The Atomic Force Microscope

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1 Introduction

In the early Eighties *Gerd Binning* and *Heinrich Rohrer* of the IBM research laboratory in Rüschlikon, Switzerland, developed a new characterisation technique: *The Scanning Tunneling Microscopy, STM.* (Rastertunnelmikroskop, RTM in German.) It's based on the quantum mechanical principle of *tunneling*. As known the number of electrons tunneling through a potential barrier and the resulting current depends on the height and the thickness of this barrier. The tunneling current can be used directly or in a feedback i.e. to image surface of the studied sample or position of electron reservoirs. The invention of the STM allowed to obtain a lot of new information about local properties of various materials and structures.It was so important for physics that it was awarded by the Nobel Prize in 1986.

Unfortunately the STM technique allowed to examine only conducting materials and the applied voltages can be a disadvantage in some experiments. Organic molecules for instance could be damaged or tunneling electrons could destabilize a labile state. This was a motivation to develop other methods allowing to study local properties such as*field microscopy* or the *atomic force microscopy*. They all have in common that they scan the surface line by line, with an extremely high resolution and record studied properties point by point.

1.1 AFM operating principle

An AFM is used to study the surface topography with possibly even atomic resolution. This technique is based on the detection of the force between a very sharp tip mounted on a thin cantilever and the surface of the studied sample. Before the scanning process begins, the tip is moved towards the surface until required force (set point) between the tip and the surface is measured. The final interaction force is usually given by forces of various origin and it can be attractive or repulsive. Because of the wide variety of surfaces and their specific properties (consisting atoms / molecules, therefore structure, contamination) there exist different imaging modes (also called "scanning modes" or "operating modes") for measuring the influence of the specific potential on the cantilever.

1.2 Imaging modes

As we know - or can see in fig. 1 - the force/distance dependence for an AFM - sample surface interaction typically shows an attractive and a repulsive part. The exact form depends on a lot of factors such as sample material, sample contamination, magnetic or electric fields etc.

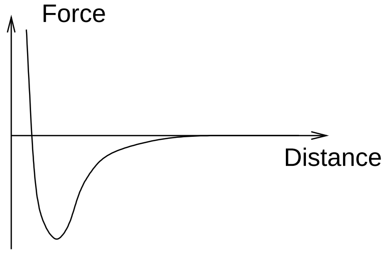


Figure 1: Force vs. distance.

If the the cantilever is close to the surface this force acts on the tip either by "pulling it down" or "pushing it away" (see fig. 2). The modes are respectively called "non-contact" and "contact".

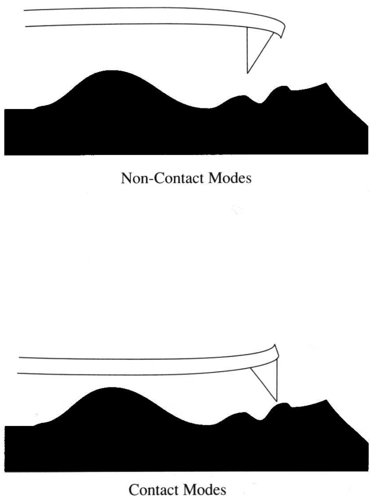


Figure 2: Cantilever behavior in *contact* and *non-contact* mode.

In both this regimes one can make a static scanning (1.2.1) or a dynamic scanning (1.2.2). I'll describe only the most used modes, for more details take a look at table1 in appendix C.

1.2.1 Static contact scanning mode

The force attracts or repulses a tip on a cantilever by a distance x. A reflection of a laser beam by the cantilever (see fig. 3) detected by a photodetector can be used to measure this distance: The signal provided by the photodetector depends on the position of the laser spot on it. A value of this signal given by y ($\simeq x$; the proportionality is valid as long as x is small) gives information about an interaction force between an AFM tip and a sample surface. One can estimate this force knowing properties of the cantilever and using Hooke's law $F = -k \cdot x$. You can plot this y-value (it's the *lever signal* in section 2.3.1) and you'll get an image of the surface.

Hooke's law describes a linear connection between force and x-distance, which only is granted as long as x is very small. It means that the structures on the mapped surface can not be very high. Therefore one usually uses a more sophisticated technique: A controller holds the interaction tip – surface constant, i.e. the photodetector signal which corresponds to y-value is kept constant. The controller has to continuously adjust the Z-position of the whole scanner unit (including cantilever *and* laser) with the respect to the sample surface in such way, that the deviated laser beam hits the photodetector always at the same point. This is done using a feedback loop: the *is*-value is compared several thousands times a second with the *shall*-value, which is proportional (Hooke's law) to the *set point*, the predefined value of the required interaction force(fig. 6). This method is used also in our EASYscan AFM.

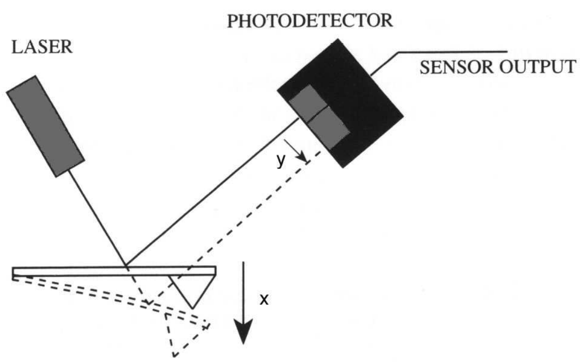


Figure 3: Measurement of the cantilever deviation.

1.2.2 Non-contact dynamic scanning mode

Non-contact dynamic scanning mode is another AFM mode very often used for the mapping of topography. In this mode the cantilever is driven by an external oscillator. External oscillation and cantilever oscillation are in phase below a resonance frequency. Approaching $f_{resonance}$ the phases are shifted, and the amplitude of the cantilever increases. Above $f_{resonance}$, the amplitude decreases rapidly and the phase shift goes towards 180°. If the tip is near the sample, the force acts on the cantilever as if there would be an additional mass and shifts the resonance frequency to a lower value. Fig. 4 illustrates described behavior of the cantilever.

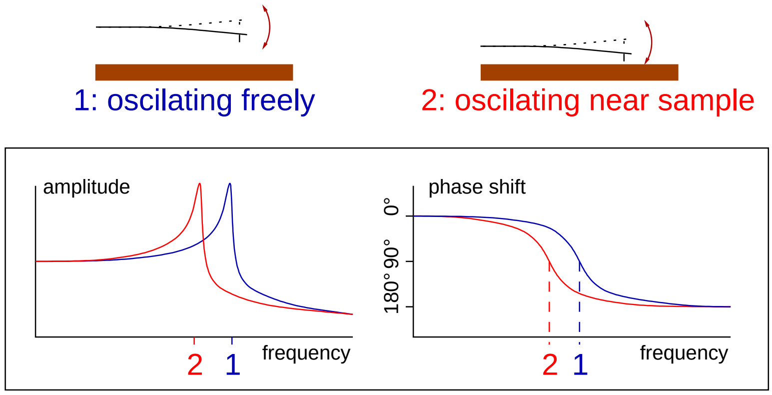


Figure 4: The amplitude maximum depends on the resonance frequency and the resonance frequency depends on the distance from the sample (left). A dependance of the phase shift on the driving frequency (right). 1 - dependance if the cantilever oscillates freely, 2 - dependance if it's near the surface and has an additional *imaginary* mass.

In the dynamic scanning mode one uses as a set point a selected phase shift or an amplitude shift instead of the constant shift of the reflection of the laser beam at the photodetector, which is used in the aforementioned static scanning mode. By the other words, the tip is moved in the direction of the surface until the required phase shift or amplitude shift is obtained and than the tip is moved above the surface. The phase or amplitude shift (i.e. tip-sample distance) is kept stabile again using the feedback electronic during the scanning procedure. By the phase and the amplitude shift is meant a difference between the value when the tip is far away from the surface and the actual value.

Some applications require more advanced controlling system. In such case so called phase-locked loop (PLL) is introduced. One finds the resonance frequency of the cantilever $f_{ref_{free}}$. When the cantilever gets close to the surface a phase shift appears. The PLL-electronic reacts and changes the driving frequency (looking for the actual valid$f_{resonance}$) until the phase shift is suppressed, i.e. the cantilever is always driven at the actual $f_{resonance}$. A preselected frequency shift is used as a set point and kept constant during the scanning procedure if the PLL-electronic is used (fig. 5). Actually two feedback loops are used in such case. One keeps constant (0) the phase shift and the second one keeps constant the frequency shift, i.e. the distance tip-sample surface.

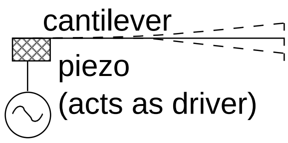


Figure 5: The driver is calibrated while the cantilever oscillates freely. Later the difference of the calibrated frequency to the new resonance frequency is used as input for a z-feedback controller, see text.

1.3 Resolution

Probably the most important property of any microscope is its maximum resolution. As I mentioned in the introduction, with AFM it's possible to recognize single atoms in a surface structure. (It's even possible to manipulate single atoms in the same manner but that's another subject...) Of course, not every microscope is able to reach such resolution. There are many factors which limit the maximum resolution e.g. mechanical vibrations, acoustic noise (can be suppressed by vacuum experimental conditions), electric noise and contamination of the sample surface. The shape of the tip is also an important factor in this context. One can not simply detect holes in the surface narrower than the scanning tip or distinguish the surface pattern if the distance of the surface objects is smaller than the tip size.

Artifacts might occur and limit the resolution as well (see AppendixB). Another point to think about is the motion and positioning of the cantilever in steps of nm: How can you reach such resolutions in the positioning of the AFM tip? How do you determine the exact position of the AFM tip?

1.4 Application

Scanning techniques have a broad range of application. Some branches of today's research couldn't have reached today's level of knowledge without them (e.g. nanophysics, advanced surface examinations, DNA and virus visualization, molecular design etc.) Of course, not for all of these AFMs are necessary, but often you can't use a STM because the current could harm the sample or destroy a labile molecule. Explicit applications of the AFM are for instance:

- determining impurities

- controlling surface finishing (of polished materials such as ceramics or metals for example)
- paint quality analysis
- surface quality control of optical components
- visualization of semiconductor structures

2 The EASYscan AFM system

The system used in this experiment is a EASYscan AFM by `Nanosurf AG`. It's small, relatively cheap and very simple to handle and control. I'll describe the components of this AFM here briefly. For more detailed info use the manufacturer documentation. (or take a look at: `http://www.nanosurf.ch`)

2.1 Overview

The AFM system consists of three main components: a microscope head with the scanning tip, an electronics and a power supply and a software. The whole system is controlled using a PC software. The software is used to control the measurements, visualize and analyze the data. The AFM is operated in static contact mode and it is relatively easy to handle it. It takes about 5-10 minutes to prepare everything for your experiment. It is much less in comparison with many more sophisticated microscopes which often require a lot of knowledge about the system and the experiment.

2.2 Scanning head, actuators, laser

The scanning head is the hexagonal piece mounted on the sample holder. It consists of the cantilever, some actuators to move the cantilever in the XY-plane and another actuator to move the cantilever up and down (Z-direction). The electromagnetic actuators behave similarly as piezoelectric-crystals usually used in AFMs but they performance is linear and they show no hysteresis.[1] The measurement requires a laser beam to detect the changes in the position of the cantilever tip relatively to the cantilever base. This is done by measuring the reflected beam (see 1.2.1). In the EASYscan AFM a IR laser (830 nm, power < 0.4 mW) is used. A photodetector measures the position of the incoming reflected beam. This signal (a current)is passed to the control electronics, see (next section2.3.1).

2.3 Control electronics

2.3.1 Layout

The layout of the control electronics is shown in fig. 6.

The *photodetector* transforms the position of the incoming reflected laser beam into a current. The current is converted into a voltage in the *I/U-convertor*. This signal (which is directly related to the bending of the cantilever) can be either directly taken as data for the imaging of very flat surfaces, or it's passed as input signal to the feedback loop. (The feedback loop system is described in the next section 2.3.2.) Both methods can be selected by the software (for details see 1.2.1, the first paragraph, the key word *y-value*).

[1] `Nanosurf AG` doesn't reveal what these actuators actually are made of.

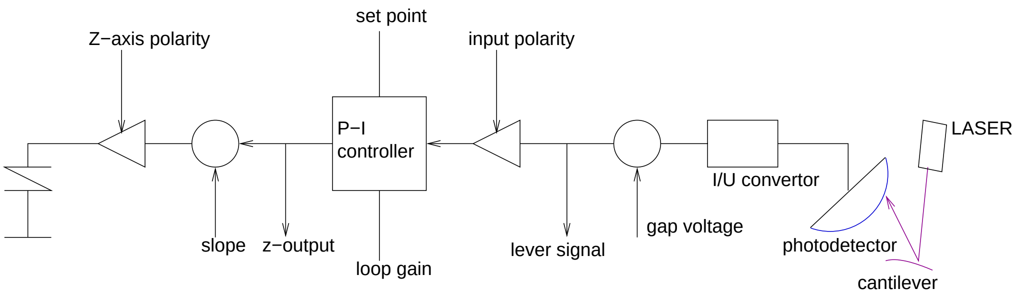


Figure 6: Layout of the electronics and data flow in the AFM system.

The user can adjust several parameters which influence the electronics performance. The most important are "set point" and "loop gain" for the feedback loop (in our case it's a PI-controller, see 2.3.2 below). With "slope" it's possible to compensate non-parallelism between the sample surface and the scanning plane which otherwise would be interpreted as a continuously ascending or descending surface.

2.3.2 PI controller

As I mentioned above (1.2.1 & 2.3.1) "set point" and "loop gain" are very important settings. They act upon the PI-controller (see [3]). PI-controller checks if the measured force corresponds to the force adjusted in "set point". The result of the comparison is subsequently used to control the Z-position of the whole scan unit above the sample surface via Z-actuator. The loop is repeated 3000 times per second. How fast the Z-adjustment is done is determined by the "loop gain" value. A small number causes a "lazy" behavior of the loop while a large number is responsible for undamped or slowly damped oscillations (see appendix B for an explanation and screenshots of this effect).

A described feedback loop allows to keep the AFM-tip - sample surface distance constant. The value (voltage) used to control the Z-actuator is the Z-output that is shown as the picture on the computer screen and it is directly related to the topography of the studied surface. If you switch off the PI controller, you still have a measurement. You monitor the bending of the cantilever, called the "lever signal". But take care! This only works in a small Z-range where the cantilever follows Hooke's law, i.e. *linear response*. If there are larger structures in the sample, the tip could touch it and be damaged! (see last paragraph in 1.2.1.)

2.4 Software

The AFM is controlled via the software running on a PC compatible computer. Essentially it's a user interface for the settings *scan range, scan speed, loop gain, set point, X- and Y-slope, ...* It also reads the *Z-data* or the *lever signal* prepared by AFM control electronics and draws nice pictures based of them. A proper calibration of the microscope allows to convert the obtained data to the topography image of the studied surface. The calibration means that we determine the Z-distance which corresponds to the certain change of the electronic signal. Included software tools allow to analyze the obtained data, e.g. they allow measuring of angles and distances. For more details see appendixA and the manufacturer manual.

3 Experiment / Tasks

It's important to become familiar with the instrument, to check out the user interface (UI), and to understand the influence of the aforementioned settings on the AFM-system performance.

The technical data sheet of the `Nanosurf` EASYscan AFM promises a Z-resolution of 0.3 nm (which is about the distance of single atoms!), and a lateral resolution in X- and Y-direction of 1.5 nm.

1. **Why there is the difference in the vertical and lateral resolution? Try to find an explanation!**

3.1 Characterization of the calibration grid

Characterization of the calibration grid is a good start if you want to become familiar with the microscope and the software. You'll find one in the sample box with other samples. It's a small squared chip (ca. 4x4 mm) mounted on a metallic sample holder using a double-sided tape. In the middle of the chip there is an area about 2x2 mm that has a different reflection than the rest of the surface. This indicates another surface structure which you will examine now.

Follow the steps described in 4.1 to prepare the sample and the AFM for the experiment, then switch the instrument on (4.2), approach the tip (4.3), and the first lines will appear on the screen. Adjust the slope (4.4) and enjoy the pictures appearing line by line.

After some lines you'll recognize the structure of the grid - regular bumps. (see scheme in fig. 7 and section 5.1). You can zoom in (4.5) or take "photos" (4.5). If you decide to do the latter, another window will open with a copy of the measured data. In this window you can use the tools included in the software and perform the data analysis:

1. **What's the period of the bumps, what's their height and width? Compare the figure below with a scanned picture! Is the description of the figure done properly?**

After this first result, you should experiment with different settings of *speed (s/line), set point, loop gain, forward scan, backward scan*... What is their influence on the AFM system performance? Try to find optimal settings that don't show any artifacts (B). However, they should be as fast as possible. What are this settings, write them down and use them later. Are they suitable for any surface?

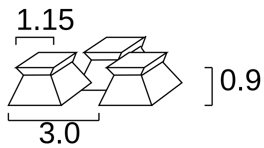


Figure 7: An illustration of the calibration grid. Dimensions are in μm.

3.2 A CD-ROM surface

There's a CD-ROM in the locker next to the door. Scan its data-side and show the topography (see 5.2).

1. **Measure the characteristic lengths of the observed structure! How are the data stored? What about a self made (burned) CD-ROM? Is there a difference?**

3.3 A semiconductor structure

There is another sample in the sample box - a metallic ring with a semiconductor structure. Make the details of the structure visible, zoom in as much as possible, change the settings you found during scanning on the calibration grid.

1. **What is the size of details which you are able to resolve? Are they artifacts or real? What is size of the semiconductor structure which can be used for the electronic circuit definition (the rest of the structure are leads). Show the force-distance profile obtained on the surface of the semiconductor structure, on the metallic leads and out of its area!** (There exists another software tool to do this described in the manual. Use a positive from-value and a negative to-value, it's more accurate than vice versa, fig. 19)

3.4 Your turn!

At this point you should be able to handle the instrument and know its limits. It's time for your own ideas. You should scan one or more samples which surfaces you would like to image. I can give you some ideas:

- If you always wanted to know how the surface of a floppy disc looks like or how is the structure of the surface of a plastic folder try to scan it!
- How does a scratch on the metallic surface look like?
- What about the detail of a pencil line on a piece of a paper?
- How does a hair look in μm-scale?
- How flat is the sapphire glass of your watches?

Measure characteristic lengths and heights, compare them with known macroscopic and atomic sizes.

4 HOW TO...

4.1 ... setup the scanning head and prepare the sample

Gluing of the sample on a little metallic disc makes its handling much easier. Please, use tweezers to handle the samples, and avoid touching of their surface. Take a piece of a double-sided tape and fix the metallic disc with the sample on the holder. Then unlock the scanning head from its safety position and put it in the scanning position (there are three holes without thread). Move the sample under the cantilever (it's only hardly recognizable) using two micrometric screws of the holding plate with the sample.

4.2 ... switch on the microscope and start the software

Plug the power supply in. A red LED starts to flash. Boot the computer in Windows 2000. There's no password required, just press `ENTER`. Start the AFM user interface via the icon "easyscan AFM". Now an AFM initialization - a short data exchange between the computer and the control electronics started. The software shows a progress bar, and once it is finished, the LED on the electronics changes to a steady green light. The microscope and the software are calibrated now and ready to scan.

4.3 ... approach the tip to the surface

Take a look at the microscope scanning head. You'll find two lenses right above the chip with the cantilever. One allows to see the cantilever from the top, the other from the side (see fig. 8).

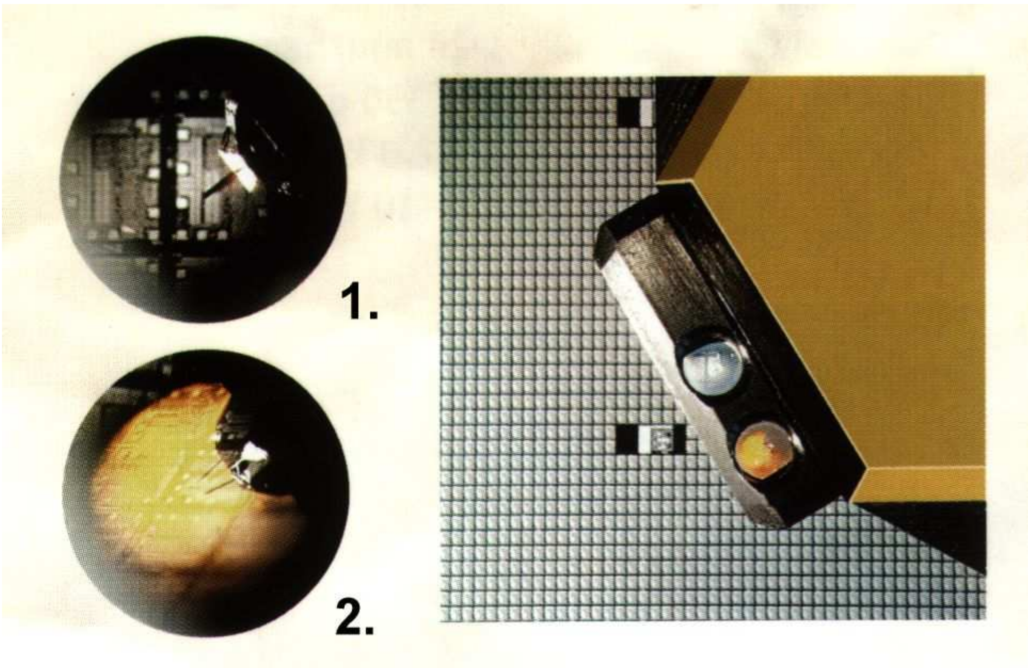


Figure 8: A photo of the scanning head with two lenses (right). Views through the two positioning lenses. 1. shows the cantilever from the top, 2. from the side.

Decrease the distance between the sample and the cantilever using three screws, but avoid crashing the tip to the surface! At the beginning you can't see the mirrored image of the cantilever on the sample surface in one of the lenses. As soon as this mirrored image appears (as shown schematically in fig. 9), do not use the positioning screws any more but the software interface.

Continue in approaching of the tip via the *Approach Panel* (see the screenshot in fig. 21, window number 7, button `DOWN`[↓]). Still control the height above the sample via the lens! If you find out you're close enough (scheme in fig. 10), it's time to use an automatic approach controlled by the software.

Enter a suitable value for the set point and click the `APPROACH`-button. If the calibration fails, change the set point slightly and try it once more. If it fails again, check if the

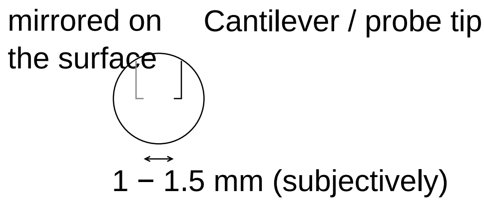


Figure 9: A scheme of the view trough the lens 2. The cantilever is mirrored on the probe. It is time to use the software interface for the tip approach.

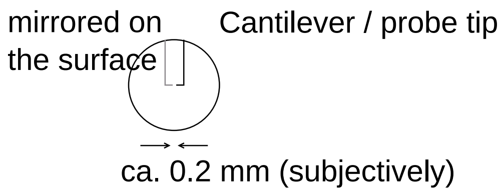


Figure 10: A scheme of the view through the lens 2 before the automatic (software-controlled) approaching. There's only a thin gap between cantilever and its mirrored image observable.

tip is "close enough" to the surface, and if it necessary adjust the distance. Otherwise click `WITHDRAW` and retry beginning with the `DOWN`[↓]-button.

Once the tip registers the predefined force (i.e. it's in the correct distance from the surface), the microscope starts scanning by itself. You can see how the picture develops line by line, and the `START` button in the upper left corner of the window switches to a pressed status and shows the label `STOP`. If you click on it, it will take a short time to finish the current scan line, then the AFM will reset and the button will be switched back to `START`.

4.4 ... define the position and the slopes of the sample

In the UI (in the *scan panel* to be more precise) you can see several different presentations of the acquired data. At the beginning there's one very important view upper-left (called ZOutput[...]-Raw-LineView). It shows the profile of the currently scanned line. Your first task is to define the slopes in the X- and Y-direction. Because the sample and the scanning plane of the microscope head are very probably not exactly oriented in the same plane, one can correct this via the UI. You have to adjust the slope value in the one direction first, then rotate the scanning direction by 90° and adjust the slope again.

Of course, if you zoom-in you probably will have to adjust the slopes more precisely.

4.5 ... zoom-in and take "photos"

You should set the scanning region to it's maximum size (about 80μm in each direction) at the beginning of the experiment. After localization of interesting structures on the sample surface, you can zoom in and focus on these structures. In the window presenting the top view you can draw a square by clicking the left mouse button in each corner. You can also move this square around and double-click at the end. The double-click determines a new scanning region, and the old picture will be overwritten.

Press the `PHOTO` button to save collected data. It takes a short time (1-2 seconds) and another window containing an exact copy of the data will pop up *behind* the work bench. Make this window active, and subsequently activate any view in the “photo”. Now the “file”-“save” menu can be selected to save the data.

4.6 ... take measurements using the tools and print

You can use tools for measuring lengths or heights. The procedure is quite simple: you select a tool and you define dimensions you want to measure by mouse-clicks. It’s very easy if you know any drawing tool (software) and it’s quite intuitive if you don’t. For further assistance consult the manual, or look at the figures in the appendix.

If you want to print your results, make sure that the computer at the STM experiment is running (printer sharing), and the printer too, of course. Then activate the window you want to print, use the tool, which results you’d like on the print too, or activate any view in the window. Finally press the print button, or select “file”-“print”. The HP DeskJet should be the default printer, and after several seconds, it should start printing.

4.7 ... change the probe

CAUTION! Make sure the laser is switched off before you continue! It can happen that your images don’t show any reasonable structure but only artifacts, or the image quality gets worse and worse. One of the reasons can be that the probe is polluted or has suffered damage from a “tip crash”. In this case, you can change the cheap with the cantilever.

You must turn the scanning head upside down. Near the cantilever you’ll find a small hole, where you insert **carefully** the *sensor change tool* (it is stored in the locker). The holding flap opens and you can remove the chip (see fig. 11 for a scheme).

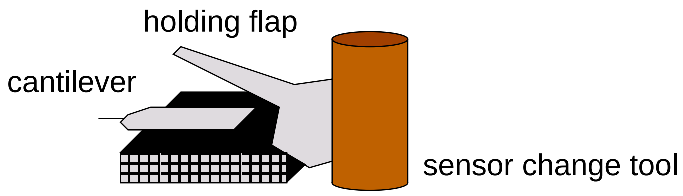


Figure 11: The cantilever sits on its holder, change tool is inserted into the hole and flap is open.

Take a new cantilever out of the box. You should slightly turn it left and right with the tweezers during this procedure since it is glued to a transparent foil (see fig. 12).

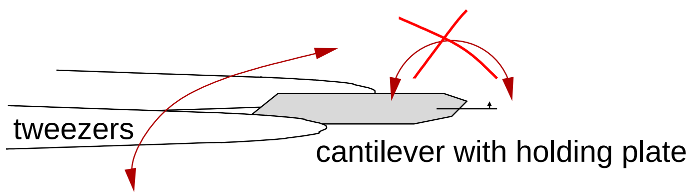


Figure 12: Remove the cantilever from its storing position carefully.

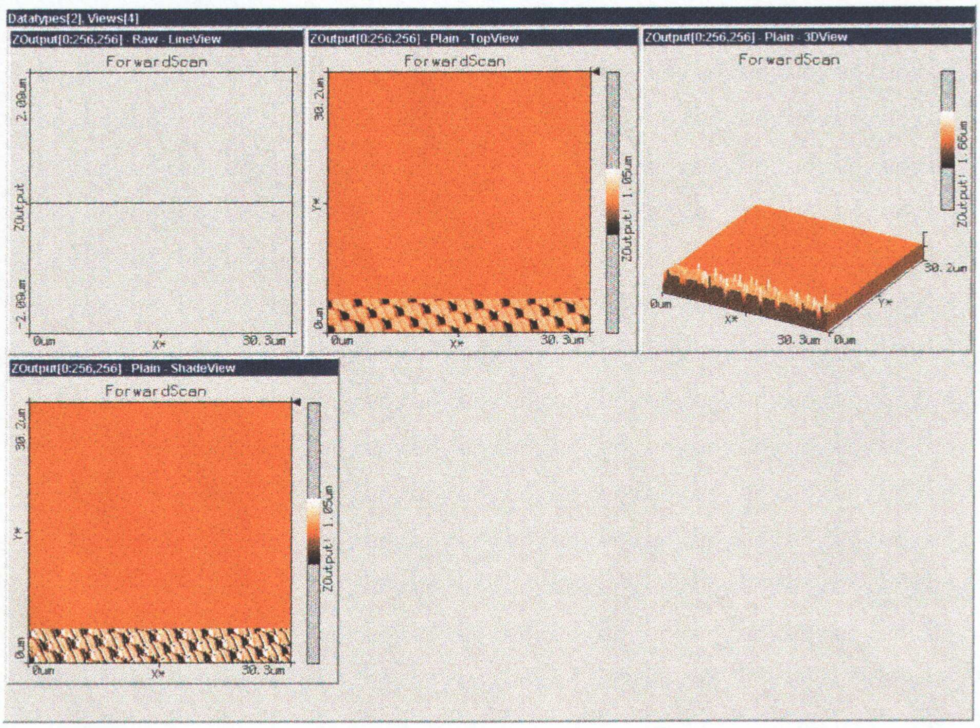
Put it on the holder and remove the sensor change tool slowly **slowly**. The holding flap fixes the new cantilever.

5 Examples

Some pictures imaging surfaces of different samples often taken with the varying AFM settings.

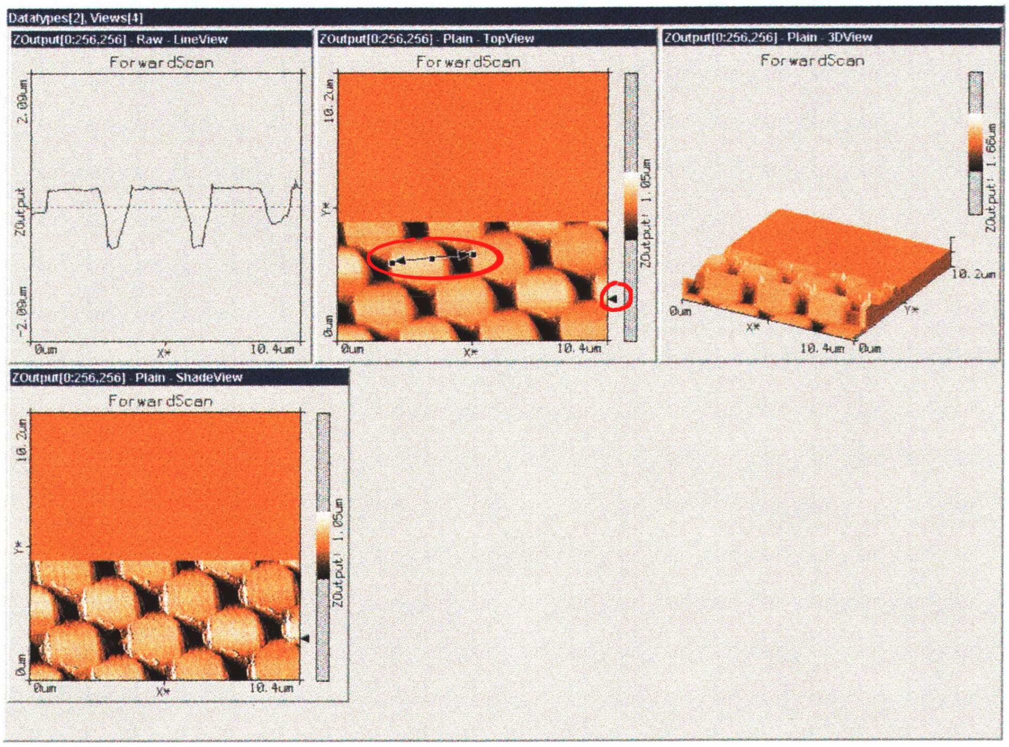
5.1 Calibration grid

The first three prints show a part of the calibration grid. The pictures aren't complete but they show all the essential. The first figure gives you an idea how the AFM picture is developing line by line. The second shows an example of the distance determination in the 2D top view, the third shows the height determination in the profile.



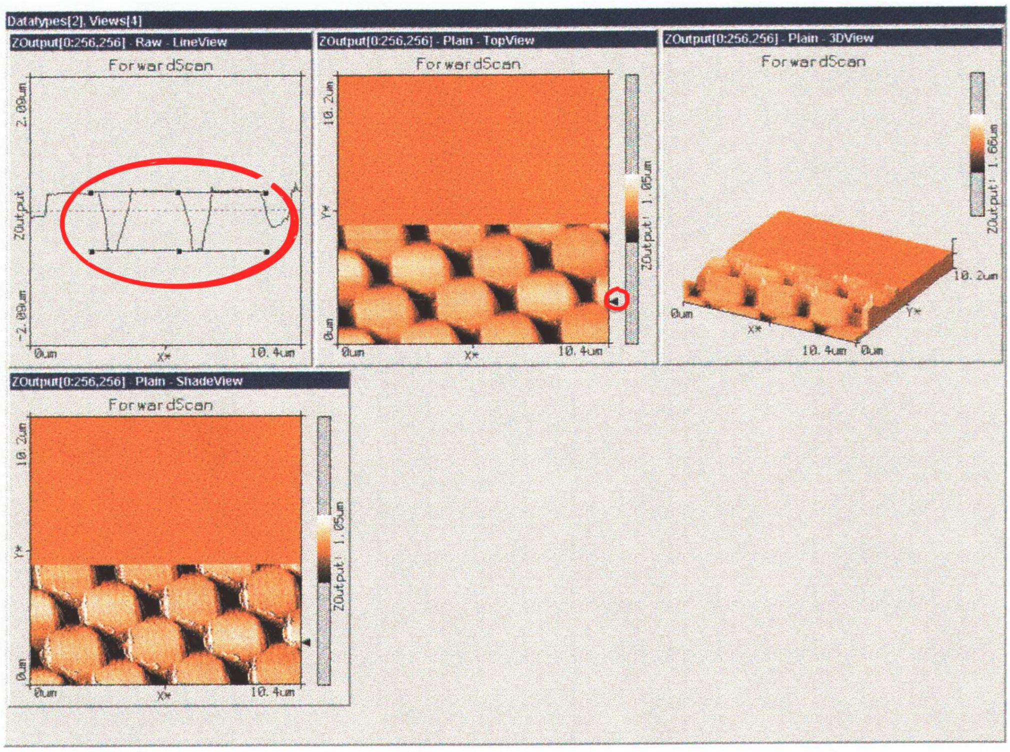
-- Scan --		ZOffset	= 1.43um
ScanRange	= 30.3um	Date	= 19-11-2001
ZRange	= 4.19um	Time	= 11:10:12
InputRange	= 1.94um	-- Feedback --	
Time/Line	= 1.6s	SetPoint	= 49.2nN
ScanDir	= Up	LoopGain	= 12
XSlope	= 0.66	LoopMode	= Run
YSlope	= -0.45	-- Global --	
Rotation	= 90	ScanHead	= AFM
XOffset	= 0um	Mapping	= scanhead.map
YOffset	= 0um		

Figure 13: The first lines of the scan on the calibration grid. The *scanning range* is more than 30 μm.



-- Tool --		XOffset	= 0um
Length	= 3.13um	YOffset	= 0um
DeltaZ	= 0.115um	ZOffset	= 2.23um
-- Scan --		Date	= 19-11-2001
ScanRange	= 10.4um	Time	= 11:42:38
ZRange	= 4.19um	-- Feedback --	
InputRange	= 1.94um	SetPoint	= 49.2nN
Time/Line	= 1.6s	LoopGain	= 12
ScanDir	= Up	LoopMode	= Run
XSlope	= 0.66	-- Global --	
YSlope	= -0.45	ScanHead	= AFM
Rotation	= 90	Mapping	= scanhead.map

Figure 14: The *length tool* was used between corresponding points in the *TopView* to determine the period of the grid. The *scanning range* is about 10 μm now.

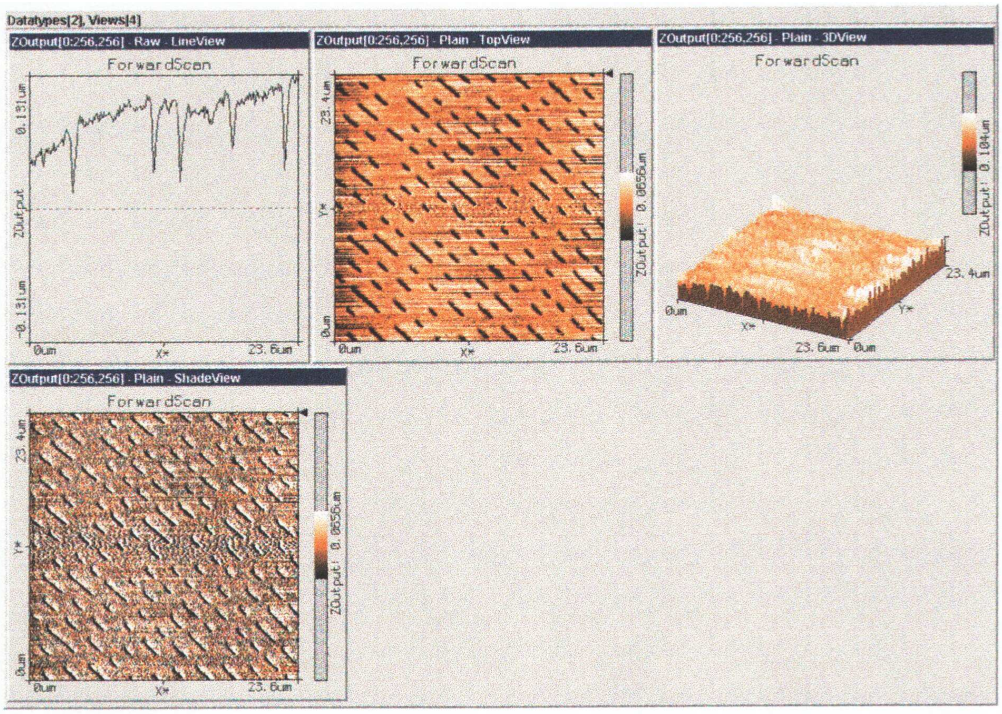


-- Tool --		YOffset	= 0um
Distance	= 0.924um	ZOffset	= 2.23um
-- Scan --		Date	= 19-11-2001
ScanRange	= 10.4um	Time	= 11:42:38
ZRange	= 4.19um	-- Feedback --	
InputRange	= 1.94um	SetPoint	= 49.2nN
Time/Line	= 1.6s	LoopGain	= 12
ScanDir	= Up	LoopMode	= Run
XSlope	= 0.66	-- Global --	
YSlope	= -0.45	ScanHead	= AFM
Rotation	= 90	Mapping	= scanhead.map
XOffset	= 0um		

Figure 15: The *distance tool* was used in the *LineView*. It allows to determine a height of the structures. One can see that the height of the bumps on the grid is about 1μm.

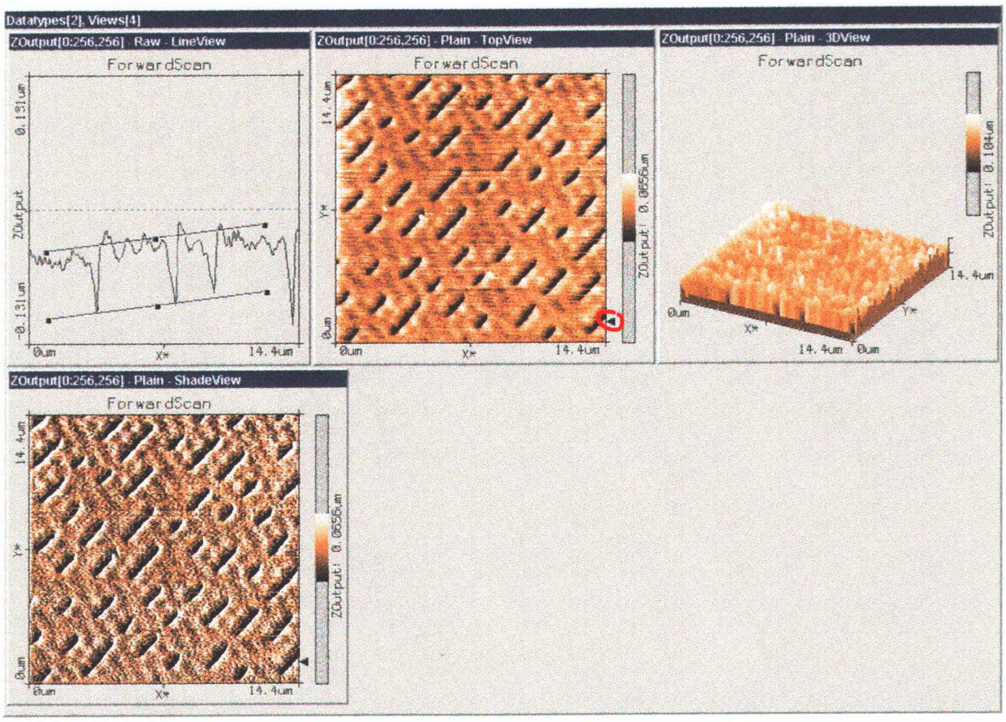
5.2 CD-ROM

The next two pictures show the surface of a CD-ROM disc in two different resolutions. In the second picture you can't only see the profile, but also artifacts between two pits. The so called "land" should be flat, but the AFM picture shows little bumps.



-- Scan --		ZOffset	= -1.78um
ScanRange	= 23.6um	Date	= 19-11-2001
ZRange	= 0.262um	Time	= 12:44:33
InputRange	= 1.94um	-- Feedback --	
Time/Line	= 1.49s	SetPoint	= 60.7nN
ScanDir	= Up	LoopGain	= 12
XSlope	= 0	LoopMode	= Run
YSlope	= 2.86	-- Global --	
Rotation	= -1.8	ScanHead	= AFM
XOffset	= 1.98um	Mapping	= scanhead.map
YOffset	= 1.17um		

Figure 16: An initial scan of the surface of the pressed CD-ROM.

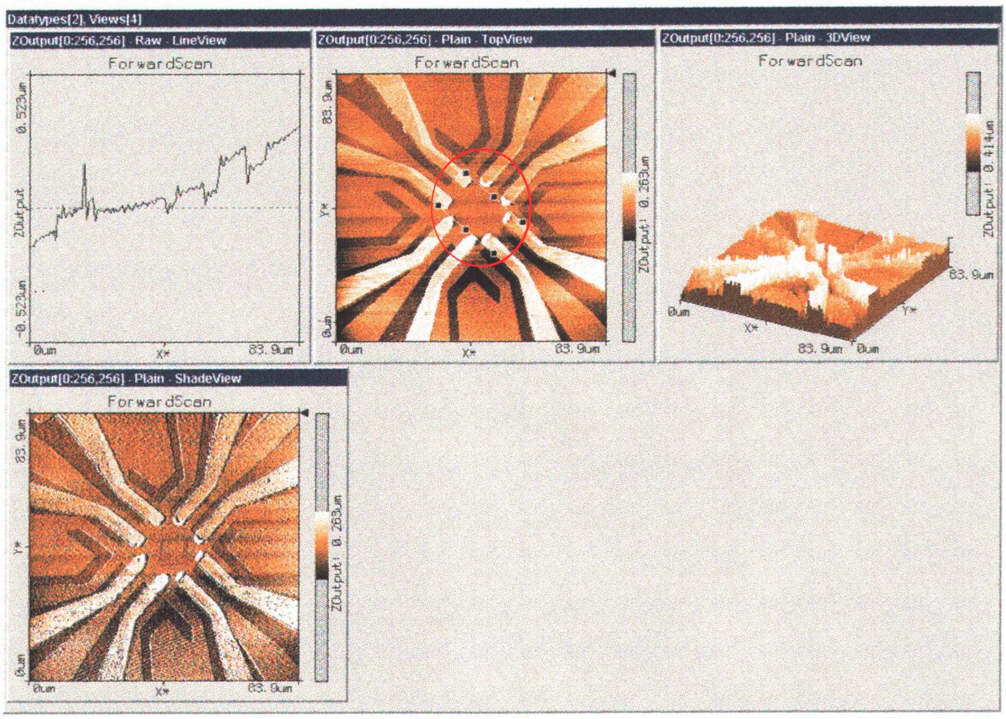


-- Tool --		YOffset	= 4.53um
Distance	= 0.0667um	ZOffset	= 0.665um
-- Scan --		Date	= 19-11-2001
ScanRange	= 14.4um	Time	= 13:04:00
ZRange	= 0.262um	-- Feedback --	
InputRange	= 1.94um	SetPoint	= 60.7nN
Time/Line	= 0.493s	LoopGain	= 12
ScanDir	= Up	LoopMode	= Run
XSlope	= -0.5	-- Global --	
YSlope	= 2.94	ScanHead	= AFM
Rotation	= -90	Mapping	= scanhead.map
XOffset	= -2.54um		

Figure 17: A detailed scan of the surface of the pressed CD-ROM. The *distance tool* was used to determine the depth of the *holes:* about 0.06 μm.

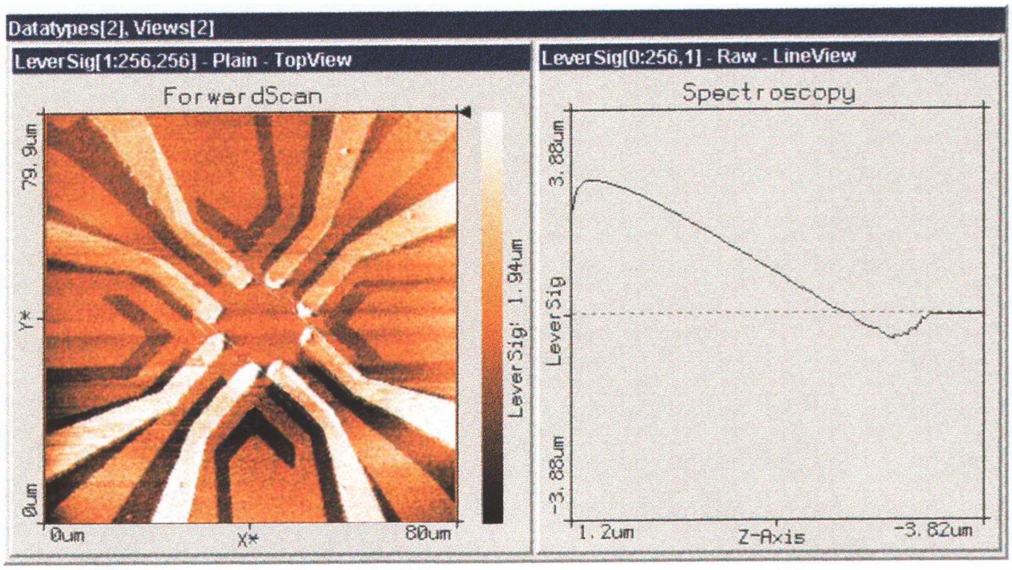
5.3 Chip structure

An overview of a semiconductor chip is what you see on the next picture. In the square area in the middle (which measures about $13 \times 13\mu$m) the semiconductor device or circuit will be prepared. The 8 arms are the leads which contact structure in the center to the contact pads at the edge of the chip.



-- Tool --		YOffset	= 0um
Distance	= 13.1um	ZOffset	= -0.921um
-- Scan --		Date	= 19-11-2001
ScanRange	= 83.9um	Time	= 13:43:06
ZRange	= 1.05um	-- Feedback --	
InputRange	= 1.94um	SetPoint	= 60.7nN
Time/Line	= 1.49s	LoopGain	= 12
ScanDir	= Up	LoopMode	= Run
XSlope	= -0.4	-- Global --	
YSlope	= 1.43	ScanHead	= AFM
Rotation	= 0	Mapping	= scanhead.map
XOffset	= 0um		

Figure 18: The middle part of the chip. The *Distance tool* was used to measure dimensions of the free area in the center where devices like transistors can be prepared.

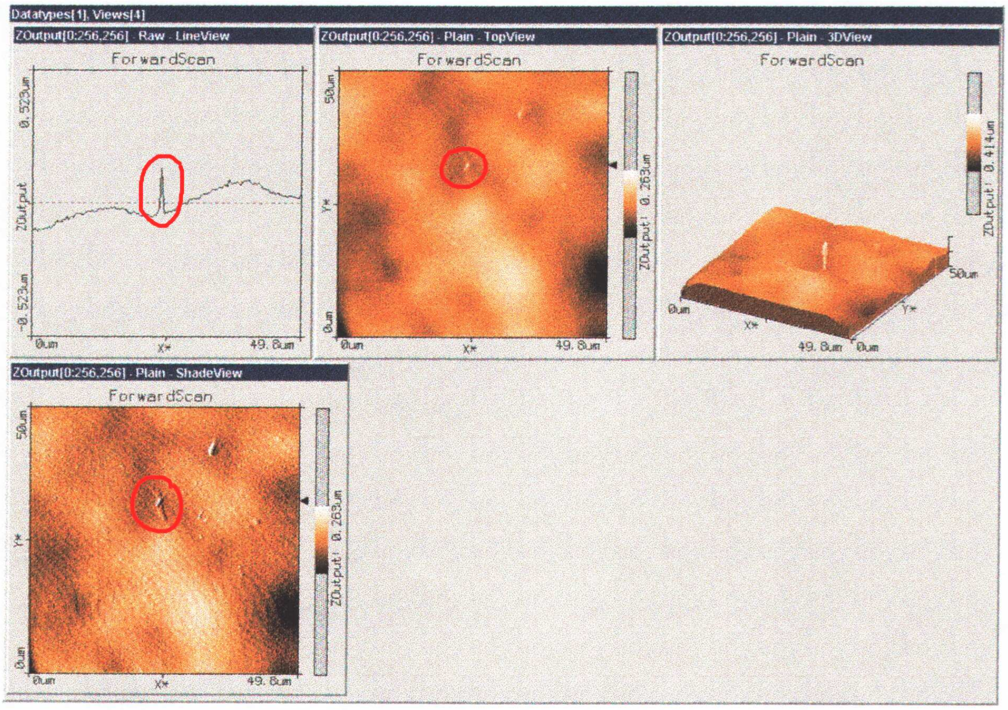


-- Spec --		AbortMode	= StopSpec	YOffset	= 0um
ModOutput	= Z-Axis	Date	= 10-12-2001	ZOffset	= -2.75um
ModFrom	= 1.2um	Time	= 12:15:10	Date	= 10-12-2001
ModTo	= -3.82um	-- Scan --		Time	= 12:06:00
Time/Mod	= 1s	ScanRange	= 80um	-- Feedback --	
Relative	= TRUE	ZRange	= 2.09um	SetPoint	= 40nN
Samples	= 256	InputRange	= 1.94um	LoopGain	= 11
Averages	= 32	Time/Line	= 0.5s	LoopMode	= Run
Points	= 1	ScanDir	= Up	-- Global --	
XFrom	= -23.4um	XSlope	= 0	ScanHead	= AFM
YFrom	= -35.2um	YSlope	= 0	Mapping	= scanhead.map
InpRange	= 7.75um	Rotation	= 0		
InpOffset	= 0um	XOffset	= 0um		

Figure 19: The force-distance dependence measured on the chip. When you prepare the measurement, pay attention to the boundary values for the Z-axis!

5.4 Graphite surface

The last picture of this series shows a graphite surface. There's visible one dominant structure - a sharp peak. It is difficult to say what is material of this structure. It can be a piece of graphite or a piece of dust of an unknown origin. One can get more information about the peak using e.g. the force-distance curve measurement or the STM.



-- Scan --		ZOffset	= -1.48um
ScanRange	= 49.8um	Date	= 26-11-2001
ZRange	= 1.05um	Time	= 09:48:50
InputRange	= 1.94um	-- Feedback --	
Time/Line	= 1s	SetPoint	= 101nN
ScanDir	= Up	LoopGain	= 11
XSlope	= 0	LoopMode	= Run
YSlope	= 2.59	-- Global --	
Rotation	= 0	ScanHead	= AFM
XOffset	= 0um	Mapping	= scanhead.map
YOffset	= 0um		

Figure 20: The surface of a piece of graphite. A sharp peak in the center of the picture is the dominant structure on the surface. The "structure" you can see are *artifacts*, not single atoms!

A UI of the software

In fig. 21 is shown design of the window of the UI. The *Scan Panel* (1) is the *main window* with the different presentations (2-dimensional view, 3-dimensional view, shadow view etc.) of the collected data. These views can be set up in the *View Panel* (5). The buttons in the group 2 open the *Approach Panel* (7), the *Scan Panel* (1), the *Feedback Panel* (6) and the *Spectrogram Panel* (not shown here; used for force-distance profiles measurements). The buttons in the group 3 are for opening the *View Panel* (5), the *Data Info Panel* (8) and the *Tools Info Panel* (9). The *The Result Panel*, which is accessed from the 4th button in this group, isn't shown. It's also opened automatically by using any tool from the group 4. There are three tools which can be used to measure lengths, heights and angels. The input box (10) below the views allows to enter the control parameters for the microscope electronics as mentioned in 2.4.

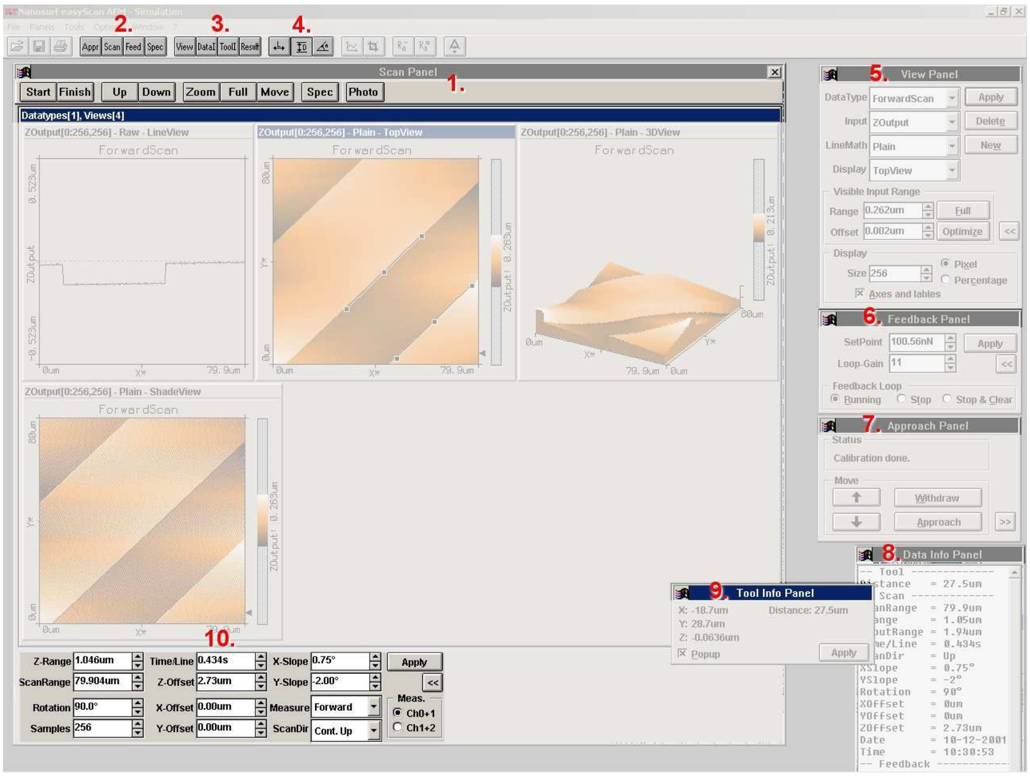


Figure 21: The window of the UI.

B Artifacts

As I mentioned in 1.3, artifacts can appear during the scanning procedure and complicate the evaluation of measured data. They can even get so dominant that you can't recognize any structure anymore. Probably two most important reasons are the PI-controller adjustment and the scanning speed. The following examples will help to clarify it: Let's assume that there is a sharp step on the surface. If the probe hits the step with high velocity PI controller is not able to react fast enough. It means that the studied structure is blurred or even not visible and the tip can be damaged in the worse case. Of course, one can always change the adjustment of the PI controller so it will react faster. However, such adjustment can become an origin of another kind of artifacts. When the tip reaches the edge of the step and feedback is reacting to fast, the Z-position will be over-corrected and oscillations will appear (fig. 22). On the other hand, low scanning speeds make the procedure extremely long. It's important to find a reasonable compromise.

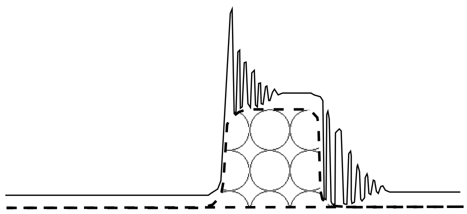
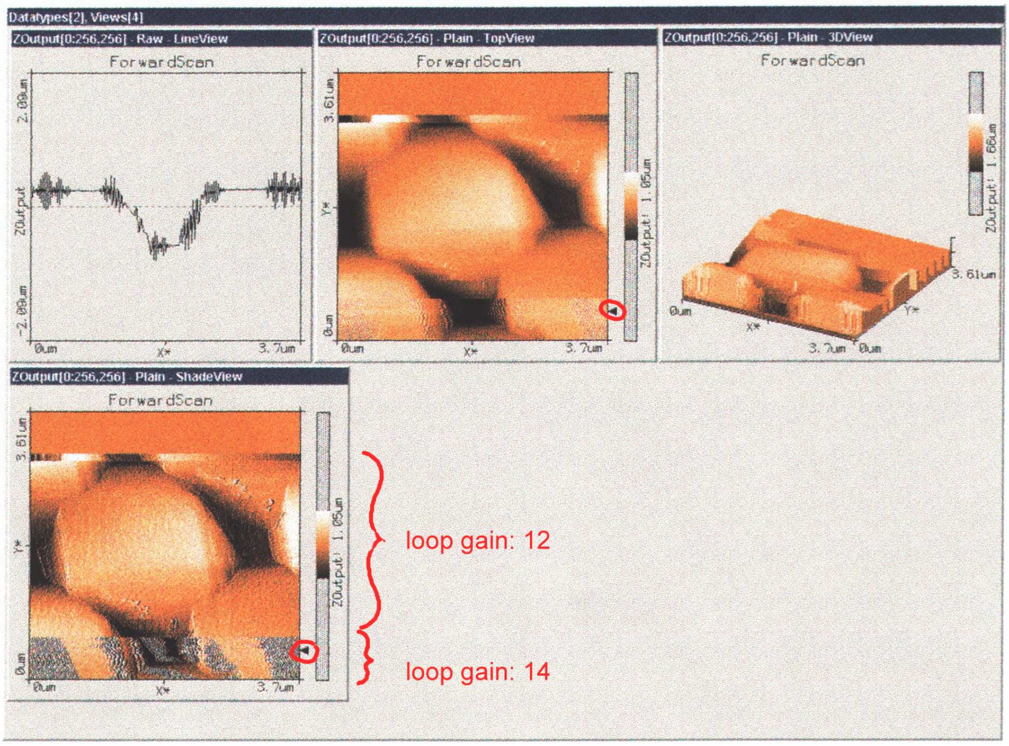


Figure 22: An influence of incorrect adjustment of the PI controller on the obtained results is shown in the schematic cross section of the scanning image. The PI controller is reacting too fast and oscillations appear during the scanning procedure.

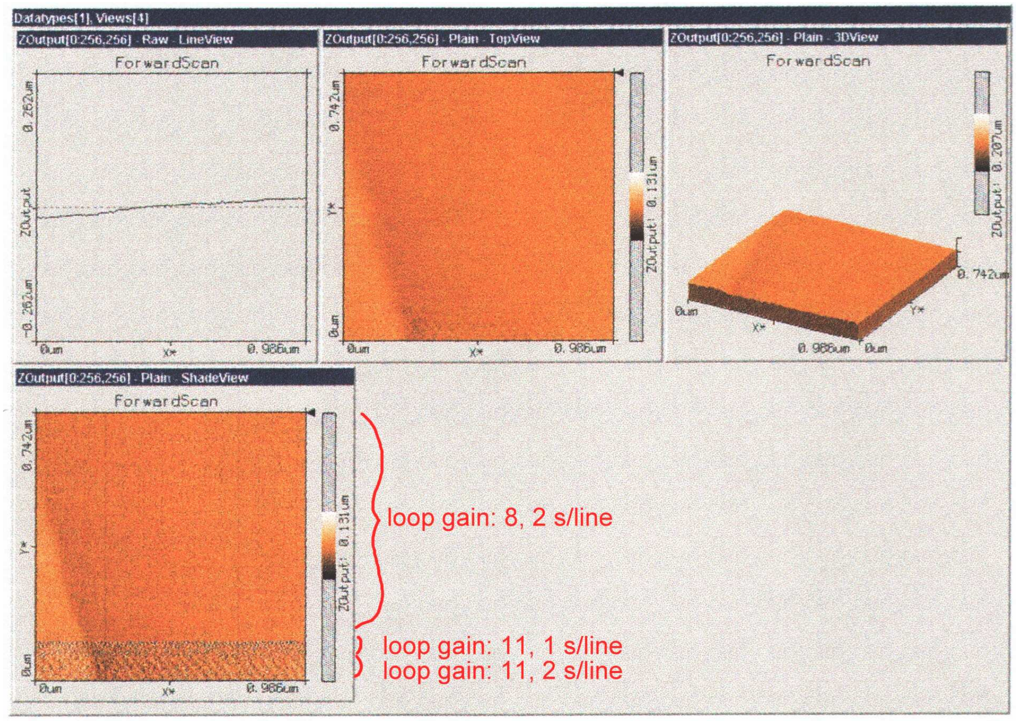
Fig. 23 illustrates an effect of the PI controller adjustment on the real scanning image if the feedback is too fast. The calibration grid was used in this experiment. The picture was taken with a constant *scan speed* of 1.6 s/line. Two different *loop gains* of 12 and 14 are used, the difference is obvious in the top view and in the cross-section view as well.

The next picture shows the graphite surface and illustrates the influence of different *loop gains* and *scan speeds* on the behavior of the scanner. While in the lower two sections *loop gain* is set to 11, in the upper part it's 8. If the *scan speed* value 2 s/line *loop gain* value of 11 gives an AFM image of the reasonable quality. However after an increase of the *scan speed* to 1s/line PI controller is not fast enough anymore. The same result one gets for the speed 2s/line if the *loop gain* is adjusted to 8.



-- Scan --		ZOffset	= 0.0197um
ScanRange	= 3.7um	Date	= 19-11-2001
ZRange	= 4.19um	Time	= 12:08:10
InputRange	= 1.94um	-- Feedback --	
Time/Line	= 1.6s	SetPoint	= 49.2nN
ScanDir	= Up	LoopGain	= 14 upper part: 12
XSlope	= 0.66	LoopMode	= Run
YSlope	= -0.45	-- Global --	
Rotation	= 90	ScanHead	= AFM
XOffset	= 1.98um	Mapping	= scanhead.map
YOffset	= 1.17um		

Figure 23: A high detail of the calibration grid. The picture was obtained with *two different loop gain values*. The region where the loop gain 14 was used shows a lot of artifacts due to the instability of the feedback.



-- Scan --		ZOffset	= -0.885um
ScanRange	= 0.986um	Date	= 26-11-2001
ZRange	= 0.523um	Time	= 10:40:46
InputRange	= 1.94um	-- Feedback --	
Time/Line	= 2.1s	SetPoint	= 101nN
ScanDir	= Up	LoopGain	= 8
XSlope	= 0	LoopMode	= Run
YSlope	= 2.59	-- Global --	
Rotation	= 4	ScanHead	= AFM
XOffset	= -1.26um	Mapping	= scanhead.map
YOffset	= 6.35um		

Figure 24: A high detail of the graphite surface. Even at this resolution you can't see atoms. The noisy "structure" in the lowest part of the AFM images are *artifacts*, not single atoms. The picture illustrates the influence of different *loop gains* and *scan speeds* on the behavior of the scanner.

C Image modes continuum

The table 1 shows a list of the various image modes and their basic characteristic. It's taken from [2]. Performance of the scanner depends on the influence of the environment (e.g. mechanical vibrations, acoustic noise and electric noise). One can significantly improve a quality of the images paying attention to this influence.

Mode	Type	Force regime	Feedback method	Cantilever type	Cantilever freq. [kHz]	Cantilever ampl. [Å]	Lateral resol.
DC (contact)	Contact	Repulsive	Displace-ment	Soft	0	0	High
Lateral force	Contact-friction	Repulsive	Displace-ment	Soft	0	0	High
Force modulation (Spectrosc.)	Contact-compliance	Repulsive	Displace-ment	Soft	5	5-10	High
DC (attractive)	Non-contact	Attrac-tive	Displace-ment	Soft	0	0	Low
Low ampl. resonance	Non-contact	Attrac-tive	Phase or ampl. shift	Hard	5-500	2-100	Low
High ampl. resonance	Non-contact	Attrac-tive	Phase or ampl. shift	Hard	50-500	100-1000	Low

Table 1: A list of the various image modes and their basic characteristic.

D Figures, tables & references at a glance

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References

[1] *Physik*, Paul A. Tipler, Spektrum Akademischer Verlag, Nachdruck 1995

[2] TopoMetrix technical report, *AFM Imaging Modes*, TopoMetrix technical report, TopoMetrix Corporation, Santa Clara, CA 95054

[3] ABB Online Database, *PI-Controller*, see:
http://www.abb.com/global/abbzh/abbzh251.nsf!OpenDatabase&db=
/global/seapr/seapr035.nsf&v=63136&e=us&c=
F8BF4F317333AFAEC1256903003918DA