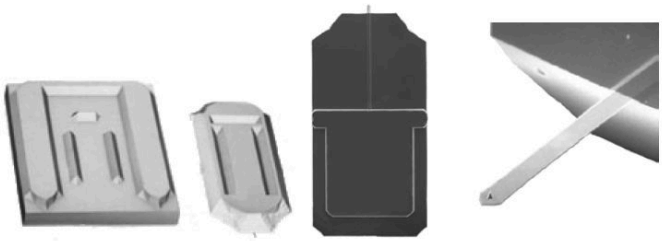


Figure 14: (Left) Alignment system. (Center) Cantilever chip viewed from the top. (Right) Cantilever, 450 µm wide with integrated tip.



Procedure (8/30)

PHYWE

Caution:

- Nothing should ever touch the cantilever.
- The Cantilever Holder Spring is very delicate. NEVER touch or pull on it! It will become bent and unusable otherwise!
- Always close the DropStop before handling the cantilever. If you fail to do so, the cantilever can fall into the Scan Head, causing malfunction of the microscope, particularly of the scanner.
- If a cantilever has dropped into the Scan Head, and the microscope is malfunctioning, contact your local support. Never open the Scan Head, because this

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Procedure (9/30)

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To remove the old cantilever:

1. Flip open the AFM cover including the scan head (Figure 15: The open AFM).
2. Remove the Cantilever Insertion Tool from the DropStop
3. Close the DropStop (see Figure 16: Closing the DropStop). The laser beam is now blocked by the DropStop. As a consequence, the Probe Status light on the PHYWE controller will now blink red.
4. Place the cantilever insertion tool into the hole behind the alignment chip (Figure 17: Mounting the cantilever, top left). The Cantilever Holder Spring opens.
5. Use the Cantilever Tweezers to remove the old cantilever from the instrument (Figure 17: Mounting the cantilever, top right).

Procedure (10/30)

PHYWE

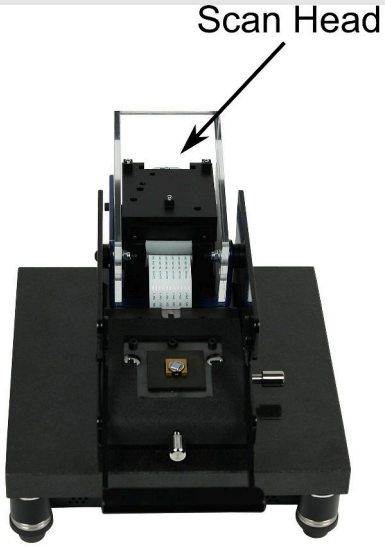

Figure 17: The open AFM

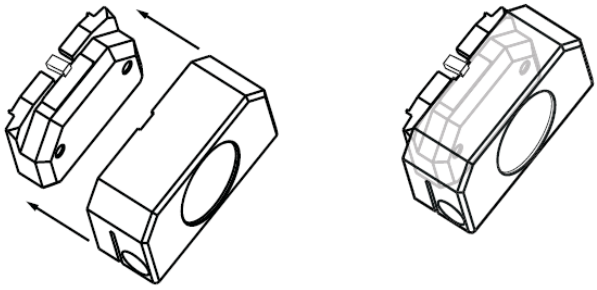

Figure 18: Closing the DropStop

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Procedure (11/30)

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To insert the new cantilever:

1. Take the new cantilever out of its box with the cantilever tweezers.
2. Place the cantilever carefully on the alignment chip in the Scan Head (Figure 19: Mounting the cantilever, top right).
3. Verify that the cantilever does not move with respect to the Alignment Chip by carefully tapping on it with the tweezers. If the cantilever does move, it is probably not inserted correctly. Refer to Figure 20: Cantilever Alignment for correct alignment and examples of incorrect alignment.
4. Gently pull the cantilever insertion tool out of the hole. The Cantilever Holder Spring closes and holds the cantilever chip tightly in position (Figure 19: Mounting the cantilever, bottom right).
5. Remove the DropStop. The laser beam is now unblocked, and the Probe Status light on the PHYWE controller should now stop blinking red. If this is not the case try to re-align the cantilever.

Procedure (12/30)

PHYWE

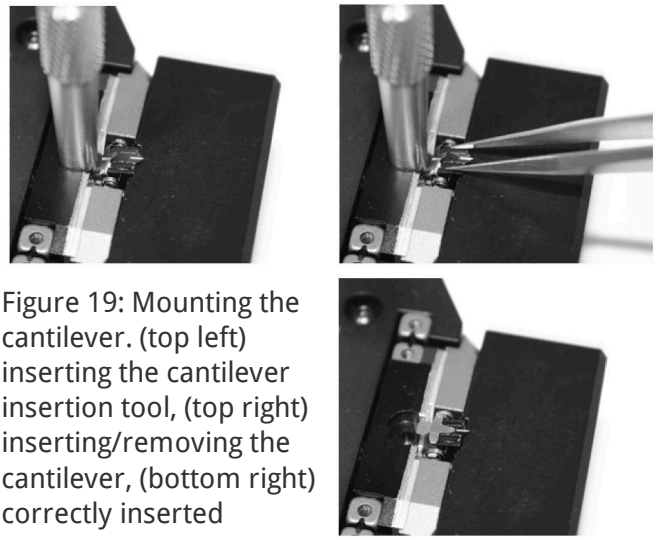

Figure 19: Mounting the cantilever. (top left) inserting the cantilever insertion tool, (top right) inserting/removing the cantilever, (bottom right) correctly inserted

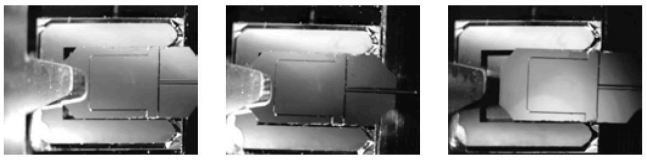

Figure 20: Cantilever Alignment. (Left) correct: the mirrored environment shows a reflection that is continuous over the cantilever and the alignment chip, and small triangular gaps can be seen between the edges of the alignment chip and the corners of the cantilever chip, (center & right) incorrect: the mirrored environment shows a reflection that is different on the cantilever and on the alignment chip, and no nice triangular gaps can be discerned.

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Procedure (13/30)

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Sample preparation

In the present sample kit only the glass bead sample needs to be prepared. The kit contains an empty glass slide and a vial of diluted bead solution, which will be used to create the sample. In this case the beads have a diameter of 120 nm (may vary in future). Once the sample is prepared, it can be used for measurements as long as it remains clean. To prepare the sample:

Take the following materials from the sample kit:

1. Glass slide
2. Diluted bead solution
3. Ethanol
4. Clean tissue

Procedure (14/30)

PHYWE

5. Clean the glass slide and remove any accumulated dirt.
6. Drip some ethanol on the slide.
7. Wipe the ethanol off with the clean tissue.
8. Place the vial with the bead solution in a beaker partly filled with water.
9. Place the beaker in an ultrasonic bath for approximately 20 minutes. This process will break up any groupings of beads in the solution. The beads will form aggregates over time due to simple attractive interactions between them (such as Van der Waals forces), but the goal is to have individual beads come together on the glass slide and eventually form crystalline structures.

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Procedure (15/30)

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10. Use an eyedropper to place a drop of bead solution onto the cleaned glass slide.

11. Try to form the largest drop possible without spilling over the sides of the glass.

12. Dry the sample under ambient conditions. This may take several hours.

13. Fix the beads by baking:

a) Place the sample disc in an oven at 250° for 2–3 hours.
b) Allow the sample to cool completely before imaging.

Procedure (16/30)

PHYWE

Installing the samples

The PHYWE AFM can be used to examine any material with a surface roughness that does not exceed the height range of the scanning tip. Nevertheless the choice and preparation of the surface can influence the surface–tip interaction. Examples of influencing factors are excess moisture, dust, grease or other contaminations of the sample surface. Because of this, some samples need special preparation to clean their surface. Generally, however, only clean your samples if this is absolutely required, and be sure to clean very carefully in order not to harm the sample surface.

If the surface is dusty, try to measure on a clean area between the dust. Although it is possible to blow away coarse particles with dry, oil-free air, small particles generally stick quite strongly to the surface and cannot be easily removed this way. Also note that bottled, pressurized air is generally dry, but pressurized air from an in-house supply is generally not. In this case an oil filter should be installed. Blowing away dust by breath is not advisable, because it too is not dry, and the risk of contaminating the sample even further is very high.

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Procedure (17/30)

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When the sample surface is contaminated with solid matter or substances that can be dissolved, the surface should be cleaned with a solvent. Suitable solvents are distilled or demineralized water, alcohol or acetone, depending on the nature of the contaminant. The solvent should always be highly pure in order to prevent accumulation of impurities contained within the solvent on the sample surface. When the sample is very dirty, it should be cleaned several times to completely remove partially dissolved and redeposited contaminants. Delicate samples, which would suffer from such a treatment, can alternatively be cleaned in an ultrasonic bath.

All samples should be stored in their respective box. This way, it should not be necessary to clean them.

Place the Chip Structure on Silicon in the on the magnetic sample stage in the AFM using tweezers and only touching the sample holder, not the chip structure itself.

Procedure (18/30)

PHYWE

Approaching the tip towards the sample

To start measuring, the cantilever tip must come within a fraction of a nanometer of the sample without touching it with too much force. To achieve this, a very careful and sensitive approach of the cantilever is required. This delicate operation is carried out in two steps: Manual coarse approach and the Automatic final approach. The color of the Status light (at the bottom of the software interface) shows the current status of the approach:
– **Orange/yellow**
Normal state during approach: the Z-scanner is fully extended toward the sample.
– **Red**
The approach has gone too far: the tip was driven into the sample, and the Z-scanner is fully retracted from the sample. In this case, the tip is probably damaged and you will have to install a new cantilever again.
– **Green**

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Procedure (19/30)

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The approach has finished successfully: the Z-scanner is within the measuring range. To prepare for the approach process:

- Select the Acquisition tab

The controls for positioning the cantilever with respect to the sample are located in the Approach group. During the approach steps described in the following sections, use the side view of the cantilever, accessible from the lens on top of the device, to judge the distance between tip and sample surface:

Procedure (20/30)

PHYWE

Manual coarse approach

In this step, the tip is brought as close to the sample surface as possible, without touching it. The closer the two are together, the less time the automatic final approach takes.

1. Observe the distance between tip and sample in the side view of the integrated optics.
2. While observing the tip–sample distance, click and hold the “Advance” button in the Approach group of the Acquisition tab until the tip is close enough to the sample: The tip should not come closer to the sample than a few times the cantilever width (Figure 21). Now that the sample is in focus, the top view image from the integrated can be used to find a suitable location to measure on.

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Procedure (21/30)

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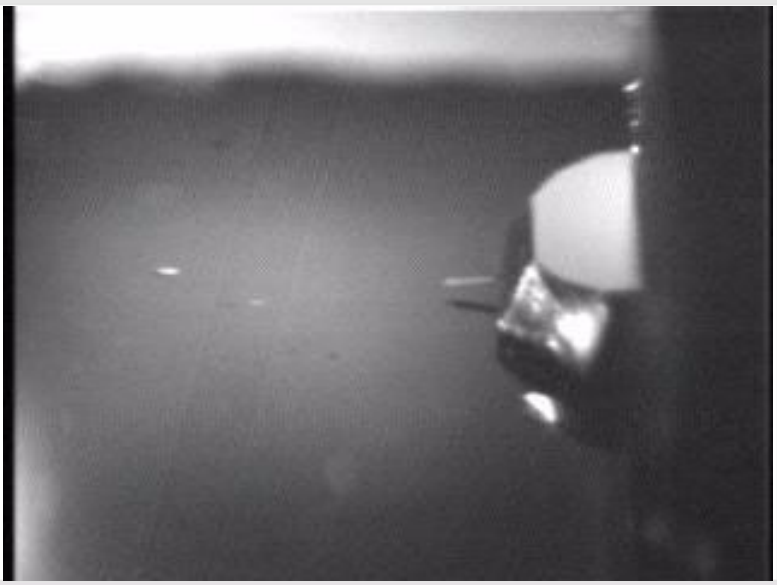
To use the top view:

1. Select video in the info pane of the Sofware interface.
2. If necessary, move the Sample Holder to find a suitable location that is free of dust particles.

Figure 21: Side view of sample and cantilever after manual approach.



Procedure (22/30)

PHYWE

Automatic final approach

In this last step, the tip automatically approaches the sample until a given Setpoint is reached. Before starting the automatic approach, select the desired operating mode and cantilever type. To do this:

- In the Preparation group of the Acquisition tab, select an operating mode and cantilever type that match the cantilever installed.

In Dynamic Force mode, the instrument will automatically determine the vibration frequency to be used during imaging. To determine the optimal frequency, the controller performs a coarse and a fine frequency sweep in which the cantilever vibration amplitude are recorded as a function of excitation frequency. It is instructive to see both frequency sweep measurements in all detail at least once. To do this, it is possible to manually perform the frequency sweeps:

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Procedure (23/30)

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1. In the Preparation group of the Acquisition tab, click the “Freq. Sweep” button: The Vibration Frequency Search dialog now opens
2. Click the “Auto frequency set” button. The SPM Control Software now sets appropriate values for the coarse and fine sweeps and performs these sweeps. The fine sweep will overwrite the data of the coarse sweep in the charts displayed in the “Vibration frequency search” dialog. To see the results of the individual sweeps:

- Press the “Coarse sweep” and “Fine sweep” buttons sequentially.

Frequency sweeps can be a used to check if a cantilever is undamaged and was mounted correctly in dynamic mode (It is not necessary to close the AFM to do so). If so you will receive a well define resonance curve and a high vibrational Amplitude (depending on the excitation amplitude).

Procedure (24/30)

PHYWE

Before final approach of the sample, it is necessary to set the scanning and feedback parameters of the control software to suitable initial values. The easiest way to do this is to use the “Auto Set” wizard:

1. In the Preparation group of the Acquisition tab, click the “Auto Set” button: A dialog will pop up, which will ask you some basic questions about your sample and your measurement needs.
2. Answer the questions of the wizard to the best of your knowledge.

Now that the initial software settings have been given suitable values, you need to name the measurement series. Each completed measurement (scan/image) will be temporarily saved (automatically) in the History folder under this name, with index numbers added to identify the individual measurements. It is best to enter the measurement series’ name now, since the control software will (by default) start measuring as soon as the final approach is done. It is also strongly recommended to move all relevant measurements to a new folder when you are finished, since the files in the History folder will be overwritten over time.

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Procedure (25/30)

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To set the measurement series name:

1. Activate the Gallery panel in the Info pane.
2. Click the History tab at the top of the Gallery panel with the mouse.
3. In the entry box at the top of the panel, enter a name by hand or use the Mask Editor dialog to create the name mask. If no [INDEX] attribute is explicitly added to the name mask, it will be implicitly applied to the end of the file name so that individual measurements can be stored and distinguished.

Procedure (26/30)

PHYWE

The automated final approach can now be started. To do this:

1. In the Approach group of the Acquisition tab, click the “Approach” button:

The cantilever is moved towards the sample via the approach stage, with the ZController turned on. This movement continues until the Z-Controller error becomes zero. From this point onward, the distance between sample and tip is maintained automatically by the electronics. The probe status light changes to a constant green, and a message “Approach done” appears:

Click the “OK” button.

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Procedure (27/30)

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Starting the measurement

Now that the tip–sample interaction defined by Setpoint is established between tip and sample, measurements can start. By default, the instrument is set to automatically start measuring after the automatic approach. If this is not the case:

- Start measurements manually by clicking the “Start” button in the Imaging group of the Acquisition tab:

Two representations of the ongoing measurement are drawn in the Imaging panel. One representation is a color coded height image (Topography) called a Color map. The other is a plot of height as a function of X* position called a Line graph. With the current settings, the software automatically adjusts the contrast of the Color map, and height range of the Line graph to the data that have been measured. To judge the imaging quality, watch the displays until at least one fourth of the measurement has been completed. When a measurement contains large disturbances, or no two scan lines are similar, stop measuring and try to reduce or eliminate the disturbances or try retracting the tip and re-approaching a different sample position.

Procedure (28/30)

PHYWE

Selecting a measurement area

If you were able to prepare your measurement so that the scan line in the Line graph reproduces stably, the color map graph should look similar to the one shown below after the measurement has finished. To zoom in to an interesting part of the measurement:

1. Activate the color map graph by clicking on it.
2. Click the “Zoom” button in the Chart bar: The mouse pointer becomes pen-shaped when moving over the color map.
3. Click on one corner of the region to be selected using the left mouse button, and keep the button pressed.
4. Drag the mouse to the other corner of the region. The size and the position of the square are shown in the Tool results panel of the Info pane.

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Procedure (29/30)

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6. Release the mouse button when the size of the square covers approximately oneperiod of the grid.

7. Confirm the selection by double clicking the color map graph using the left mousebutton. Now the selection is enlarged to the whole display size. You can abort the zoom function by clicking the “Zoom” button again.

Depending on measurement parameters you will come across bad scans as shown in Figure 22. In this case the scanning parameters need to be adjusted as shown in this manual.

Procedure (30/30)

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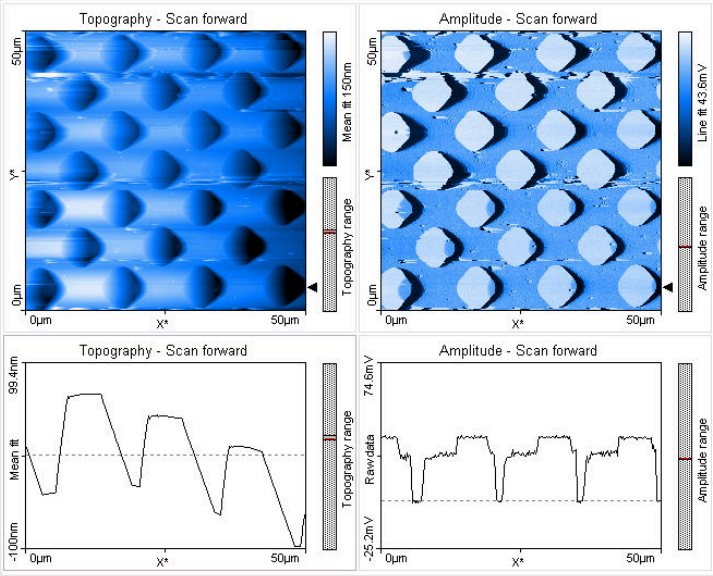

Figure 22: A scan of the microstructure sample using bad scanning parameters

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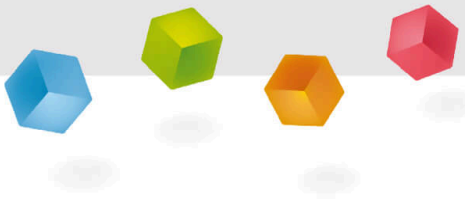

Evaluation

Task 2 (1/16)

PHYWE

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.

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Task 2 (2/16)

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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.

Task 2 (3/16)

PHYWE

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.

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Task 2 (4/16)

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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 scanner or the resonance frequency of the cantilever itself.

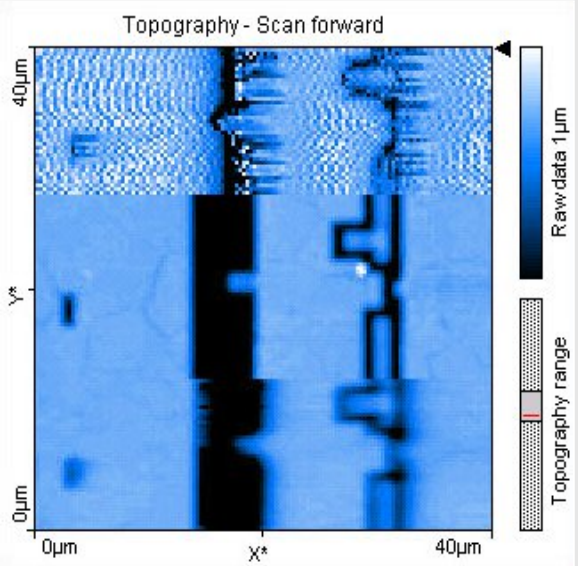

Figure 23: SCA chip structure imaged at different integral gain settings. In the lowest region of the image, the gain is too low; at the center, it is optimized; at the top, it is too high.

Task 2 (5/16)

PHYWE

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. 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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Task 2 (6/16)

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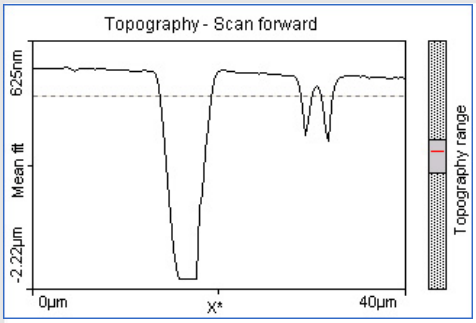

Figure 24: Optimized Gain. Optimized gain setting for SCA chip structure

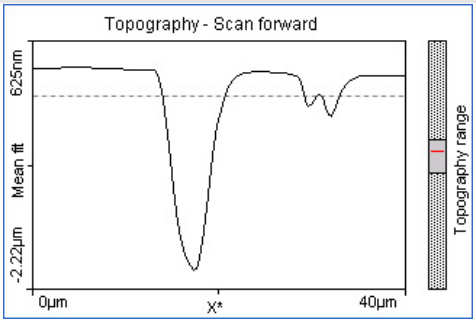

Figure 25: Low Gain. The feedback loop is not responding quickly enough.

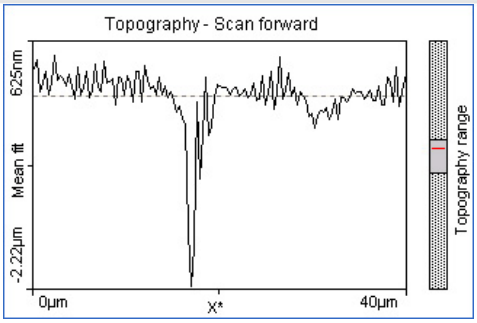

Figure 26: High Gain. Oscillating signal when gain is set too high.

Task 2 (7/16)

PHYWE

Influence of set points

The investigation of the influence of the setpoint can be observed best when measureing the carbon nanotube sample in static mode using a suitable cantilever. This sample represents the group of materials with macromolecules that are used for molecular nanotechnology. Other well-known examples are self-assembled particles, DNA, and nanotubes made of other materials.

AFMs can be used to characterize and manipulate such molecules. The well defined structure of nanotubes makes them ideal for demonstrating the influence the structure of the end of the AFM tip has on the measured image.

The carbon nanotube sample consists of a piece of silicon wafer on which carbon nanotubes are deposited. Nanotubes are less than 10 nm in diameter and can reach lengths of several 100 micrometers.

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Task 2 (8/16)

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With this sample, the tip is likely to be damaged, if the scan parameters are not well optimized. Therefore, if you start with a relatively large range (~ 15 µm) and successively zoom in on an area of interest, it may not be possible to measure the nanotubes at high resolution because the tip already has been damaged by the high scan speed in the large scan.

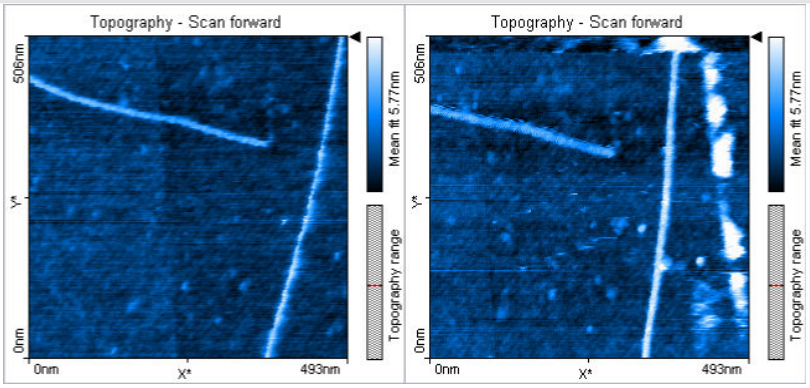

Figure 26: Static mode (Left) Force set point (10 nN) is too high. (Right) Lower force set point (2 nN). Note the dirt moved around by the previous measurement with excessive force set point.

Task 2 (9/16)

PHYWE

Image acquisition

1. Set a small scan range (2 µm or less).
2. Take a scan.
3. Optimize scanning parameters
4. Zoom out by taking a scan at a relatively large scan range (~15 µm).
5. Identify an area of interest.
6. Zoom back in.

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Task 2 (10/16)

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Figure 26 illustrates an optimization sequence. At first, the set point is too high (10nN), so the nanotube gets pushed around. This makes it appear streaky and not as wide as it should be. With the Set Point lowered, the nanotube is imaged more stably. Note that the dirt that was pushed to the side in the first scan is visible on the side of the second scan. This is and effect typical for contact mode and is the result of scratching the tip across the surface always in the same direction as the scanning takes place.

As seen in the scans any structures that are not tightly aligned on the sample surface will be manipulated by the tip scratching over them in static mode. For hard samples like single crystals usually this is not an issue, however the tip might get damaged on such samples. On the other hand, static mode measurements on soft (e.b. biological) samples damage the samples easily.
These effects can be controlled to a certain extend by adjusting the setpoint, but in general for any sample the wear of tip and sample is higher in static mode compared to dynamic mode.

Task 2 (11/16)

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Influence of vibration amplitude in dynamic mode

In dynamic mode, using a suitable cantliver, setting the vibration amplitude is crucial for achieving the best possible resolution. In static mode, the main parameter to regulate the image quality are the PID feedback settings and the Set point. In dynamic mode, the setting of the vibration amplitude additionally plays an important role. In general, the vibration amplitude must correspond to the size of the sample features:

- Low structures require a small amplitude.
- High structures requite a big amplitude.
- Small structures on top of big structures require a small amplitude and a slow scan speed.

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Task 2 (12/16)

Image acquisition

1. Find a clean spot on the sample
2. Approach the sample
3. Start the measurement
4. Adjust PID gains
5. Find the optimum vibration amplitude

Task 2 (13/16)

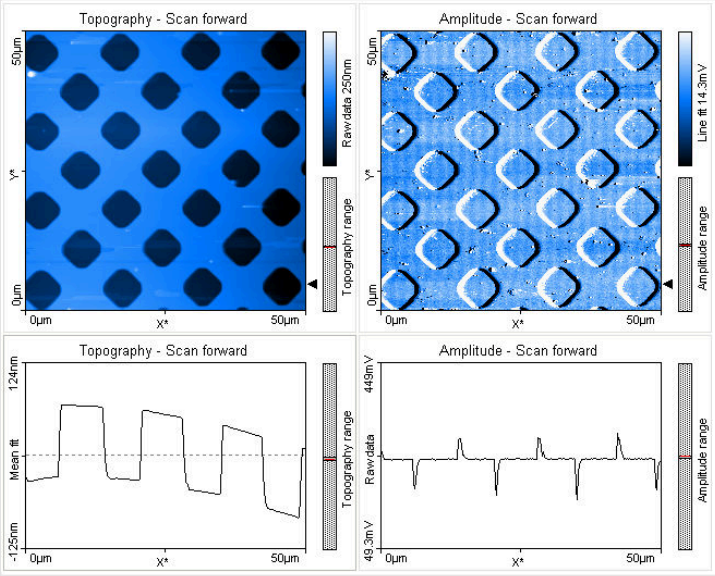

Figure 27: Large Amplitude. Topography and amplitude image of the microstructure sample. The line graphs show a cross section of the images above at the position indicated by the arrow. The vibration amplitude was set to 400 mV.

Figure 27: Large Amplitude shows the topography and amplitude image of the microstructure sample. The line graphs show a cross section of the images above at the position indicated by the arrow at the right side of the sacn. It is clearly visible that the in the topography the slopes are steep. After each perturbation the amplitude signal is also corrected to the Set point value very quickly.

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Task 2 (14/16)

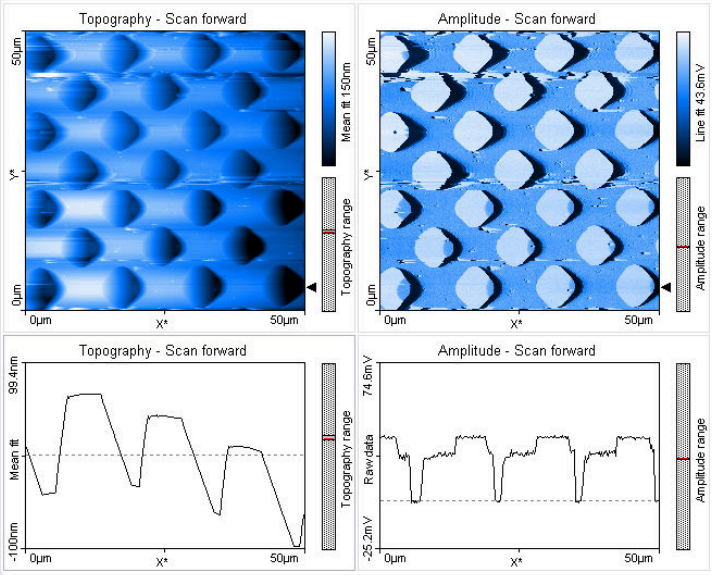

Figure 28: Small Amplitude. Topography and amplitude image of the microstructure sample. The line graphs show a cross section of the images above at the position indicated by the arrow. The vibration amplitude was set to 40 mV.

Task 2 (15/16)

Figure 28: Small Amplitude shows the topography and amplitude image of the microstructure sample with too low vibration amplitude. The line graphs show a cross section of the images above at the position indicated by the arrow. The topography image is smeared out and the topography line graph shows a too small slope. The reason therefore can be found in the amplitude signal. The peaks are larger; this means that the correction to the amplitude to the Set point value is not as quick as in Figure 27: Large Amplitude. Due to the small vibration amplitude when the tip needs more time from the moment where it lost the contact to the surface to the moment it gains contact again. During this time the topography is uncertain and the tip is vibrating at the free vibration amplitude. Increasing the vibration amplitude or decreasing the scan speed will increase the quality again.

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Task 2 (16/16)

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When scanning in dynamic mode the amplitude image should be mostly constant indicating that the feedback loop reacts fast enough on changes in the topography of the sample as ssen in Figure 27: Large Amplitude. Only at sharp features on the surface the amplitude might deviate.
When scanning a sample with too low vibrational amplitude the amplitude image will not correspond with features in the topography because the feedback loop is not able to react properly to the large changes in the amplitude when coming across a high feature on the sample surface (Figure 28: Small Amplitude).

Task 3 (1/19)

PHYWE

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.

The characterization of chips, also known as Integrated Circuits (ICs), is an important application of AFM technology. The dimensions of the structures in these circuits are decreasing rapidly, and no other tool is able to characterize these dimensions without destroying the sample.
This particular chip is a Switched Capacitor Array (SCA) chip. SCA chips are custom-made silicon chips which can sample an analog input signal at high speed (in this chip up to 950 GHz), but can then be read out at lower speeds.

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Task 3 (2/19)

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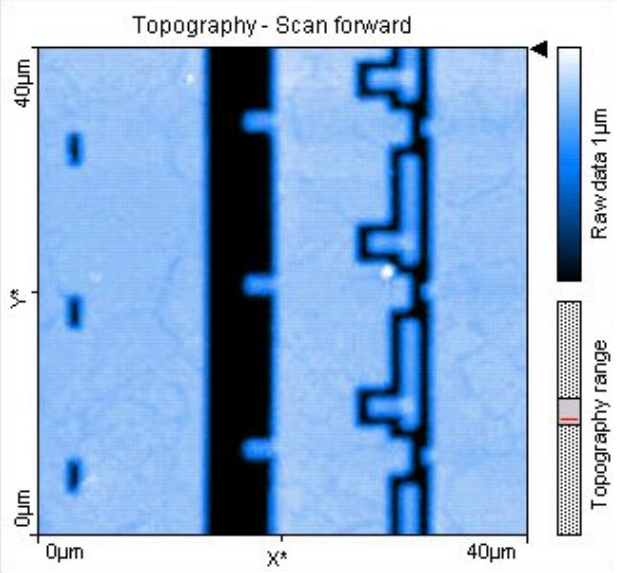

Figure 29: The SCA Chip Structure. AFM image taken at the center of the chip sample. The depth of the trenches is approximately 1.6 μm.

Task 3 (3/19)

PHYWE

Carbon nanotubes

Image acquisition

1. Set a small scan range (2 µm or less).
2. Take a scan.
3. Optimize scanning parameters
4. Zoom out by taking a scan at a relatively large scan range (~15 µm).
5. Identify an area of interest.
6. Zoom back in.

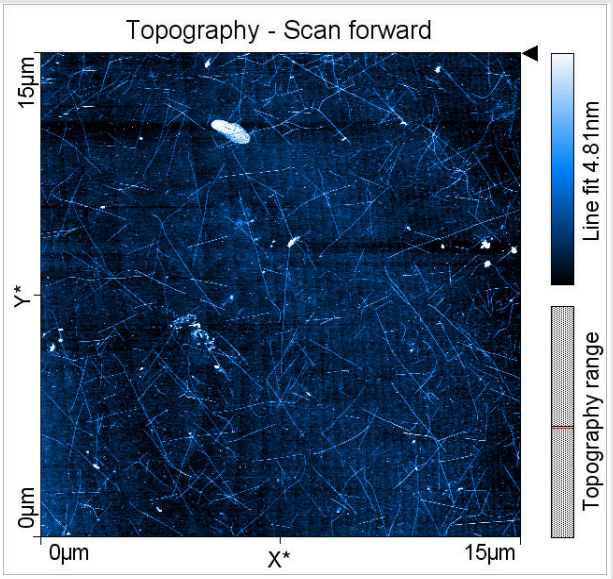

Figure 30: Nanotube Image in static mode. Carbon nanotubes can be seen lying on the silicon surface. Set point (2nN).

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Task 3 (4/19)

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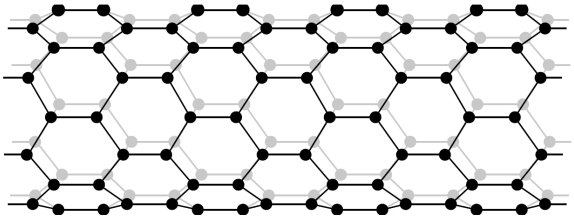

Figure 31: Nanotube molecular structure.

A carbon nanotube is, as the name suggests, a tiny cylinder composed of carbon atoms. More specifically, it is a lattice of graphitic carbon rolled into a tube. Figure 31: Nanotube Molecular Structure shows an example of the molecular structure of a carbon nanotube. The ends of the tube are not capped, but it is possible to seal a nanotube at both ends with a fullerene. A fullerene is similar to a nanotube in molecular structure, but it is spherical rather than cylindrical.

The bonds that hold nanotubes together are entirely sp2 bonds, as in graphite. These bonds are stronger than the chemical bonds of diamonds, making nanotubes very durable. Nanotubes naturally align themselves into bundles held together by Van der Waals forces.

Task 3 (5/19)

PHYWE

Microstructure

Image acquisition

1. Find a clean spot on the sample
2. Approach the sample
3. Start the measurement
4. Adjust PID gains
5. Find the optimum vibration amplitude

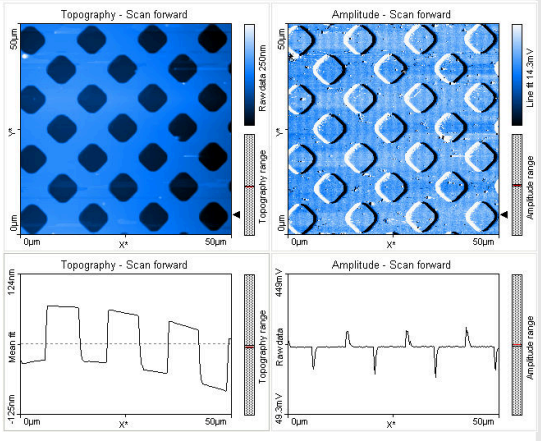

Figure 32: Microstructure measured in dynamic mode. Topography and amplitude are shown. The line graphs show a cross section of the images above at the position indicated by the arrow at the right of the scans respectively.

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Task 3 (6/19)

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The microstructure sample consists of a structured silicon dioxide layer on silicon. This sample is in general quite easy to measure and there are not any special settings to be considered. However due to the abrasive characteristics of the oxide layer, the tip quality decreases quite fast compared to usual tip wear. Due to the sharp steps, this sample is very sensitive to the settings of the feedback loop and vibration amplitude in dynamic mode.

Task 3 (7/19)

PHYWE

CD stamper

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.

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Task 3 (7/19)

PHYWE

CD stamper

Image acquisition

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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.

Task 3 (8/19)

PHYWE

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.

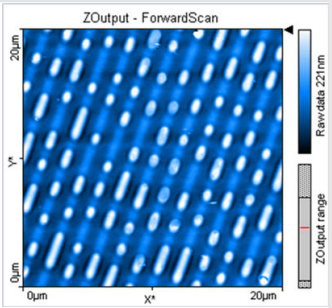

Figure 33: 20-µm Image of CD Stamper. Note that the curva-ture of the tracks is not discernible at this scan size.

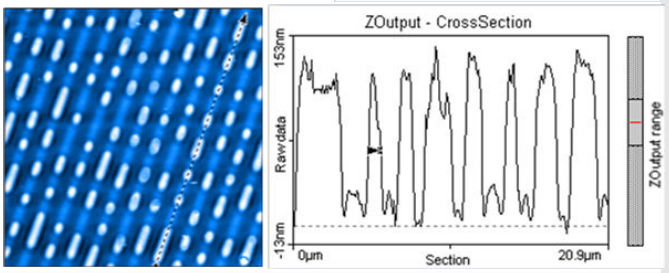

Figure 34: Bump length. Using the Measure Length tool in the track direction.

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Task 3 (9/19)

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Glass beads

Approaching the Sample

This sample is measured in static mode using a suitable cantilever. Furthermore, it is one of the more difficult to approach, as it is non-metallic, and not very reflective. If you can see the cantilever's shadow or reflection, you can use it to judge the distance. If you find it difficult to recognise the cantilever's reflection, then slightly move the sample holder: the structures on the sample will move, but the reflection will stay in the same place. If you cannot see the cantilever's reflection, perform a very slow coarse approach while judging the distance on the focal plane of the side view as follows:

- When the tip is on the sample, the focal plane crosses the sample at the tip position.
- When the tip is further away, the focal plane crosses the sample more behindthe cantilever.

Task 3 (10/19)

PHYWE

Image acquisition

1. Start with a low force set point for best results. Applying too much force may move some of the beads around and create wide horizontal stripes across the image.

If you get stripes in your image:

1. Lift the tip, and then
2. Bring it back into contact.

If the tip is simply dirty, you can remove the dirt by:

1. Retracting the tip
2. Re-extending it again.

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Task 3 (11/19)

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If there are still stripes in your image, the problem may be that the region where you are scanning does not have perfectly fixed beads. In a region of more ordered beads, the beads will stay in place. Therefore:

- Move to another region on the sample.

1. Set the scan range to 1 µm.

Since the beads are approximately 120 nm in diameter, you should be able to see about 10 of them across the image. If your image shows islands of beads surrounded by very flat areas:

- Move to a region of better ordered beads.

In general, the region with the best ordering is close to the center of the spot on the slide. Figure 35 shows a well-ordered region near the center of the spot.

Task 3 (12/19)

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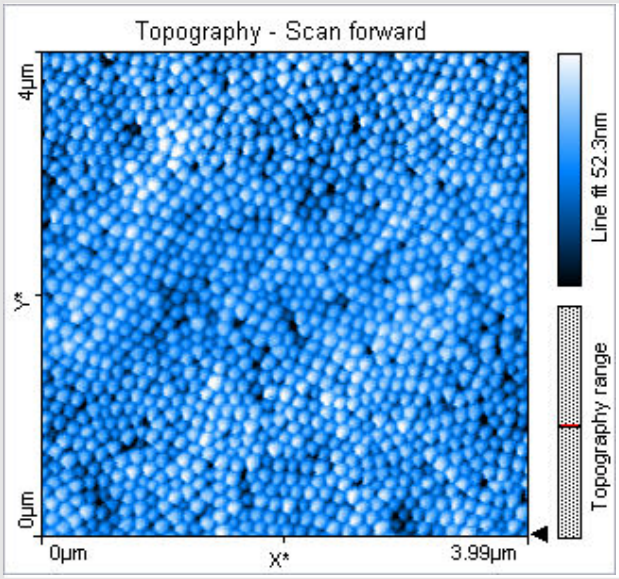

Figure 35: Well Ordered Beads in static mode. The center part of a spot of bead solution. Some sections have a crys-talline structure while others are less ordered.

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Task 3 (13/19)

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Staphylococcus aureus

Image acquisition

The glass slide is only slightly reflective, so it can be difficult to judge the tip-sample distance for the approach. If you can see the cantilever's shadow or reflection, you can use it to judge the distance. You can try to make the reflection more visible by moving the sample holder slightly.

If you cannot see the cantilever's reflection, perform a very slow coarse approach while judging the distance on the focal plane of the side view as follows:

- When the tip is on the sample, the focal plane crosses the sample at the tip position.
- When the tip is further away, the focal plane crosses the sample more behind the cantilever.

Task 3 (14/19)

PHYWE

The bacteria have been fixed to the glass slide with a burning process. The process leaves a mark where the bacteria have been burned, which makes it possible to locate the parts of the slide that are covered with bacteria.

The individual bacteria are approximately 0.7 µm in diameter, so it is possible to make out several bacteria in a relatively large scan range. This sample has regions with a very high concentration of bacteria as well as some with lower concentrations and some bare spots. The left image in Figure 36 shows a 20-µm scan region densely packed with bacteria. It should be easy to zoom in on a much smaller scan region where the bacteria are still very concentrated.
The height scale of 450 nm is small considering that the free bacteria are spherical with an approximate diameter of 0.7µm. It is likely that the process which fixes the bacteria to the slide results in flattening them as well.

Furthermore, 3D representation of the data is possible by right-clicking on a graph and select “chart type” >> “3D View” (Figure 36, right), making the scan more descriptive.

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Task 3 (15/19)

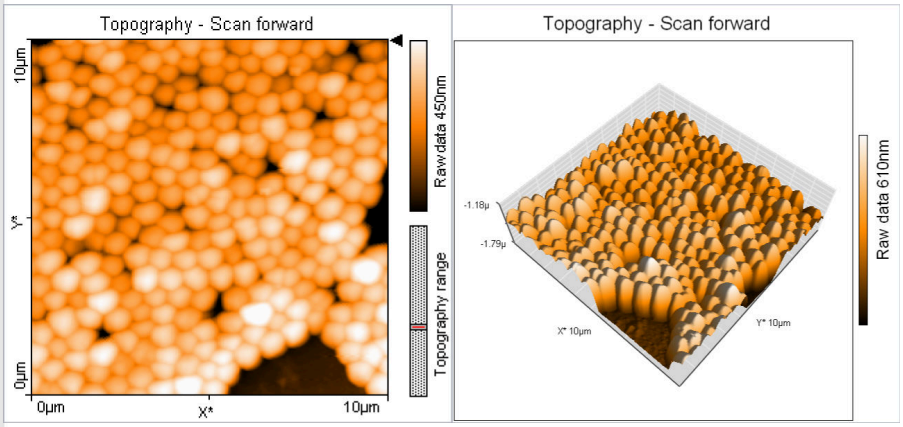

Figure 36: Staphylococcus Bacteria Images in dynamic mode. (Left) Topography with a scan range of 10 µm. Some regions appear to have almost crystalline structure, while other regions contain unordered gaps. The variations in color brightness of the individual bacteria correspond to the variations in height of the bacteria. (Right) 3D view of the left scan.

Task 3 (16/19)

Human skin

The human skin sample is an example of a soft biological sample. Although the measurement of this sample is possible in static mode, soft biological samples are likely to get damaged if measured in static mode. Therefore measurement in dynamic mode is recommended using a suitable cantilever. In contrast to the other samples in the sample kit, the macroscopic position of the AFM tip on the sample determines what kind of structures you will see. Thus, this sample is a good sample to practice coarse positioning of the sample using the included video camera. Moreover the skin is hardly visible (see Figure 37: Skin Overview)

Figure 37: Skin Overview. The image is an overview of the skin cross section sample recorded by the included video camera. The different layers are visible as well as the AFM cantilever.

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Task 3 (17/19)

PHYWE

Image acquisition

The fact that the skin specimen has many different layers is also important in scanning, since not all of the layers will be visible in one scan range.The best strategy to see all of the structures within the skin sample is:

1. Choose a large scan range (50–100 µm)
2. Begin at one side of the skin cross section
3. Take an image
4. Retract to a safe position
5. Move slowly across the sample

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