Fortgeschrittenen Praktikum I:

Rastertunnelmikroskop

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Contents

1 Introduction

A Scanning Tunneling Microscope (STM) is a device to resolve tiny structures like the topographic structure of atoms in lattices in a three-dimensional image.
The basic physical principle of the microscope is the quantum mechanical tunnel effect. A superfine metal tip is brought very closely to the cunducting surface of a sample ($\leq$1nm) so a tunneling current is measurable if a voltage is applied. With a piezo crystal the tip is then moved across the surface.
The resolution of the microscope heavily depends on the used piezo and the shielding against electrical and mechanical disturbance. Also there occure a few image defects like the hysteresis of the piezo and the thermal drift. However if it is managed to obtain a tip which is sharp on an atomic level the microscope has a resolution on an atomic scale (> 1Å). The resulution in the hight of the structure even goes down to 1pm.
This experiment shall introduce the student to the principles of the Scanning Tunneling Microscope by means of different sorts of samples.

2 Tasks

1. The structure of the half-metal graphite should be resolved and measured. Because graphite is the simplest sample to handle in this experiment, it is good for testing the goodness of the tip.
2. The topography of gold will be examined (scanrange around 200nm).
3. A sample of a semi-conductor (TaS_2) is observed in a similar way as graphite. In addition the two sorts of atoms should be distinguished by reversing the polarity of the tip voltage.

3 Theoretical Background

3.1 Quantum Tunneling [2]

The tunnel effect is a typical quantum mechanical phenomenon. It occurs because every particle is represented by a specific wave function $\Psi(\vec{r})$ which has a certain spatial expansion. When the wave function hits a (finitely high) potential barrier, it decays exponentially. Therefore there is a probability of presence $|\Psi(\vec{r})|^2 \neq 0$ on the other side of the barrier.

A commonly used example of the tunnel effect is the following.

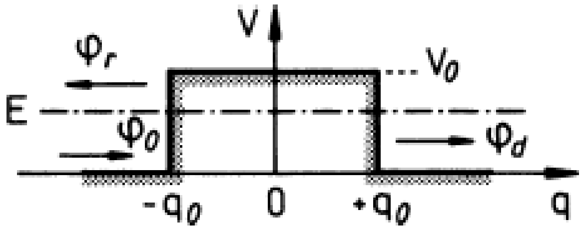


Figure 1: Illustration of the problem: φ_0: incident wave; φ_r:reflected wave; φ_d: transmitted wave; V_0: potential; $\pm q_0$: size of the wall [2]

The potential function of this problem is:

$$V(q) = \begin{cases} V_0 & \text{if } |q| \leq q_0 \\ 0 & \text{else} \end{cases}$$

The incident wave is a plain wave:

$$\varphi_0(q) = e^{ik_0 q}; \quad k_0^2 = \frac{2m}{\hbar^2}E$$

The reflectded and transmitted waves are also plain waves, however they have different amplitudes.

$$\varphi_r(q) = \rho e^{ik_0 q} \quad \varphi_d(q) = \tau e^{ik_0 q}$$

The wave function inside the barrier is written as:

$$\varphi(q) = \alpha e^{ikq} + \beta e^{-ikq}; \quad k^2 = \frac{2m}{\hbar^2}(E - V_0)$$

The problem is solved by using the requirement of continuously differentiability at the potential borders. Plugging in energies ,that are lower than the potential barrier yields a transmission probability $|\tau|^2 > 0$, which means that the electron can tunnel through the barrier.

$$T = |\tau|^2 \mathrel{\tilde{\propto}} e^{\frac{4q_0}{\hbar}\sqrt{2m(V_0-E)}}$$

In classical mechanics the electron had no chance of getting through the barrier, if $E < V_0$.

The scanning tunneling microscope uses this effect by measuring a (tunnel) current after a voltage is applied between the microscope needle and the sample that one is observing.

3.2 Scanning Tunneling Microscope (STM)

The main parts of the STM are

- the metal needle, that should have a tip as small as an atom.
- the Piezo elements, that move the needle on an atomic scale ($\sim \frac{1}{10}$Å).
- a computer, that converts the measured tunnel current into distances.

At first a potential difference between the needle and the sample is applied. A measurable tunnel current (a few nA) is observed after lowering the distance between the needle and the sample to ~ 10Å. In addition the sample should be a metal, a semiconductor or a metalloid.

As seen in section 3.1 the tunnel current is proportional to the transmission probability ($eU \ll \Phi$, d and q_0 are similar).

$$T \propto I \propto U e^{\sqrt{\frac{2m\Phi}{\hbar}} d}$$

Φ is the effective barrier height. The interpretation of the surface on an atomic scale is the one of a charge density. The only electrons that are affected by the tunnel effect have an energy close to the Fermi energy E_F in the metal. As a result this interpretation is not quite correct.

There are different modes the STM can work on. At the **constant current** mode the the tip is moved over the surface and the program tries to keep the tunneling current at a constant value. The surface is generated by converting the Piezo voltages into hight values. The **constant height** mode keeps the tip at a constant height and converts the tunneling current into height values. The oversteering effect (mentioned in section 6.1) will not appear in this mode, but it is more likely that the tip is going to crash into higher layers. Hence in this experiment the STM is used in constant current mode.

3.3 Samples

3.3.1 Metal

Metals are good conductors and the atoms are arranged as a lattice. The Fermi niveau is located in the valence band. As a result, the valence electrons can move freely in the metal. The charge density observed with an STM is almost constant. Nevertheless, missing atoms leave holes, that can be observed because the charge density drops in these holes.

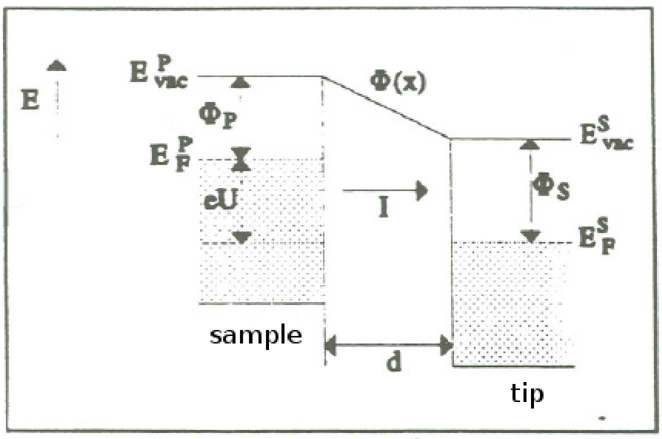


Figure 2: Illustration of the energy levels of the sample (metal) and the needle tip; Φ_P,Φ_S are the escape energies.[1]

3.3.2 Semiconductor

Semiconductors have two bands: the valence band, which is completely populated at $T = 0\text{K}$ and the conducting band, which is not populated at all at $T = 0\text{K}$. At higher temperatures it is possible that electrons move into the conducting band with thermal excitation making the semiconductor conductive. So at higher temperatures the semiconductor is a conductor and at lower temperatures it is an isolator.

If observing a semiconductor with an STM the tunnel effect is not quite the same. The current direction determines which atoms in the semiconductor are observed. This occurs because the valence band electrons are close to atoms of one certain element and the conduction band electrons are close to atoms of another certain element.

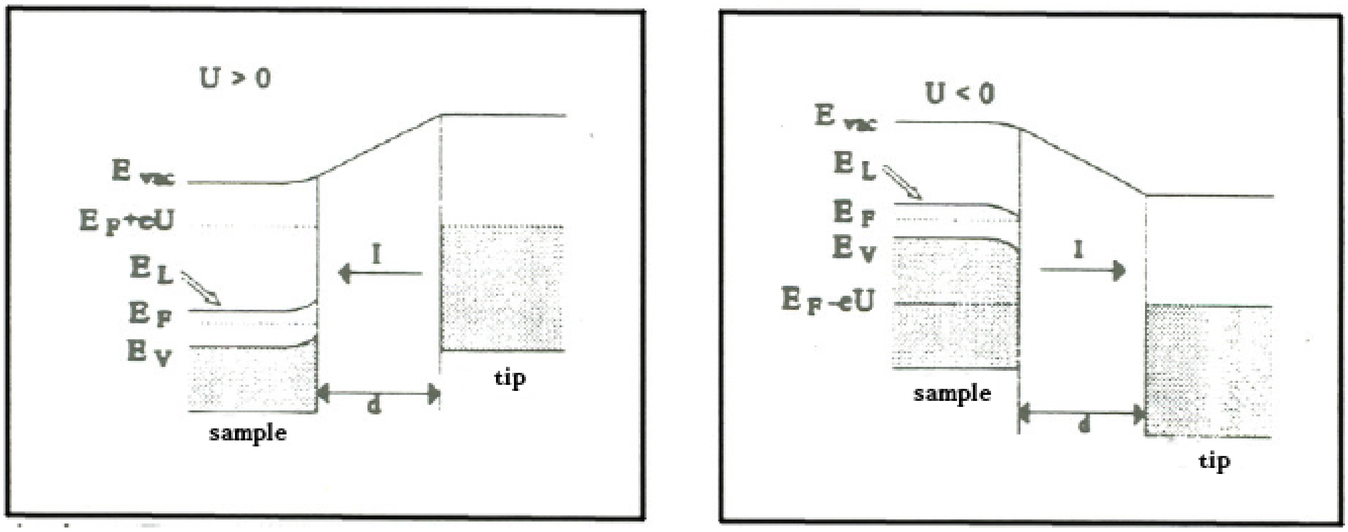


Figure 3: Illustration of the energy levels of the sample (semiconductor) and the needle tip; On the left the voltage is positive. On the right the voltage is negative.[1]

3.4 Metalloid (Graphite)

Graphite has a two dimensional hexagonal structure consisting of carbon atoms. It is made of many layers, that are connected by Van-der-Waals forces. There are two different kinds of carbon atoms: α-atoms are next to an atom of an adjacent layer and β-atoms have no neighbour atom in an adjacent layer. β-atoms have almos all conductive electrons. As a result the metalloid is conductive along the surface, but is non-conductive through different graphite layers. So it is possible to see the single atoms of graphite.

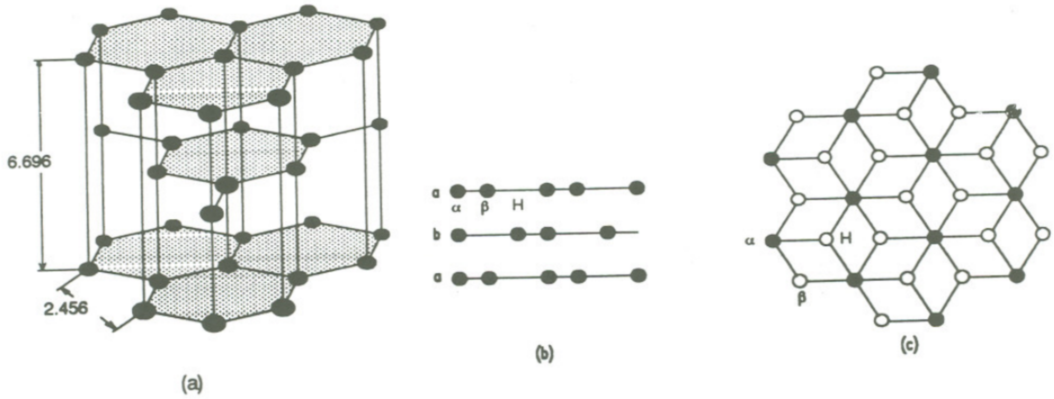


Figure 4: Crystal structure of graphite: (a) arrangement of the different layers (b) different sorts of atoms α a neighbour underneath and β without one (c) sight from above [1]

3.5 Piezoelectric Elements [1]

Piezoelectric elements have two main features: they change their shape, when a voltage is applied and they can produce voltage, when deformed. The ions in the piezo crystal are arranged in a way that the net charge is 0. Deforming the crystal moves the ions and the net charge becomes $\neq 0$. The other way around the piezo can be deformed by applying a voltage. In this experiment the first feature is used.
The order of magnitude at which the Piezo can change its shape is $\frac{1}{10}$Å.

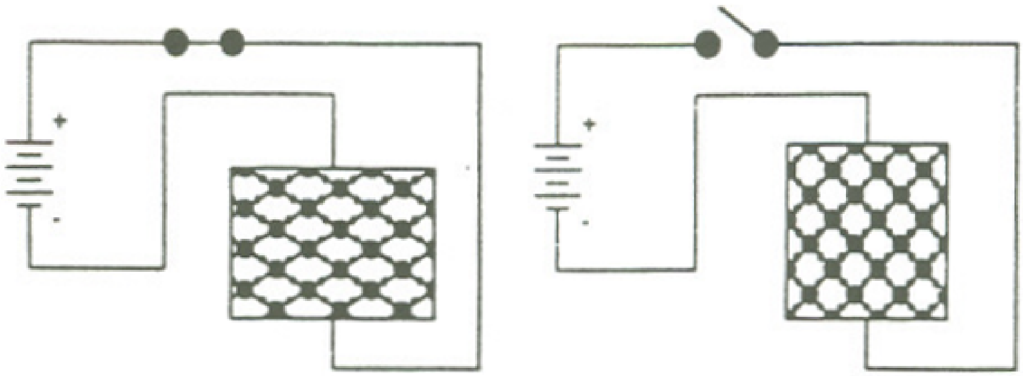


Figure 5: A piezoelectric crystal with (left) and without (right) applied voltage.[1]

4 Experimental Setup

The microscope (Easyscan 2, Nanosurf) itself consists of the electric control system and the probe head which is isolated against vibration. It can be controlled from the program Easyscan 2 on the computer where several parameters like the tip current or the field of view can be changed. Also the fine alignment is done with the program. Inside of the probe head, the tip is attached under a gold clamp and by that contacted to the circuit. With three piezos the tip can be moved across the surface of the sample with a precision of of 3pm and a scan width of 200nm on the z-axis and a precision of 7.6pm and a scan width of 500nm on the x-y-plane.
The samples are located on a conducting metal plate which can be attached to the sample holder which is brought into the probe head.

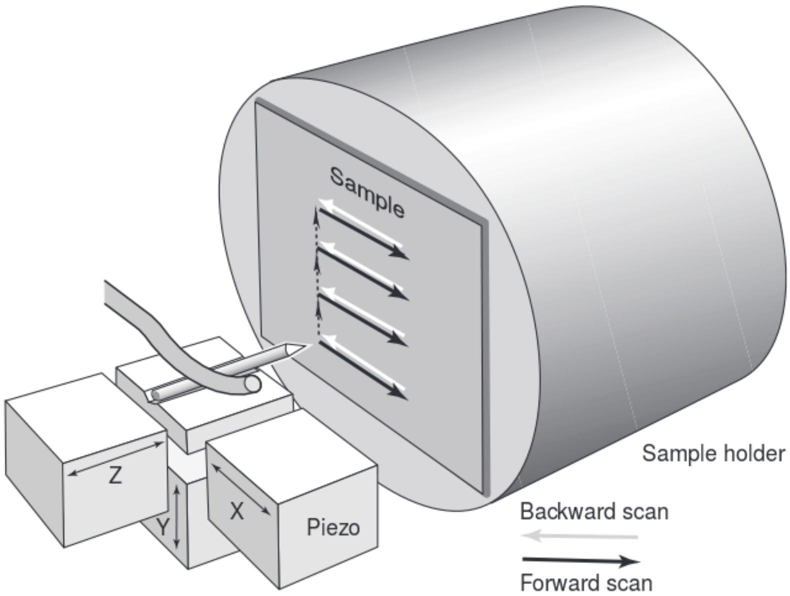


Figure 6: Setup of the piezos which navigate the tip across the probe.[3]

5 Execution

To set up the experiment for measurements these steps are mandatory.

- Turning on the Computer and the STM.
- Starting the program 'Easyscan 2'
- Producing a tip with a Platinum-Iridium-wire and a diagonal cutter. The tip should be one atom small at the top (can't be seen, obtained by chance).
- Putting the tip and the sample into the STM.
- Setting the tip voltage to 50mV. Using higher voltage if 50mV leads to crashes.
- Using the 'Approaching' function to move the sample close to the tip in bigger steps.
- Using the 'Advance' function to move the sample even closer to the tip in smaller steps until the wanted tunneling current is reached (0.5nA or 1nA).

Now the STM is ready for measurements. There are different settings to set up before recording a topography.

- At the beginning the image width should be set to the maximum ($\sim$ 600nm). If a good image is obtained, the image width can be lowered in small steps until atoms can be seen ($\sim$ 4nm).
- The time per line is very environment dependent. for example at hot days a small time is used (0.03s/line). Our best images were made with 2s/line.
- The points per line make up the resolution of the image. A too high value produces a very sharp image, but more noise is captured too. A too low value produces blurry images, but less noise is captured. Our best images were made with 128 points per line.
- The rotation is useful to verify, that the seen topography is real and not just an abberation.

Following these steps atomic resolution can be obtained, provided the tip was a good one. If the tip crashes or it is not good enough, a new tip is required and all steps after 'producing the tip' need to be repeated.

6 Analysis

For better image quality we used an SPM analysis program (SPM:'scanning probe microscopy') called Gwyddion. The used tools of Gwyddion are

- Level data by mean plain substraction.
- Level data to make facets point upwards.
- Correct lines by matching height median.
- Correct horizontal scars.
- Change scale range and color.
- Remove polynomial background.
- 3D-imaging.
- Several image filters.
- Create and edit graphs out of a one dimensional profile , fit functions.
- Perform an FFT (fast Fourier transform).

One should be very careful using these tools, because this can alter the physical results obtained by the images.

6.1 Aberrations & STM-Errors

Since it is very difficult to get a good tip, we have been collecting a lot of data showing different aberrations. The most important ones are listed below.

6.1.1 Symmetry

The first, very common, aberration is the fact that the picture looks symmetric at big scales (e.g 200nm). We assume that it really shows the topography of the sample until a certain point is reached, where the voltage limits of the Piezos is reached. Beyond this point the tip is just going back. A possible explanation is that the microscope and the program are not set up very well.

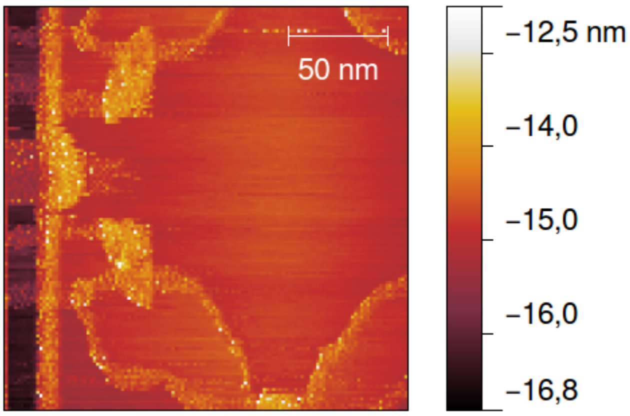


Figure 7: Graphite: The top part of the image is just a mirror image of the bottom part.

6.1.2 Parametrization

Another common aberation is due to faulty parametrization of the Piezo voltages leading to an image that is brighter in the center and dimmer on the left and right. It appears mostly in large scale images measured with a 90°-tilt. This can be partially corrected by Gwyddion by removing the polynomial background.

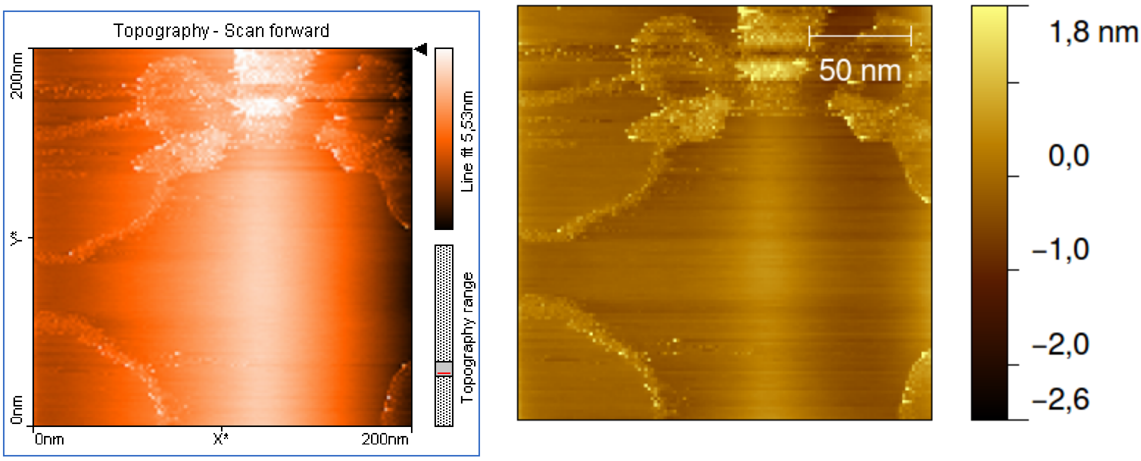


Figure 8: Graphite: same sample and sample location as in figure 7 with a 90°-tilt; left: raw image; right: edited with Gwyddion

6.1.3 Thermal Drift

The next error appears mostly on atomic resolution: the thermal drift. When the Piezos are used, they heat up resulting in a thermal expansion. The resulting drift of the tip is in the same order of magnitude as the Piezo movement speed. The affected image is streched or blured in some areas.

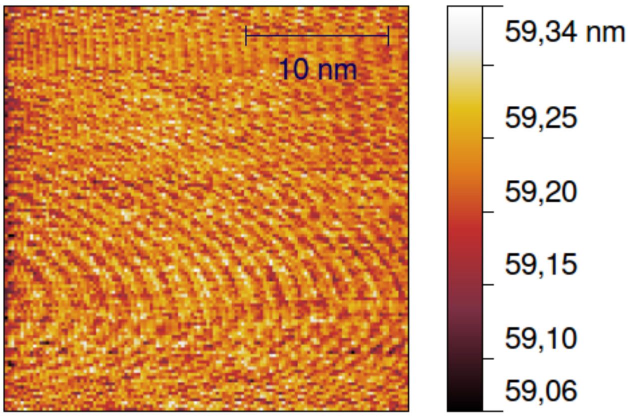


Figure 9: Graphite: The thermal drift streches the bottom of the image.

6.1.4 Bad Tip

If the tip is not sharp enough the atomic resolution cannot be achieved. In addition some non-continuous lines appear in the image. Some of the lines can be erased by using the right tools in Gwyddion.

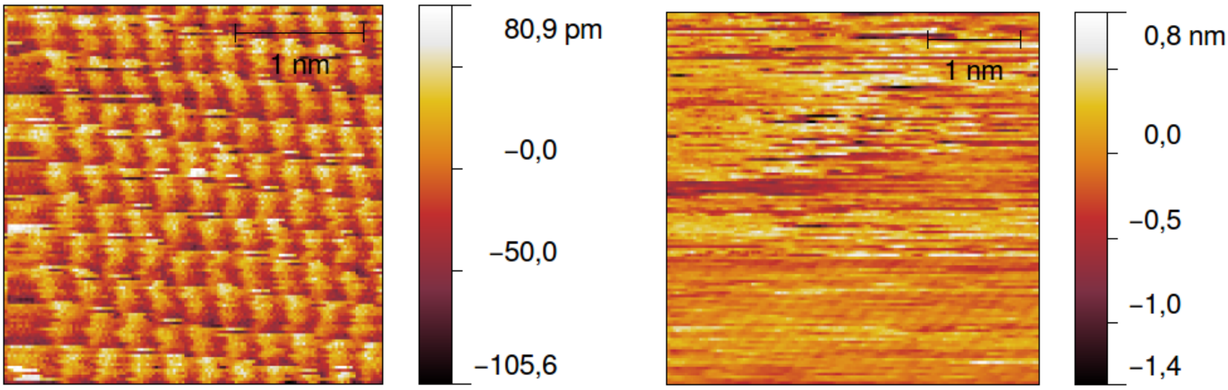


Figure 10: Graphite: atomic resolution; left: mild case of a bad tip; right: severe case of a bad tip

6.1.5 Oversteering

Suddenly measuring a very low or high tunnel current the tip oversteers a little bit to stay at the same height. This messes up the edges of surfaces by showing a too low or high altitude. The layer structure of graphite only allows a very abrupt change in height It is commonly seen at high tip speed. This can be solved by simply using a lower tip speed at the cost of getting more noise. This aberration is also seen in figure 7 on the very left of the image.

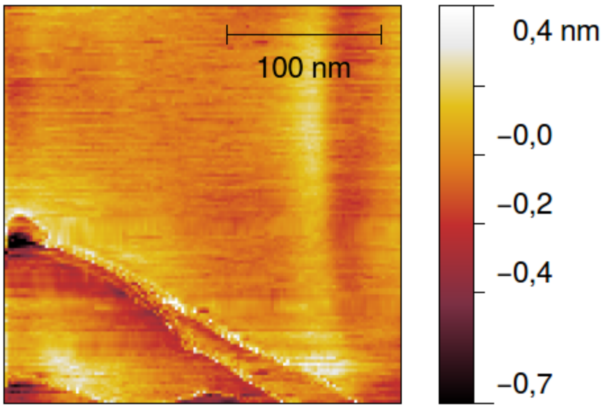


Figure 11: Graphite: slight oversteering at the fold of the surface to the right

6.1.6 Scratching Tip

Sometimes, even when the approaching speed is on the lowest setting, the STM program approaches the tip too fast. In this case the tip touches the sample and the tunnel current is going to the roof. The produced image is black and white. The only solution to this problem is to start over, because the tip is immediately destroyed on contact.

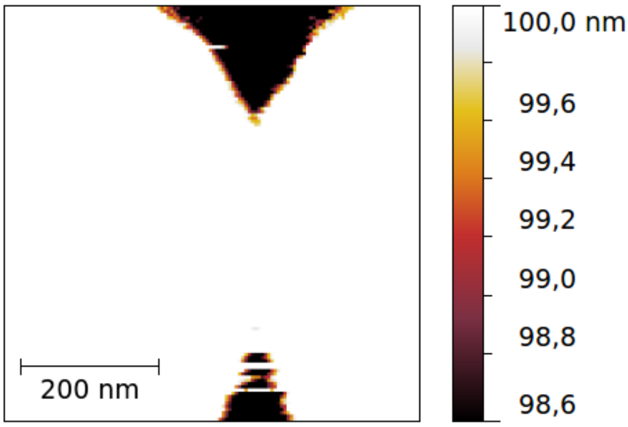


Figure 12: Graphite: This black and white image appears if the tip touches the sample.

6.1.7 No Approaching

It was not unusual that the motor started failing while approaching. The program does not recognize this and continues approaching until the set tunneling current is reached. Sometimes a noise signal is strong enough to trigger the program. So it starts measuring too far away from the sample. The result is a dark screen.

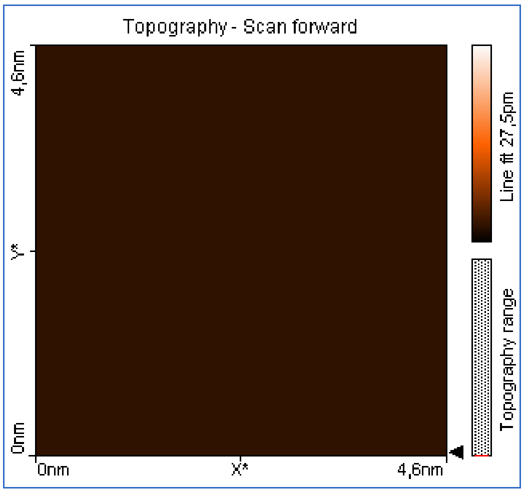


Figure 13: Void: The dark image means, that there was no measurable tunnel current.

6.2 Graphite structure

The many attempts to obtain atomic resolution, lead to a routine that differed from the suggested one in the manual. The best result was obtained by lowering the tunnel current to 0.5nA and starting at a lower scale to minimize the chances of crashing the tip. Starting at a 13.8nm scale, one can already see the crystal structure.

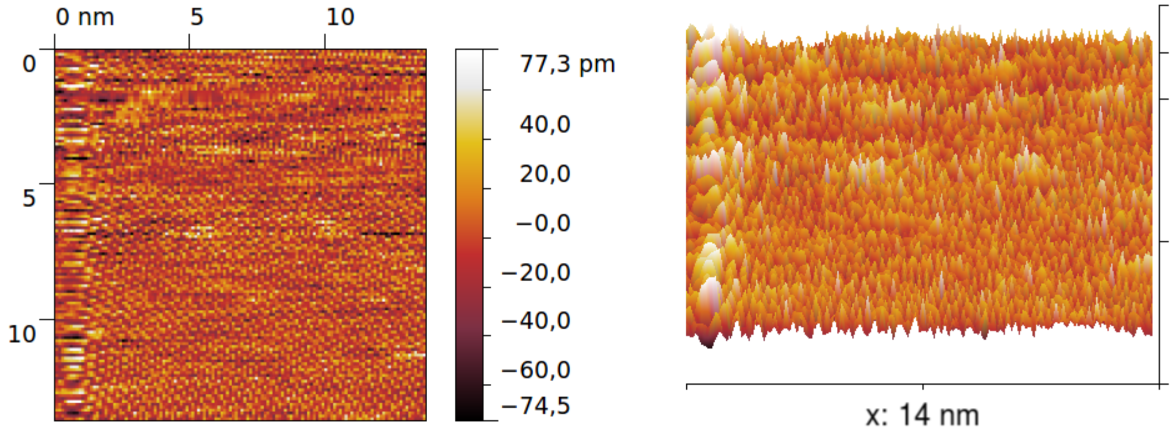


Figure 14: Graphite: Far image of the crystal structure

To obtain the lattice parameter a lower scale image is needed. A gaussian image filter is used to get a nicely looking 3D-Plot. However the filtered image is not used for the Gaussfits.

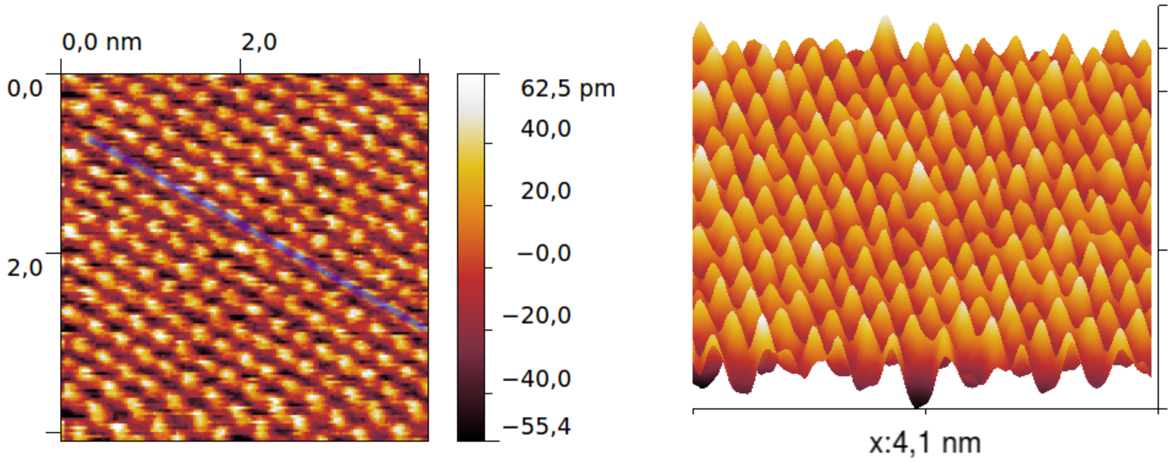


Figure 15: Graphite: crystal structure; blue: used profile

With Gwyddion the desired profile is easily extracted and Gauss fits can be done to locate the center of the atom.

$$h(x) = y_0 + ae^{-\frac{(x-x_0)^2}{b^2}}$$

The distance between the atoms yields the lattice parameter.

$$d_i = x_{0,i+1} - x_{0,i}$$

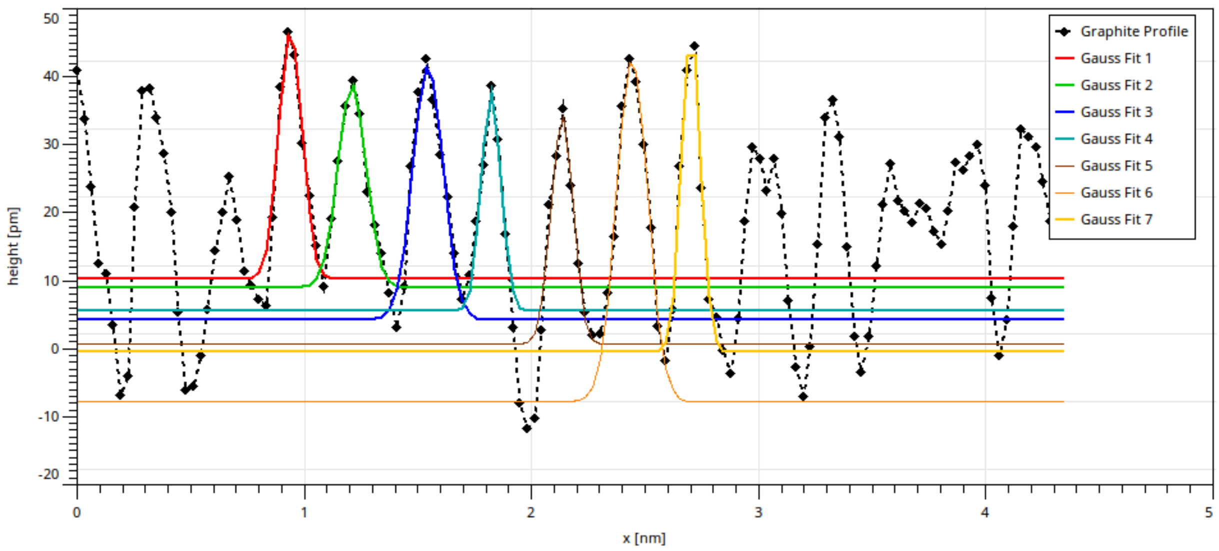


Figure 16: Graphite: one dimensional profile of the blue line with Gauss fits

All the calculated distances are merged by using the weighted mean, where the errors are the confidence intervals of the fits. The line of atoms, one is looking at, is not infinitively thin (thickness of an atom). So there is a systematic error, because the profile line can have a small tilt respectively to the atom line. The approximation of this error is:

$$s_{sys} = \bar{d} - \sqrt{\bar{d}^2 - \left(\frac{off}{6}\right)^2}$$

With $off \approx 0.17$nm (which is the measured size of an atom in the picture) the systematic error is quite important at this point ($s_{sys} = 0.0014$nm).
But the confidence intervals have no physical meaning. So one has to do an error approximation taking the averaged parameter $b/2$ of the Gauss fits.

$$s_{d_i} = \sqrt{2} \cdot 0.035\text{nm}$$
$$\Longrightarrow s_{\bar{d}} = \frac{s_{d_i}}{\sqrt{6}} = 0.020\text{nm}$$

$$\boxed{d = (2.9 \pm 0.2)\text{Å}}$$

There are also images at smaller scale, which should lead to a better result.

$$s_{d_i} = \sqrt{2} \cdot 0.06\text{nm}$$
$$s_{\bar{d}} = 0.036\text{nm}$$

The error is higher but the value is closer to the literature value.

$$\boxed{d = (2.7 \pm 0.4)\text{Å}}$$

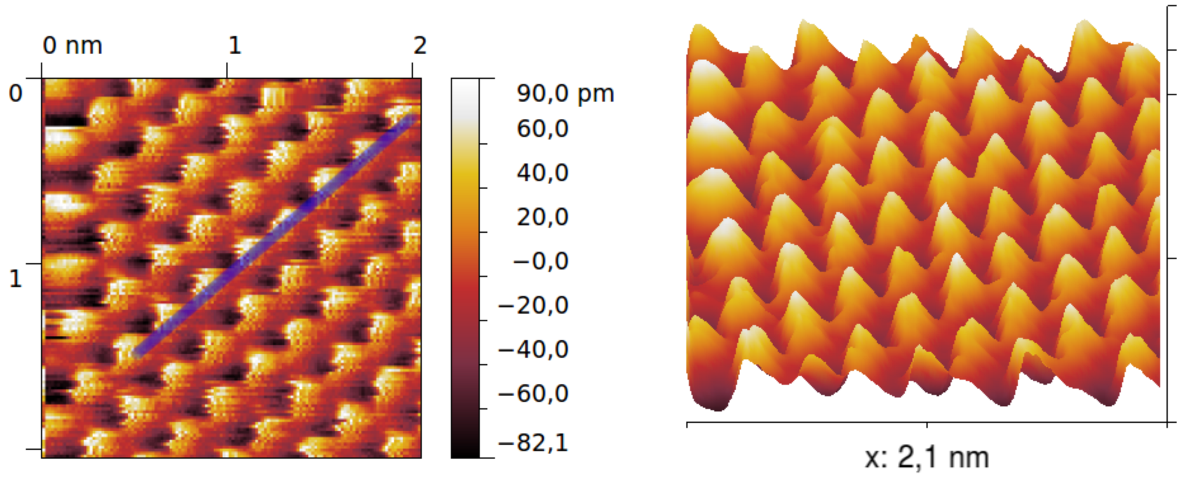


Figure 17: Graphite: crystal structure at smaller scale; blue: used profile

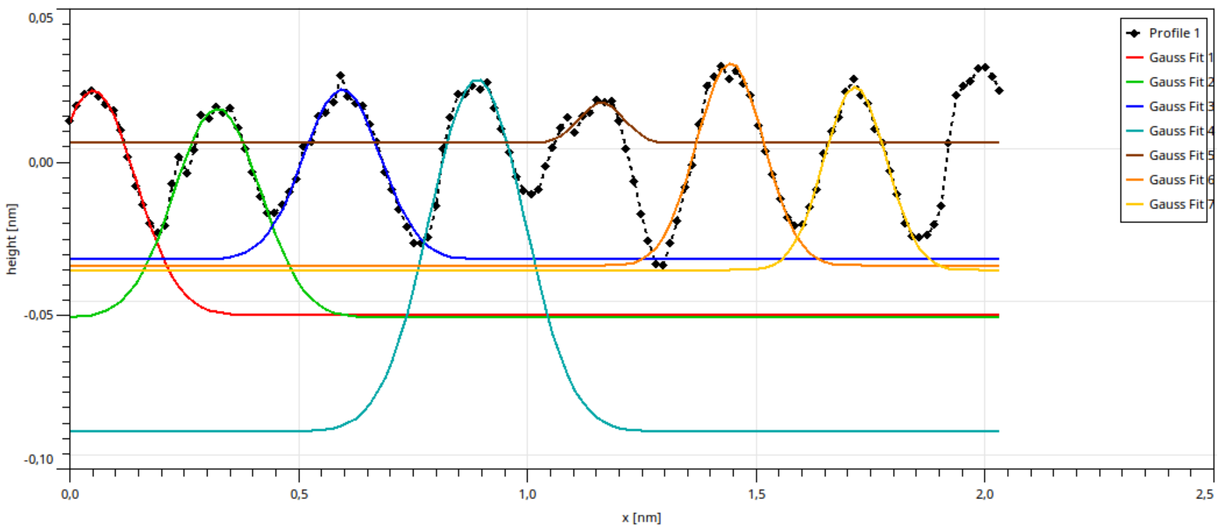


Figure 18: Graphite: one dimensional profile of the blue line with Gauss fits

To compare the obtained structure with the theoretical structure the image in figure 17 ran through some filters and a unit cell overlay was inserted.

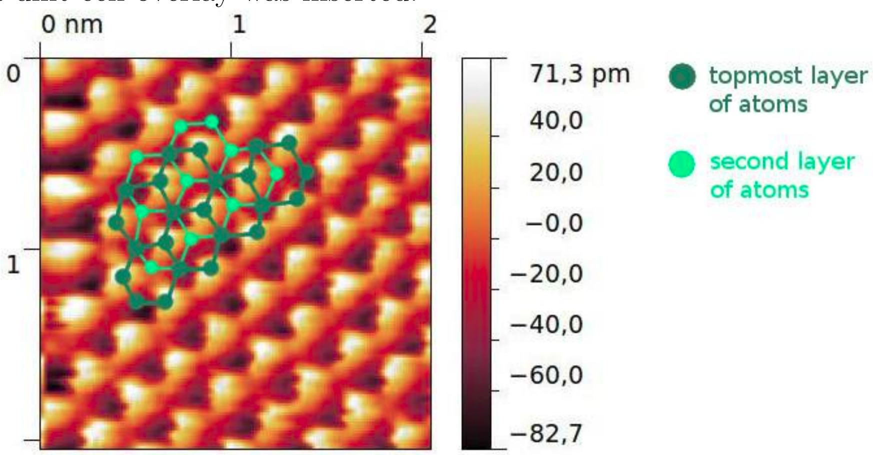


Figure 19: Comparison of the theoretical structure with the one found with the STM

In addition the larger scales also show that graphite has a hexagonal unit cell. The edges of some layers are cornered in a hexagonal way.

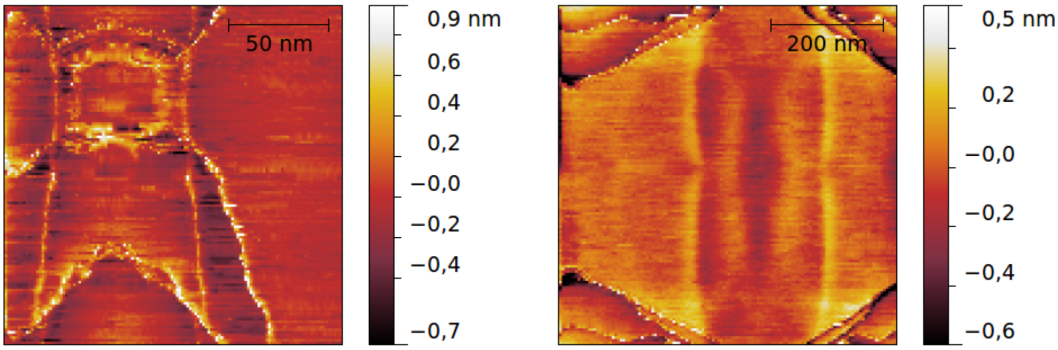


Figure 20: Topography of graphite with hexagonal structures; The right image is a larger scale version of figure 11 .

Another way to verify the hexagonal structure of the unit cell is by making a Fourier transform into the k-space, where the unit cell is shown and the atoms should be points. It is not used for calculating the lattice parameter, because the error analysis in a Fourier transformed space is very difficult.

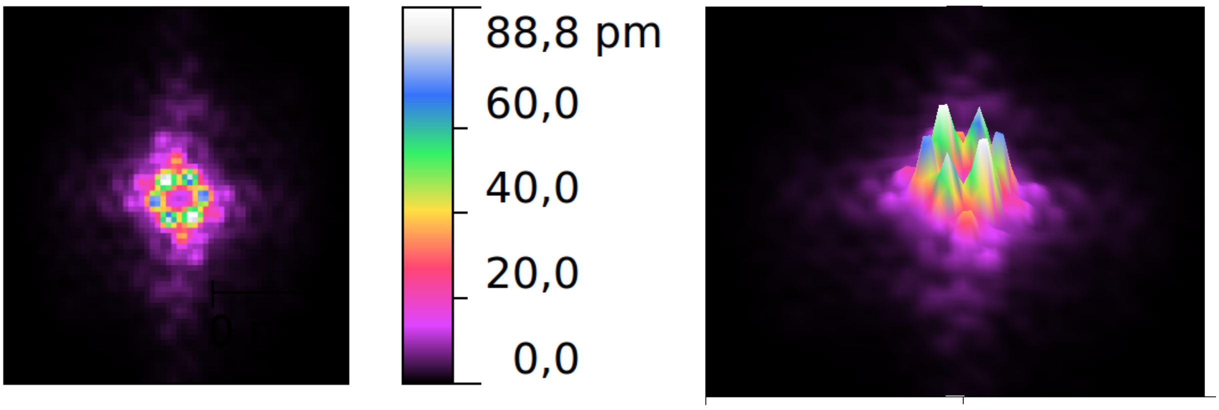


Figure 21: The hexagonal structure of the Fourier transform using figure 17

6.3 Gold Structure

The gold structure shows no atoms, because the electron density is almost constant. However, missing atoms can be spotted by looking for holes in the gold layers, because the density drops in these areas. In addition another scale color was used.

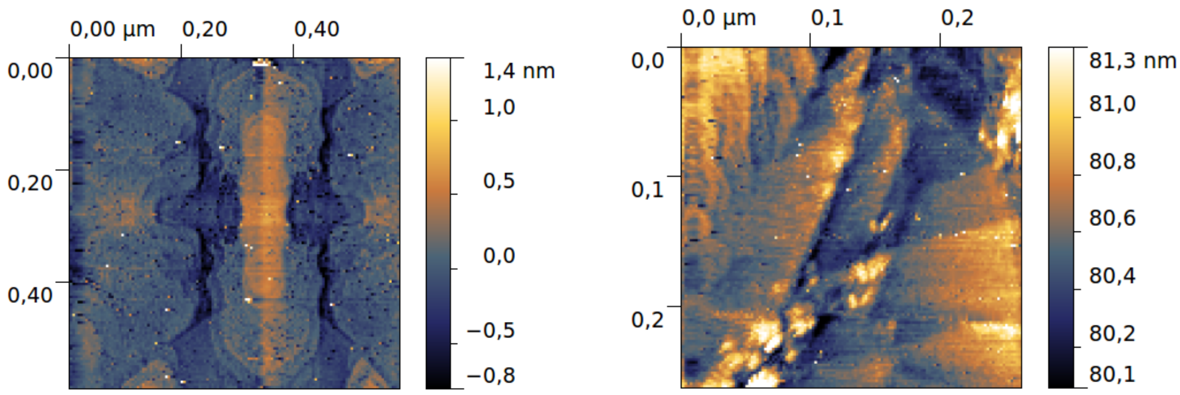


Figure 22: The topography of gold is not as well-arranged as the graphite one.

Going to smaller scales in flat areas, the holes start to appear.

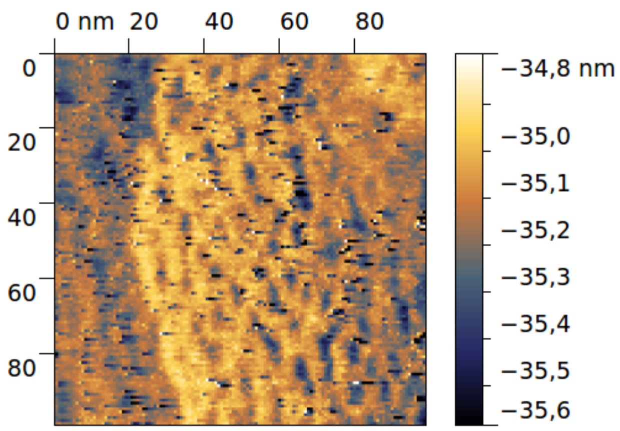


Figure 23: Two gold layers with holes. The white and black dots are noise.

On the right side there is the upper gold layer with (blue) holes in it. So this gold layer is missing some atoms. The right side of the image shows a lower layer also having some holes. The black and white dots in the image originate from the oversteering effect. The critical field strength of air is reached at the tip and a spark appears (white spot). The STM pulls the tip away from the sample the tunnel current drops rapidly (black trace).

6.4 Tantalum Disulfide Structure

Only few images were made for tantalum disulfide. It was not possible to obtain an image with atomic resolution. So a calculation of the lattice parameters cannot be achieved. However, on the lowest scale one can already see a hint of the crystal structure. At the bottom left of figure 24 some different layers can be seen.

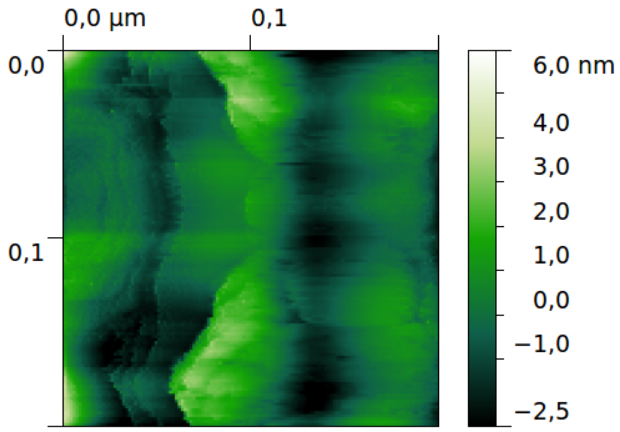


Figure 24: The topography of TaS_2 is not as well-arranged as the graphite one.

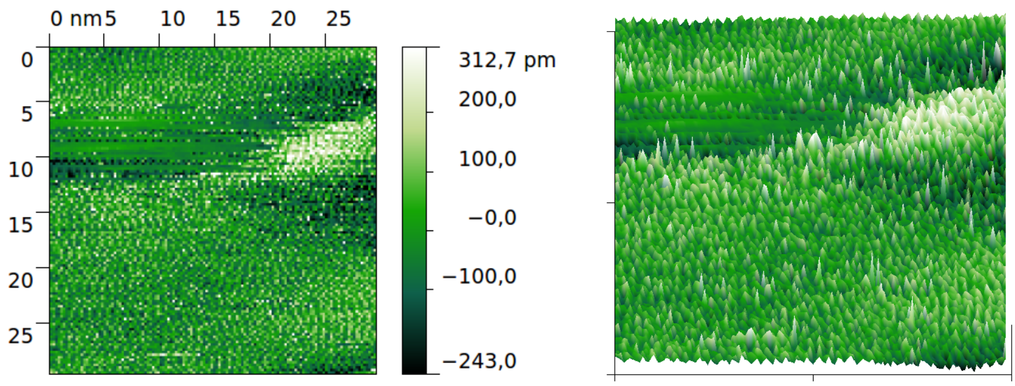


Figure 25: Lower scale image of TaS_2.

Figure 25 shows the crystal structure at a lower scale. A hint of the atomic structure can be seen, but any further measuring at lower scales did not show any atomic structure. So it is possible that the peaks are only noise.

7 Summary and Discussion

7.1 Graphite

Graphite was the only structure, that we could achieve atomic resolution with. So it is also the only one with a calculated lattice parameter.

scale nm	lattice parameter [Å]	relative errors
4	2.9 ± 0.2	7%
2	2.7 ± 0.4	15%
literature value[1]	2.456	

The calculated values match the literature value within one standard deviation. The relative errors are quite big and the only error that really matters is the estimated one. The systematic error of tilted lines is as small as the one from the confidence intervals of the fit.

Both values are too big, so there could be another systematic error. One possibility is that the sample was slightly crooked, so the STM measured a bigger distance as it should. Another solution is an inaccurate scale calculation of the 'nanosurf' program.

In the Fourier transform one can clearly see the hexagonal shape of the unit cell.

Another method of obtaining the lattice parameter would be simply counting the peaks in a certain path and dividing the path length by the number of peaks. However, for a better error estimation one should use the method of direct distance measuring via Gauss fits.

7.2 Gold

As expected, no gold atoms can be observed. Two gold layers and the effect of missing atoms could be observed. The images at higher scales show a more disordered structure than graphite. This is the case because gold is a very soft metal, so every scratch will alter the surface.

7.3 Tantalum Disulfide

The tantalum disulfide images show some high scale layers, but at a smaller scale the atoms could not be observed despite using the same tip that figure 17 was recorded with. Because of disordered structures, it is likely that the tip crashed into a higher layer.

8 Appendix

8.1 Additional images

These images are not modified with Gwyddion (some of them were exported as png from Gwyddion because the png was not saved directly with EasyScan). The caption shows the file name and the different setups are listed with the file name in the lab notes section 8.2 .

8.1.1 Graphite

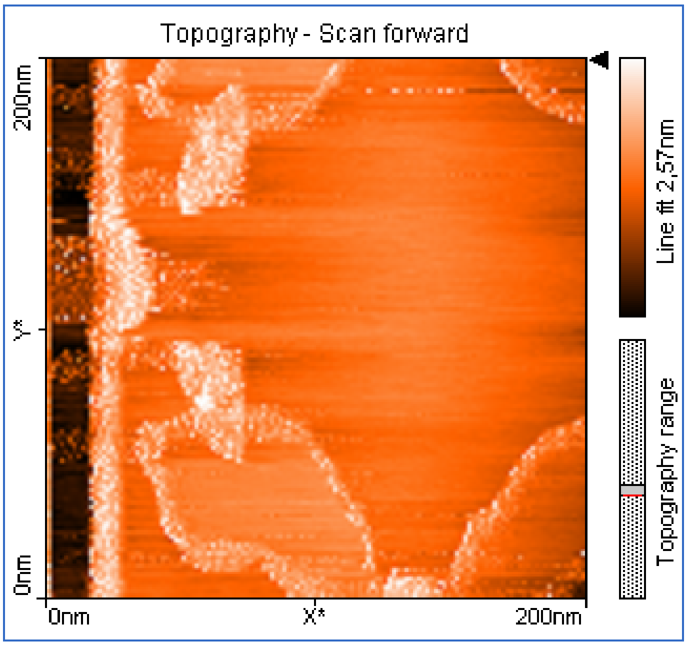


Figure 26: grafit1

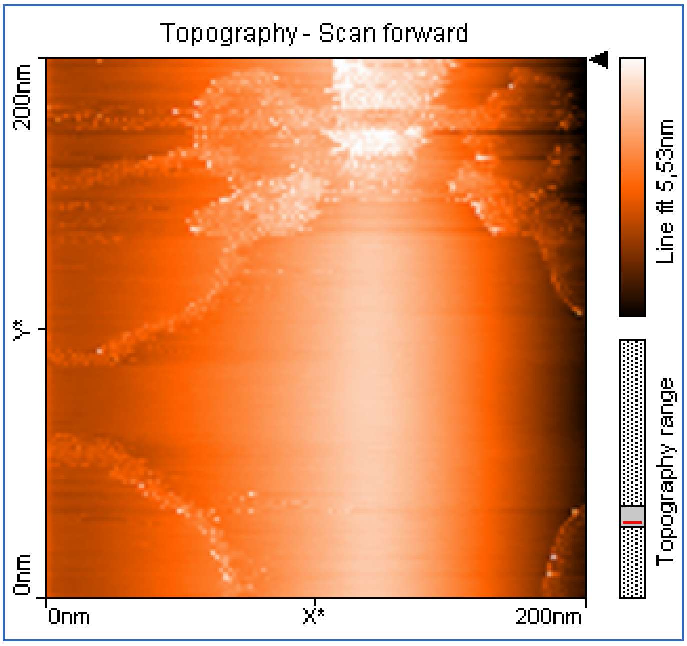


Figure 27: grafit1_90

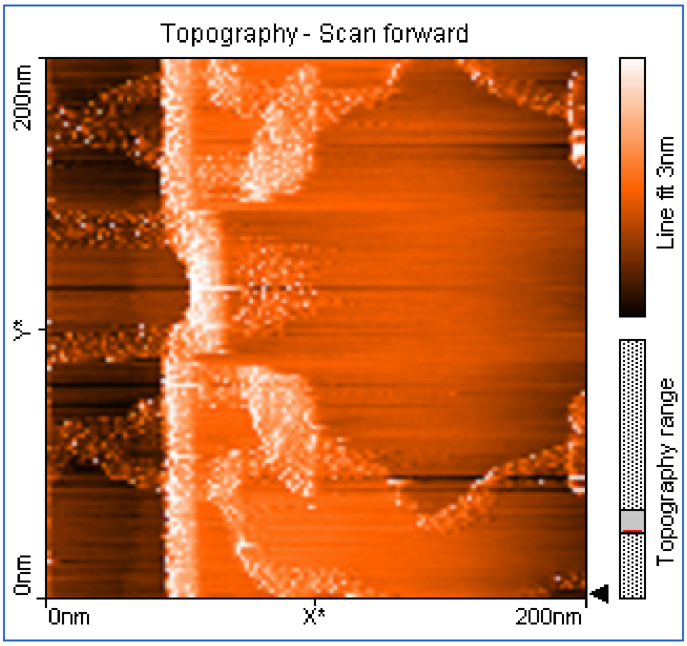


Figure 28: grafit1_01s

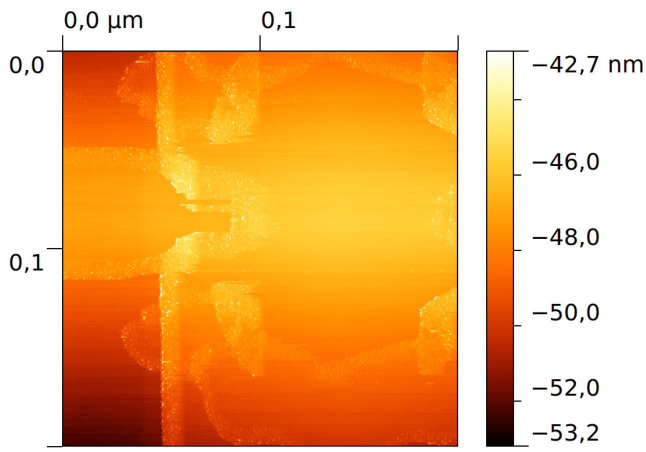
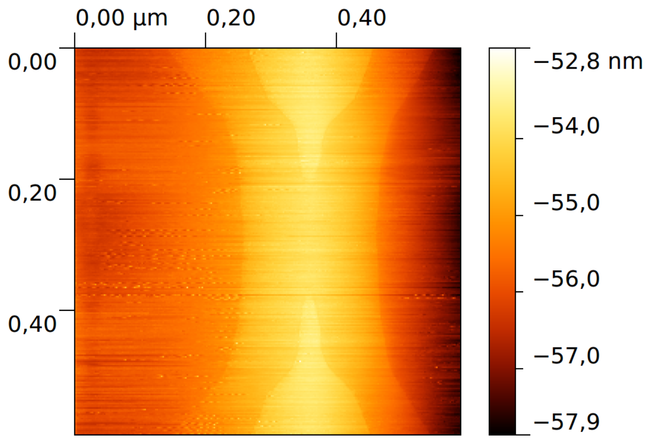


Figure 29: grafit1_256p



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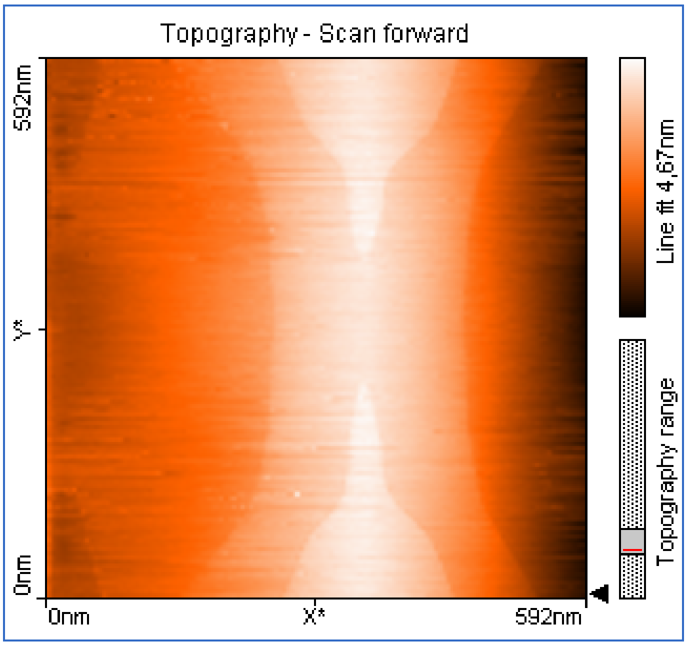


Figure 31: grafit1_500_90

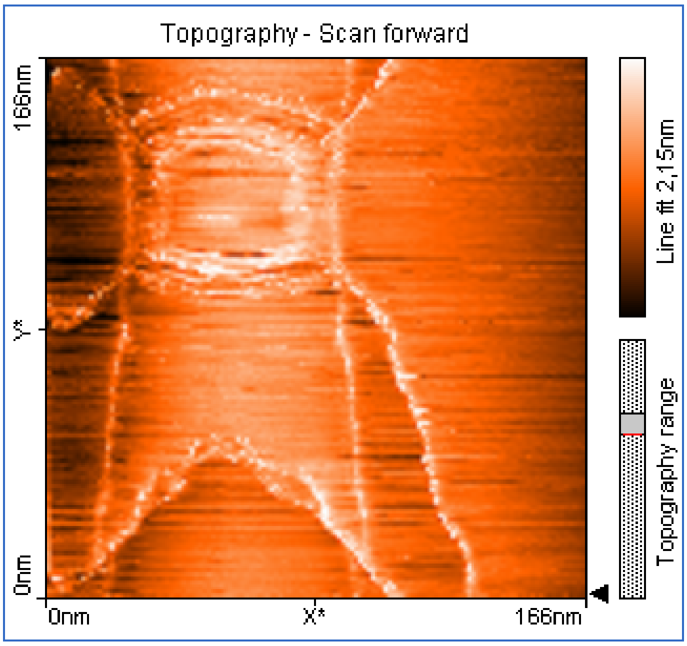


Figure 32: grafit2_1

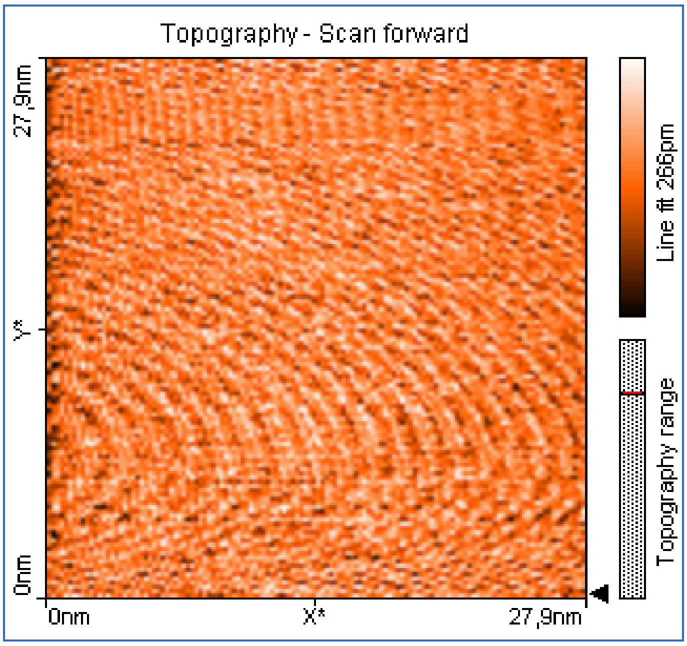


Figure 33: grafit2_2

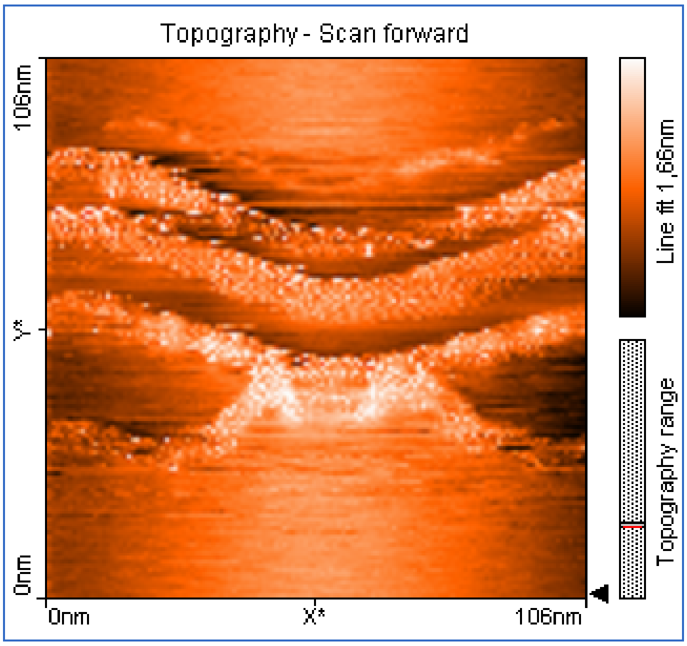


Figure 34: grafit3_1

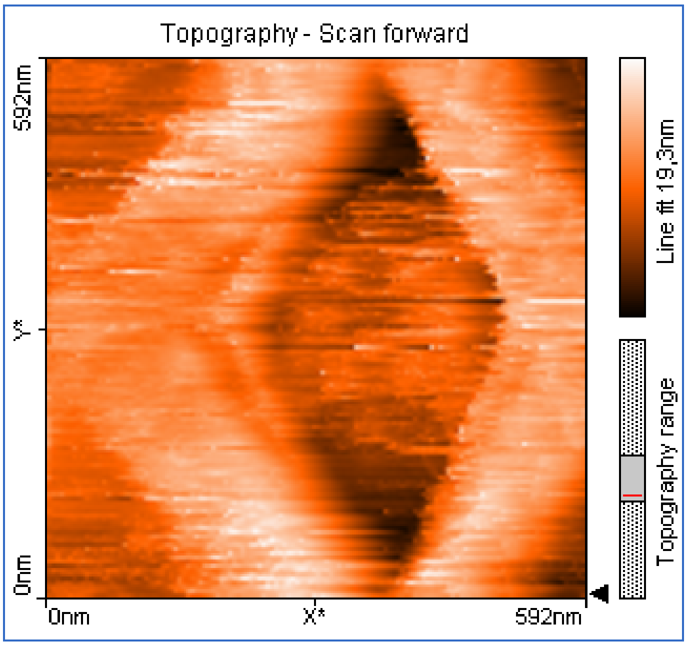
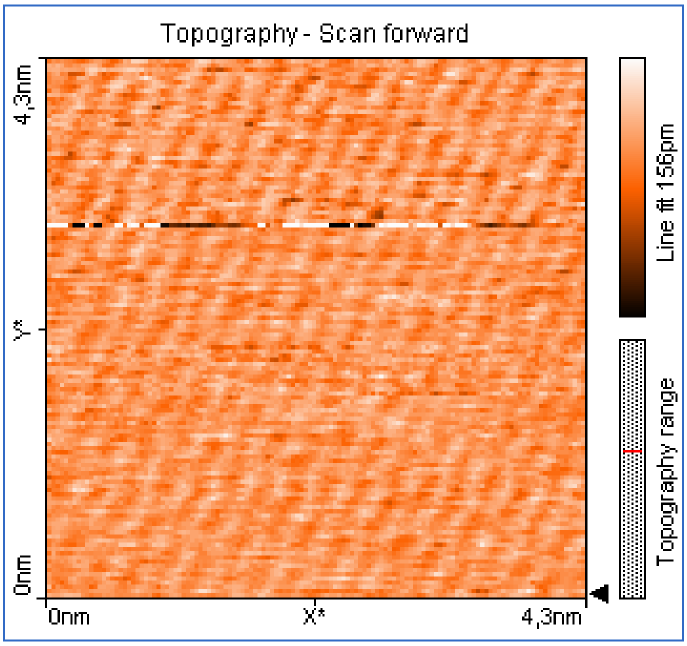


Figure 35: grafit4_1



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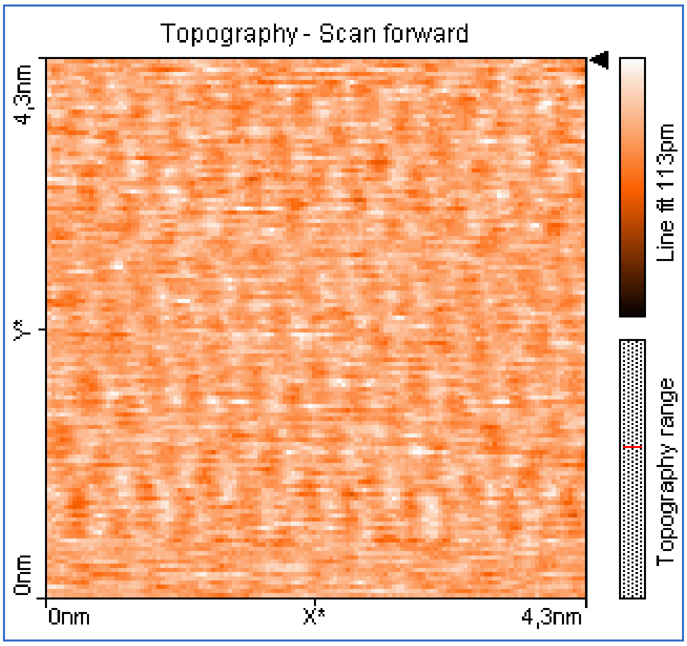


Figure 37: grafit5_2

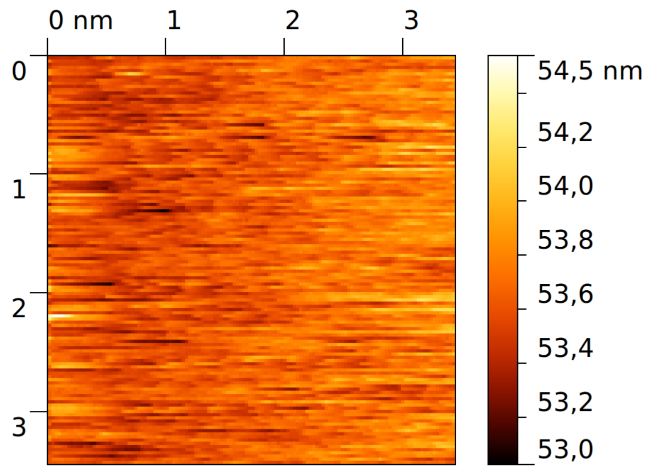


Figure 38: grafit6_1

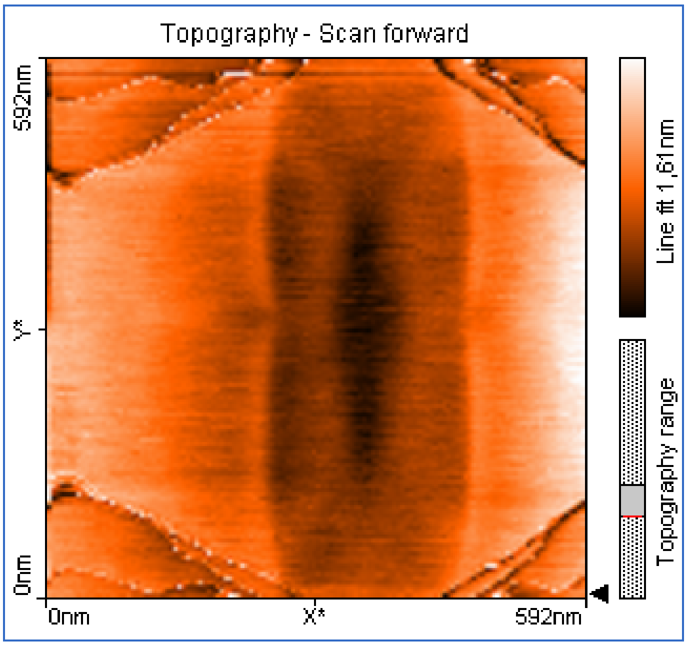


Figure 39: grafit7_1

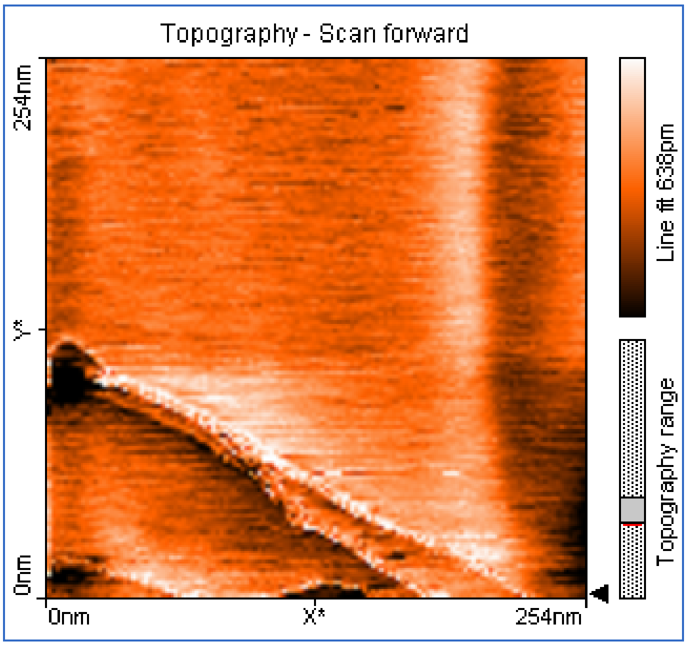


Figure 40: grafit7_2

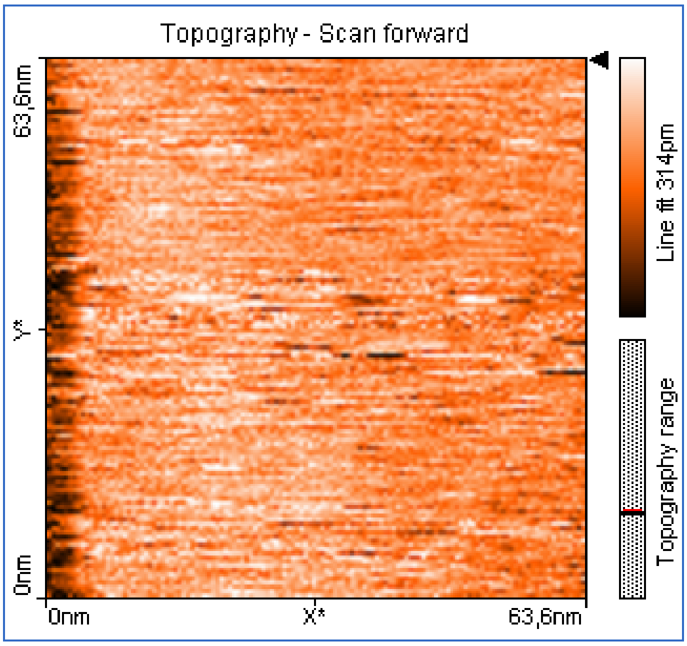


Figure 41: grafit7_3

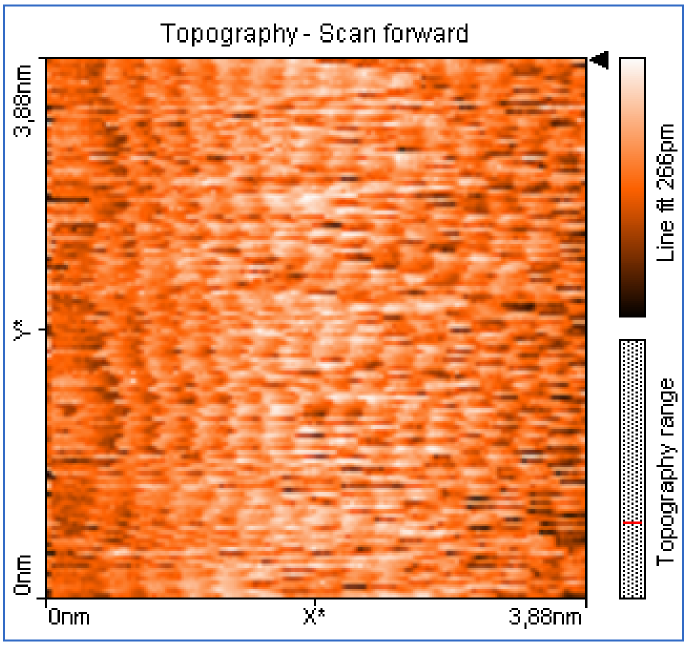


Figure 42: grafit7_4

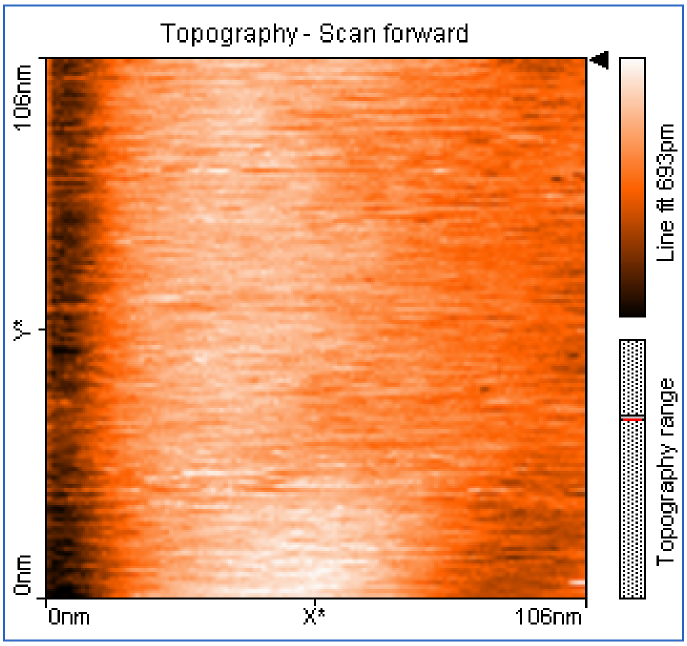


Figure 43: grafit7_5

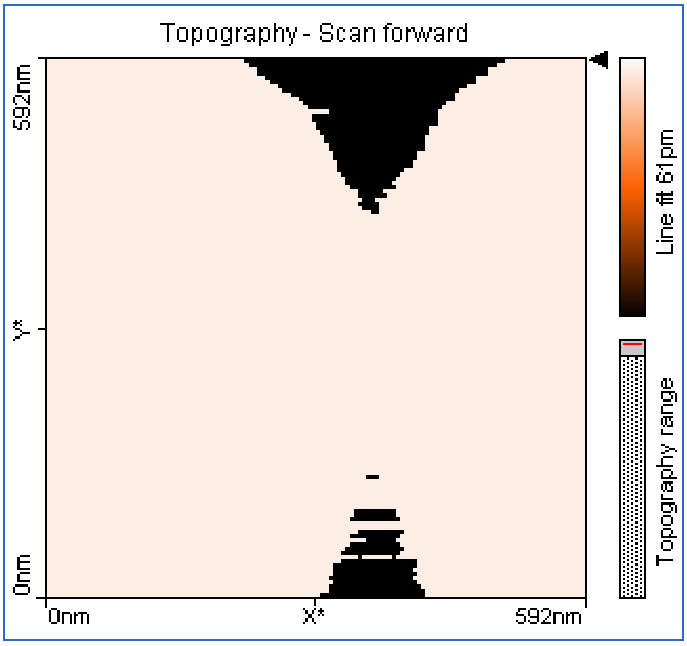


Figure 44: grafit_crash

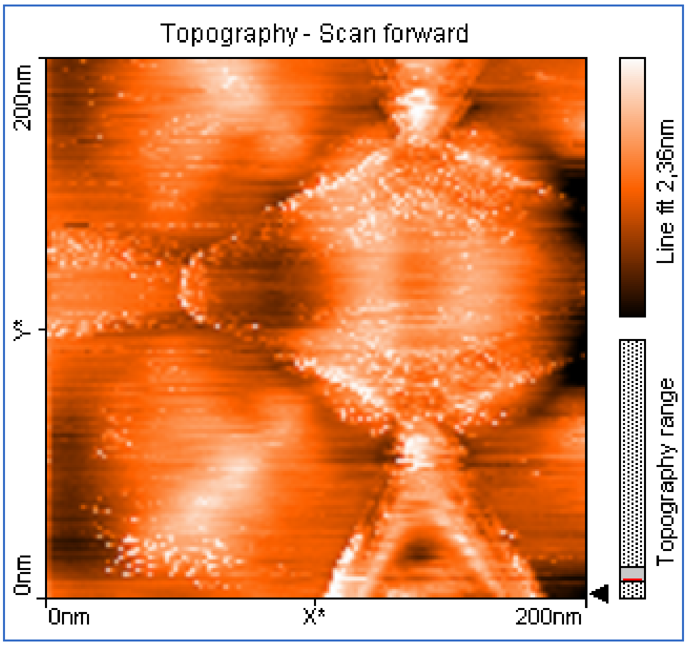


Figure 45: grafit8_1

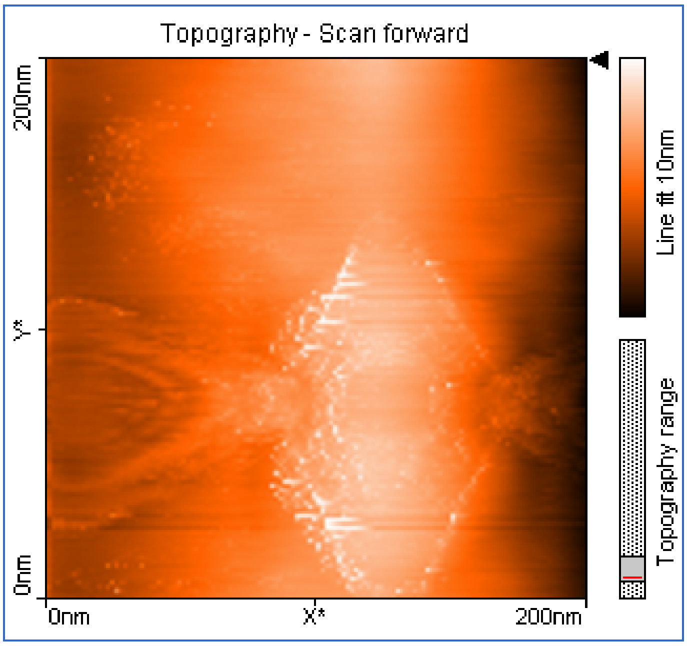


Figure 46: grafit8_2

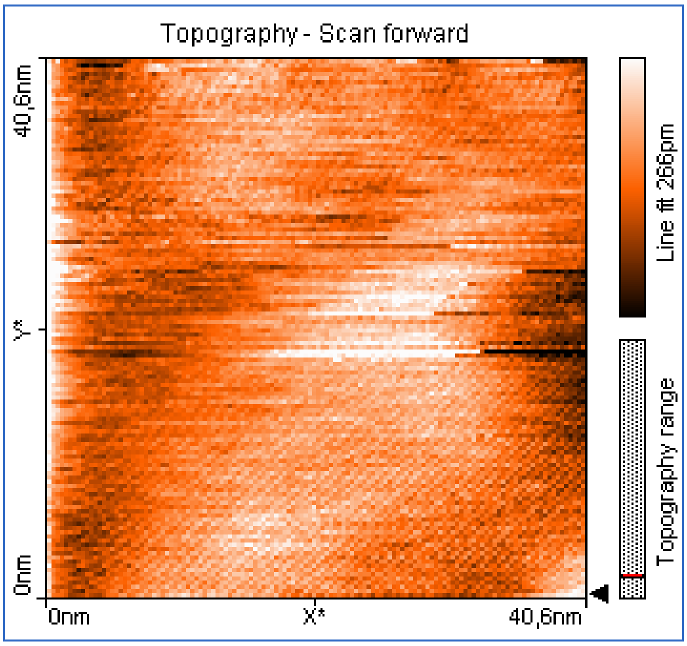


Figure 47: grafit8_3

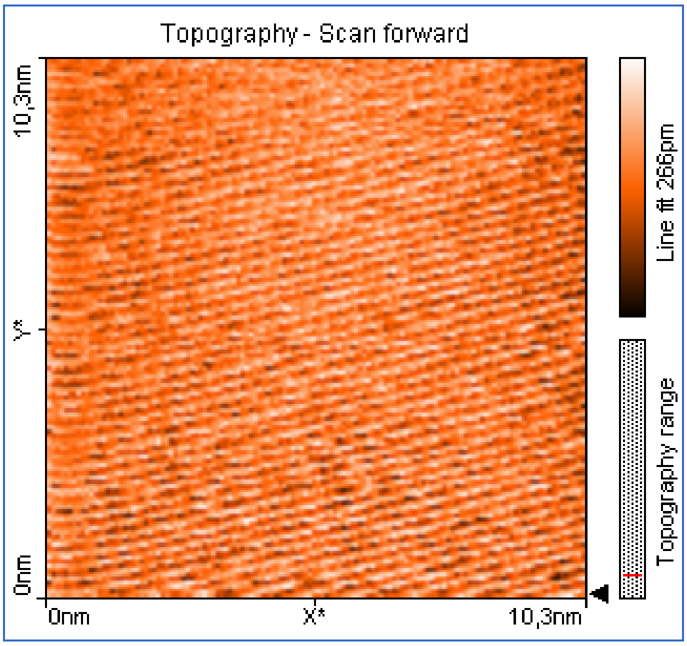


Figure 48: grafit8_4

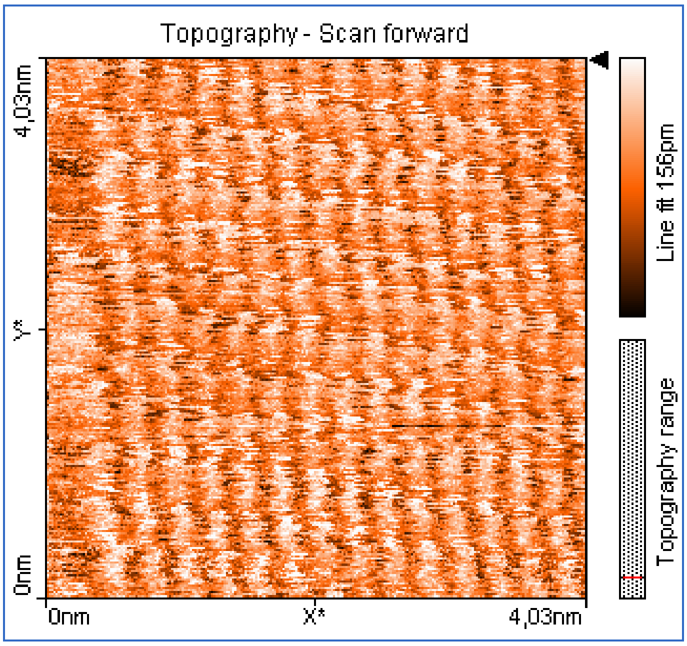


Figure 49: grafit8_5

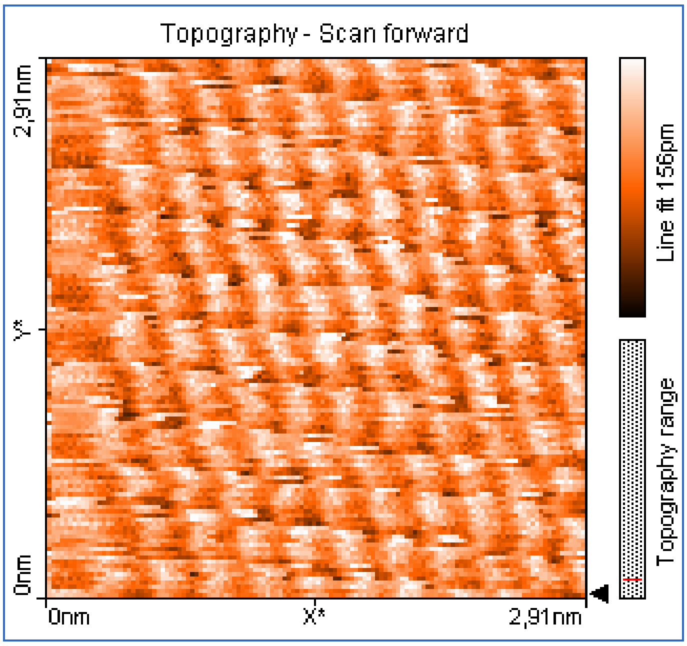


Figure 50: grafit8_6

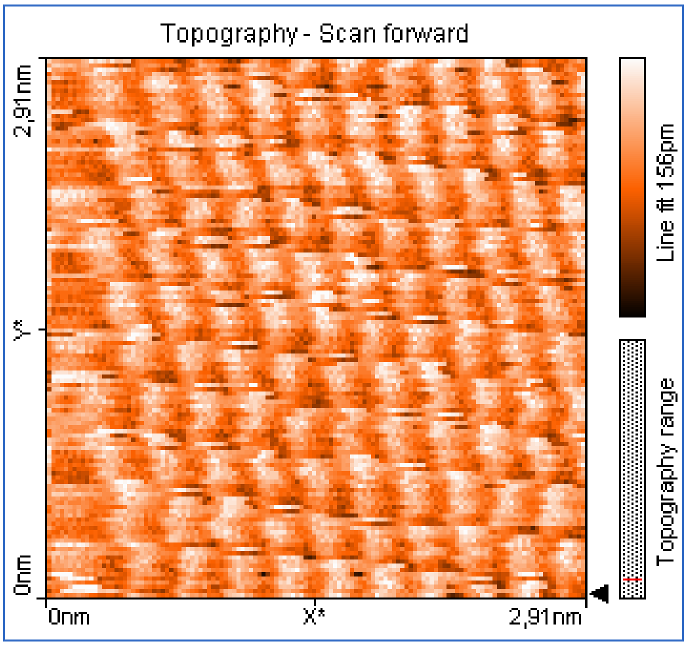


Figure 51: grafit8_7

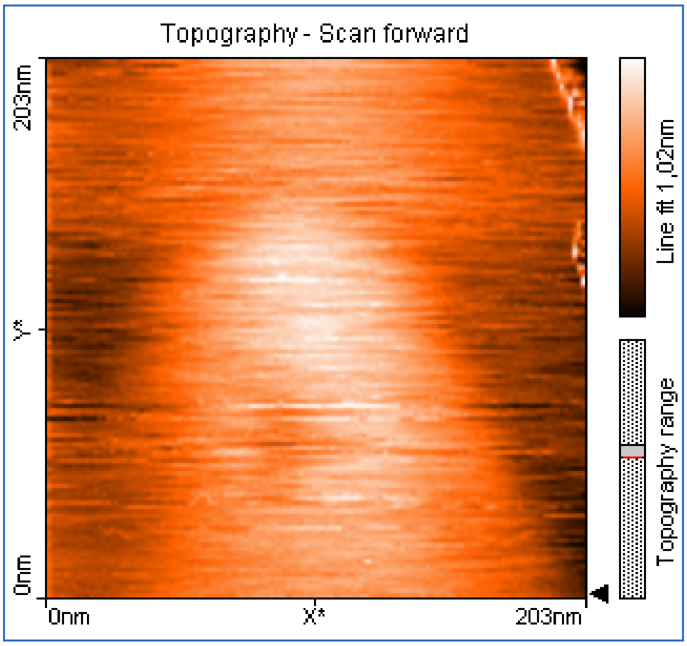


Figure 52: grafit9_1

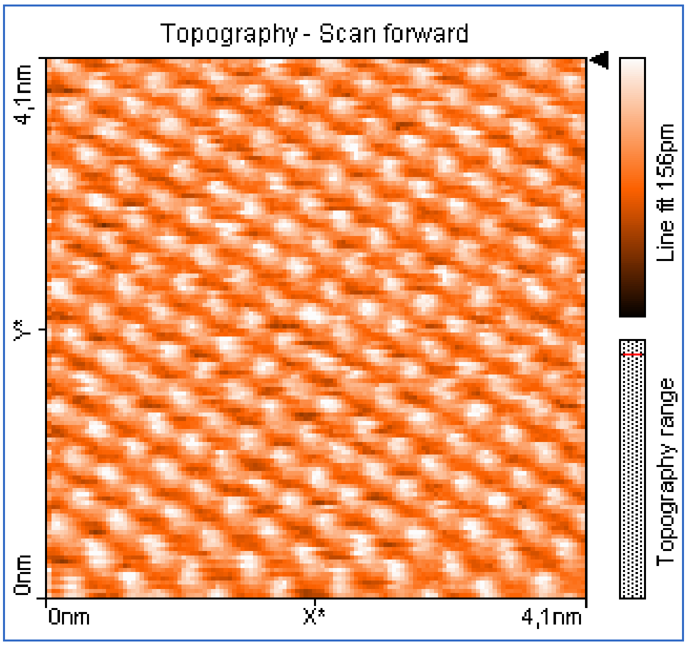


Figure 53: grafit10_1

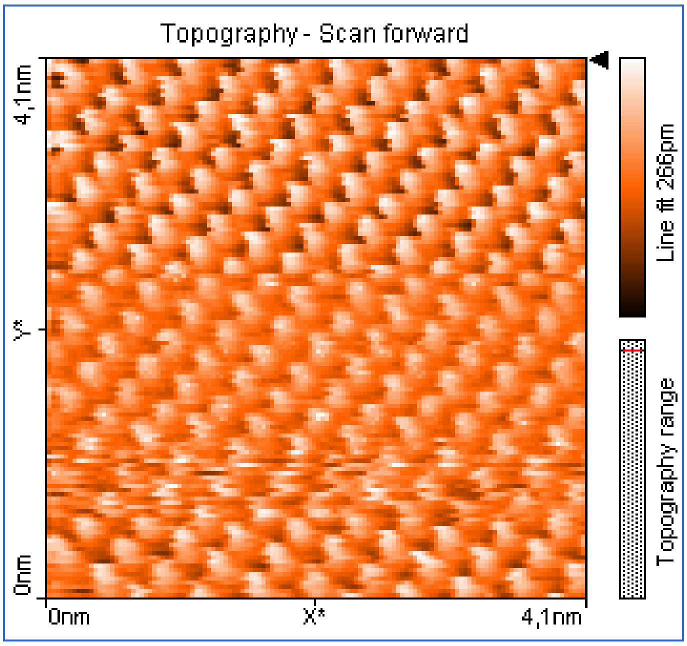


Figure 54: grafit10_2

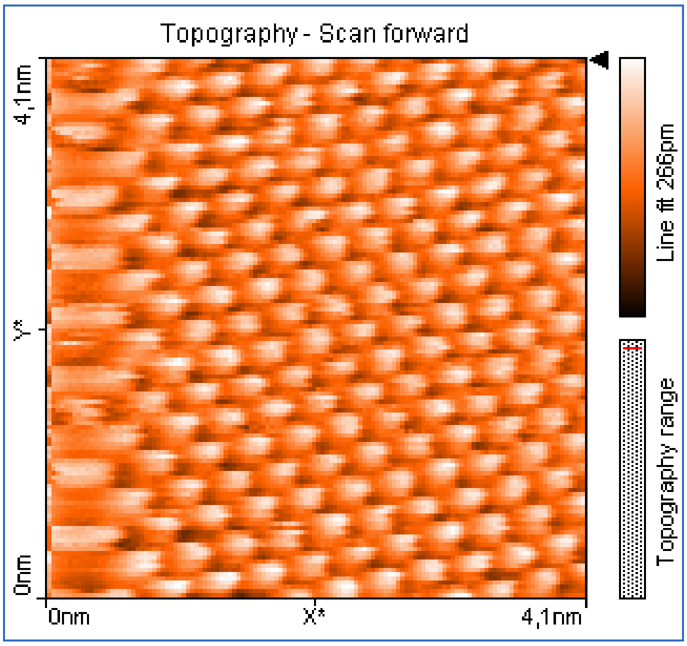


Figure 55: grafit10_3

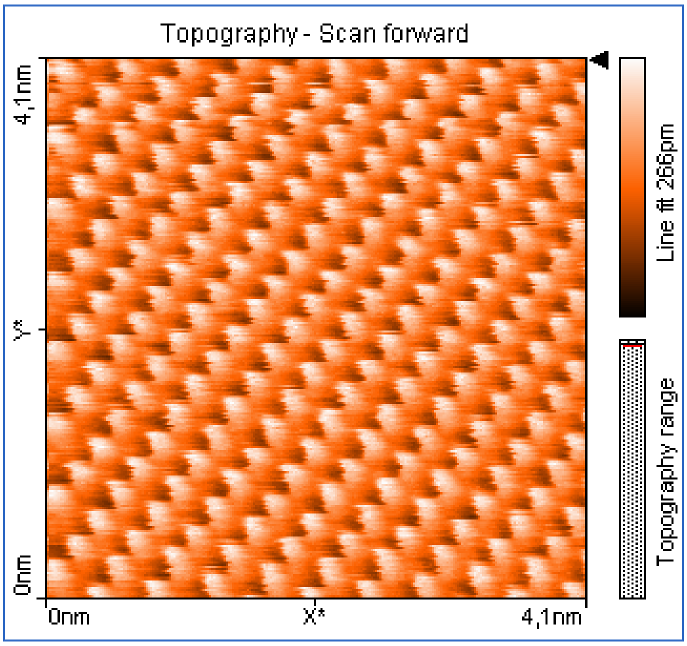


Figure 56: grafit10_4

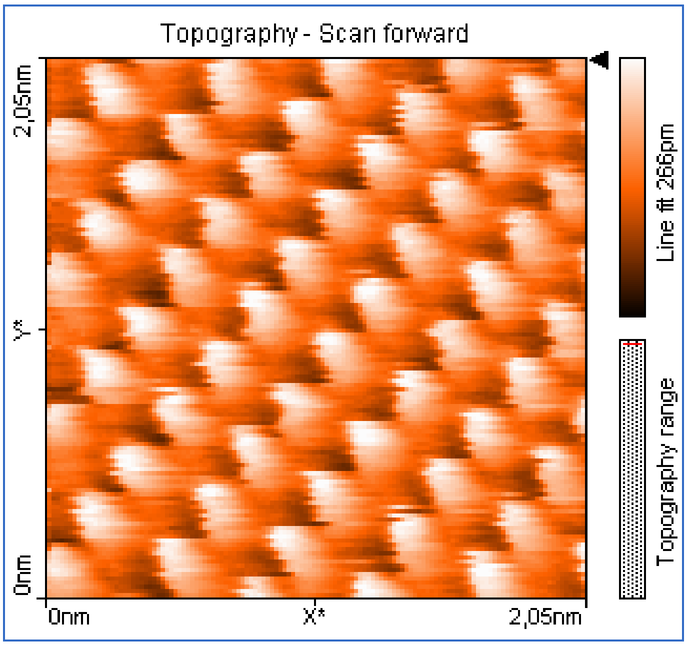


Figure 57: grafit10_5

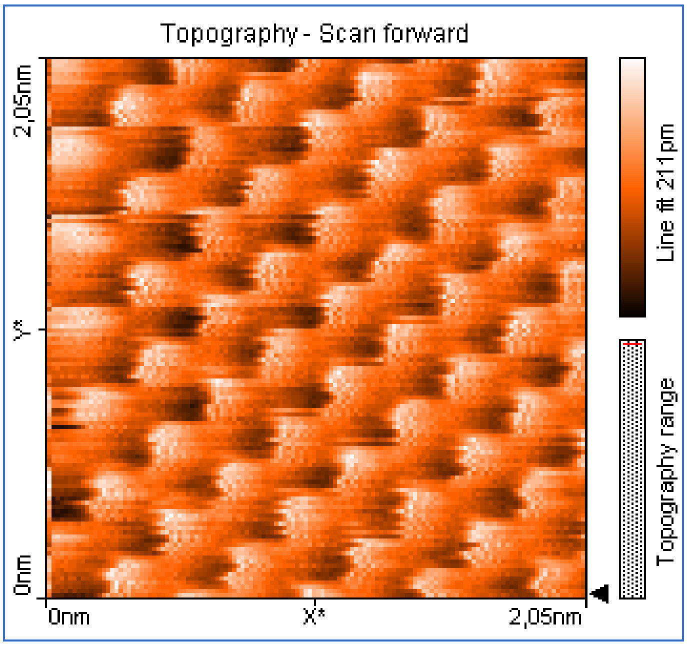


Figure 58: grafit10_6

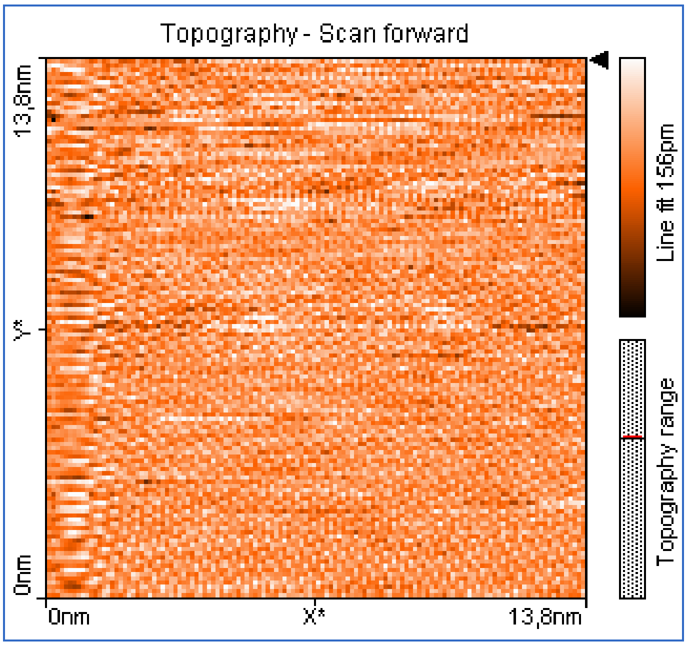


Figure 59: grafit10_7

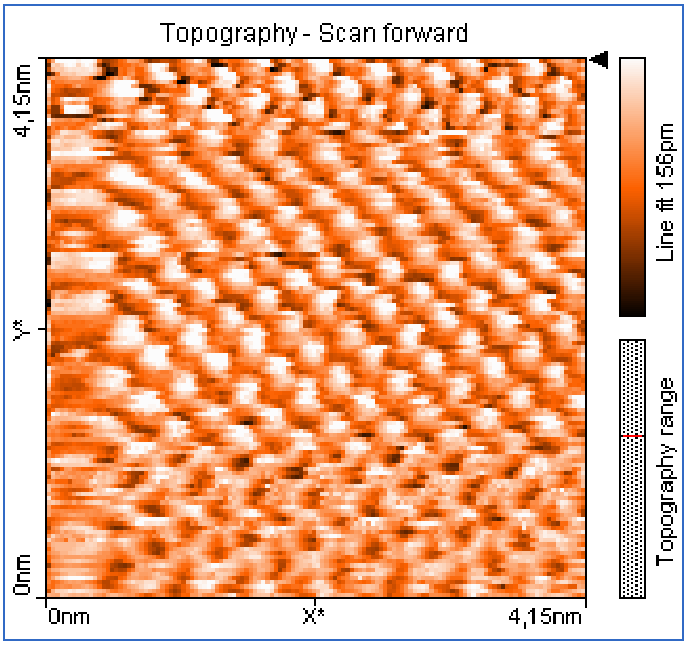


Figure 60: grafit10_8

8.1.2 Gold

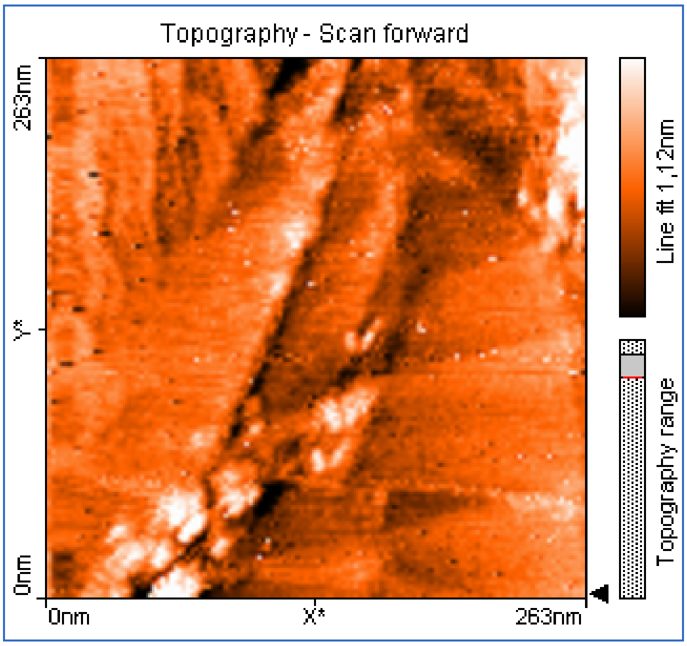


Figure 61: gold1_1

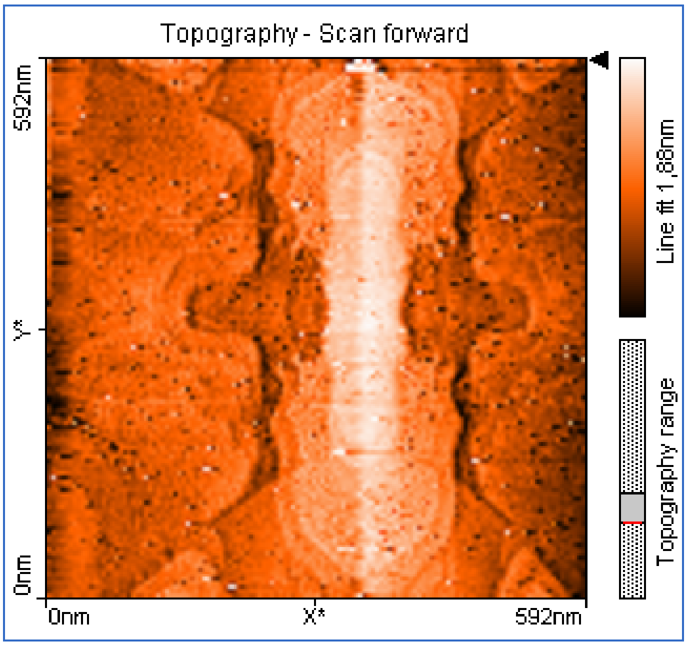


Figure 62: gold1_2

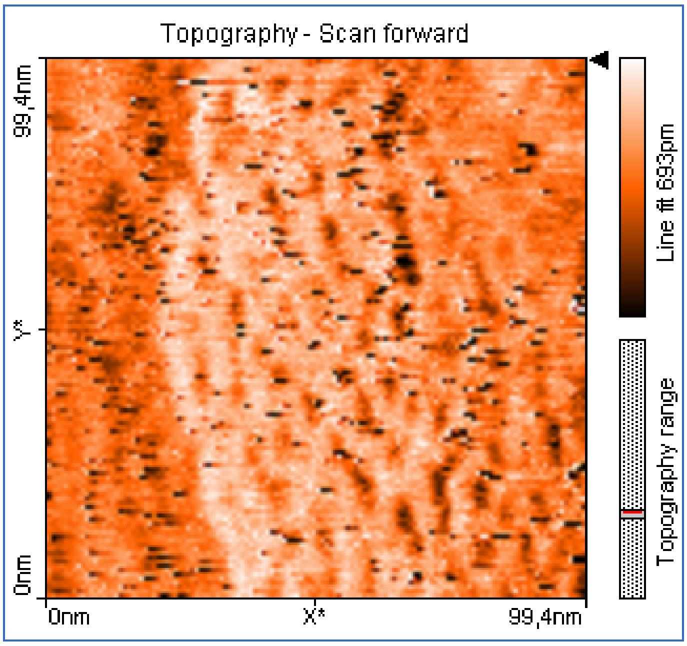


Figure 63: gold1_3

8.1.3 Tantalum Disulfide

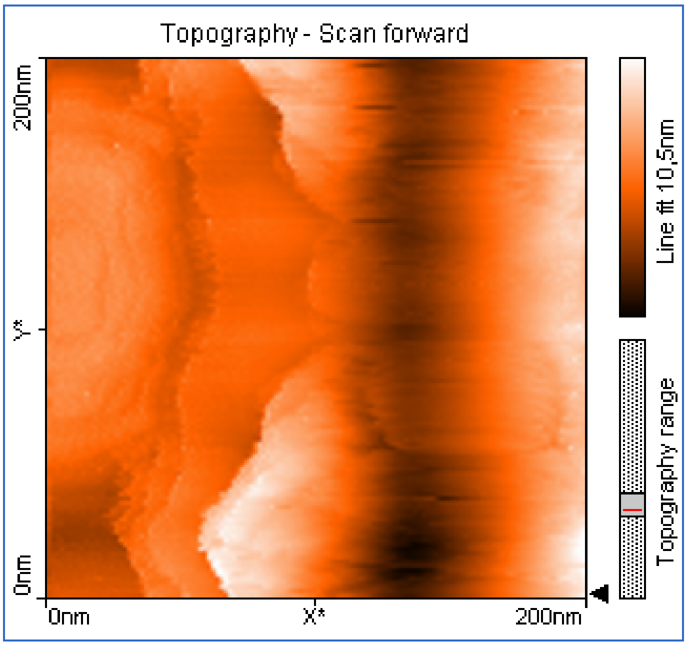


Figure 64: taS_1

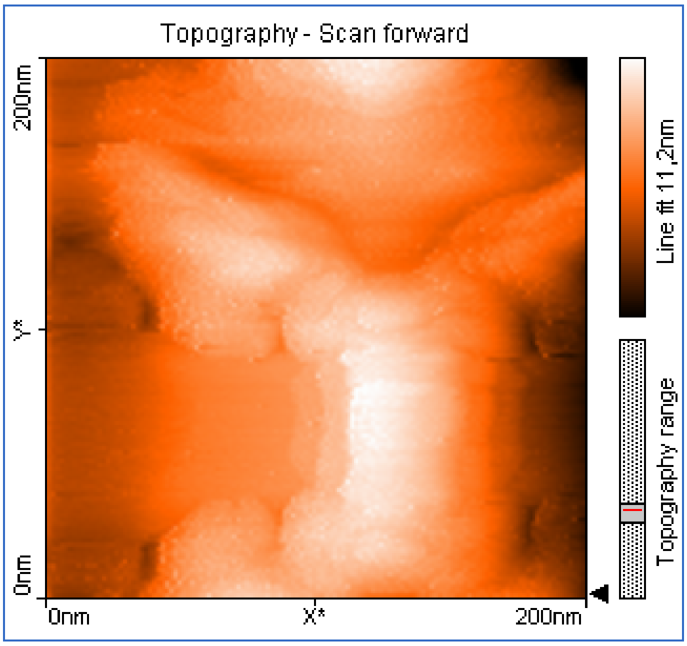


Figure 65: taS_2

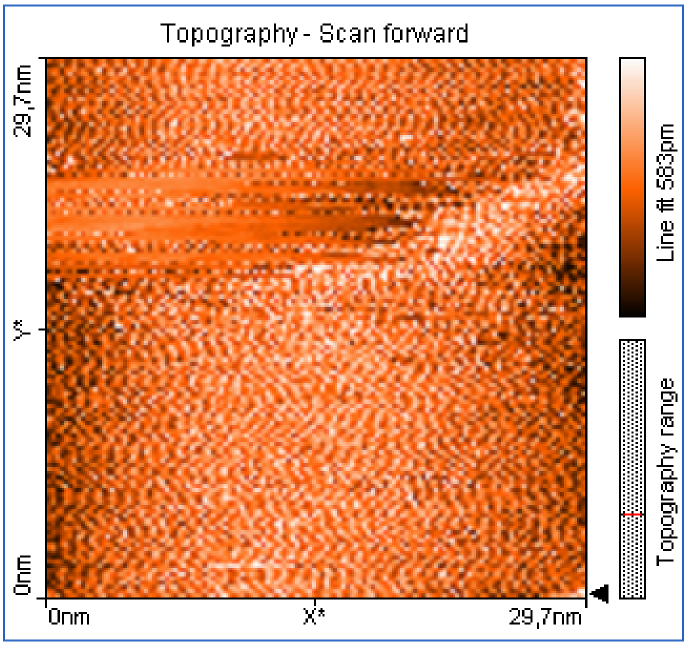


Figure 66: taS_3

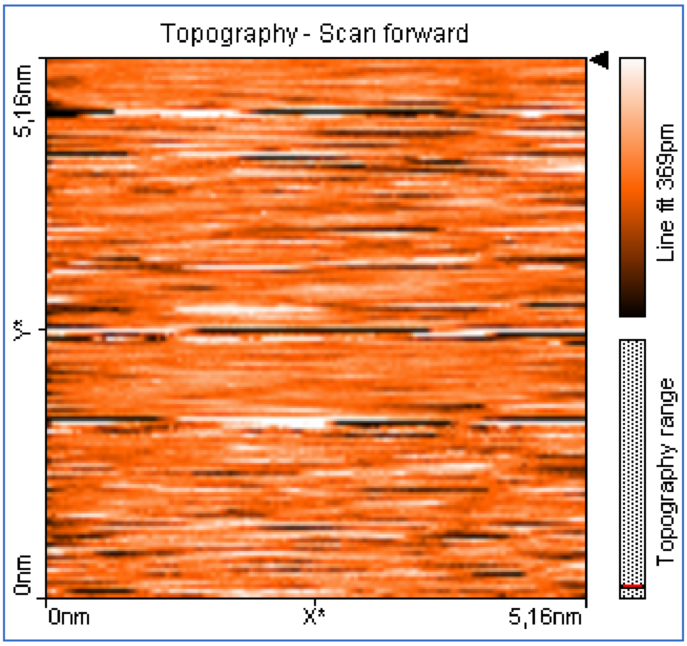
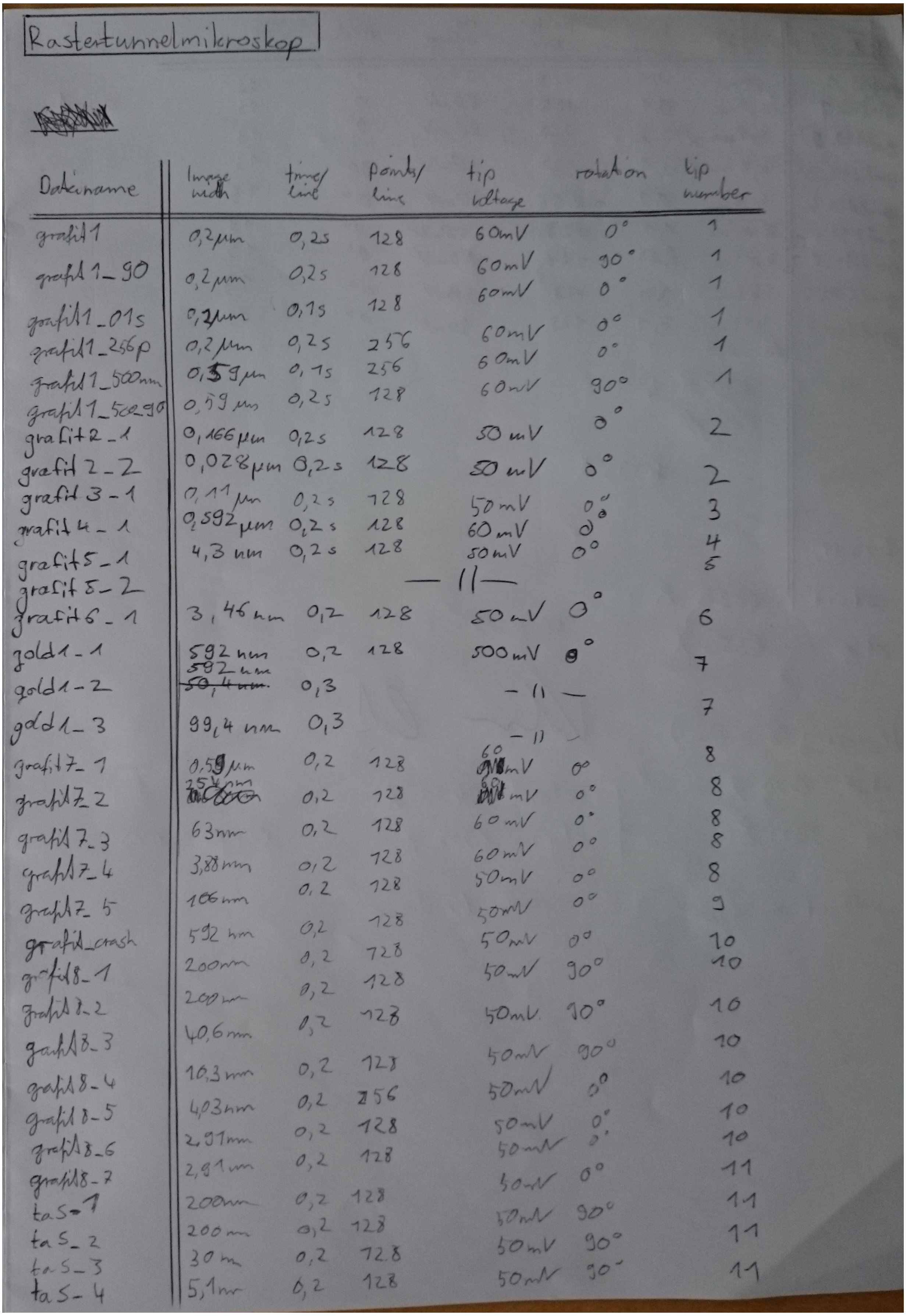


Figure 67: taS_4

8.2 Lab Notes



Rastertunnelmikroskop

Dateiname	Image width	time/line	points/line	tip voltage	rotation	tip number
grafit1	0,2µm	0,2s	128	60mV	0°	1
grafit1_90	0,2µm	0,2s	128	60mV	90°	1
grafit1_01s	0,2µm	0,1s	128	60mV	0°	1
grafit1_256p	0,2µm	0,2s	256	60mV	0°	1
grafit1_500nm	0,59µm	0,1s	256	60mV	0°	1
grafit1_500_90	0,59µm	0,2s	128	60mV	90°	1
grafit2_1	0,166µm	0,2s	128	50mV	0°	2
grafit2_2	0,028µm	0,2s	128	50mV	0°	2
grafit3-1	0,11µm	0,2s	128	50mV	0°	3
grafit4-1	0,592µm	0,2s	128	60mV	0°	4
grafit5-1	4,3nm	0,2s	128	50mV	0°	5
grafit5-2	—	—	—	‖	—	
grafit6-1	3,46nm	0,2	128	50mV	0°	6
gold1-1	592nm	0,2	128	500mV	0°	7
gold1-2	592nm ~~50,4nm~~	0,3	—	‖	—	7
gold1-3	99,4nm	0,3	—	‖	—	
grafit7_1	0,59µm	0,2	128	60mV	0°	8
grafit7_2	254nm	0,2	128	60mV	0°	8
grafit7_3	63nm	0,2	128	60mV	0°	8
grafit7_4	3,88nm	0,2	128	60mV	0°	8
grafit7_5	106nm	0,2	128	50mV	0°	8
grafit_crash	592nm	0,2	128	50mV	0°	9
grafit8-1	200nm	0,2	128	50mV	0°	10
grafit8_2	200nm	0,2	128	50mV	90°	10
grafit8_3	40,6nm	0,2	128	50mV	10°	10
grafit8-4	10,3nm	0,2	128	50mV	90°	10
grafit8-5	4,03nm	0,2	256	50mV	0°	10
grafit8_6	2,91nm	0,2	128	50mV	0°	10
grafit8-7	2,91nm	0,2	128	50mV	0°	10
taS-1	200nm	0,2	128	50mV	0°	11
taS_2	200nm	0,2	128	50mV	90°	11
taS_3	30nm	0,2	128	50mV	90°	11
taS-4	5,1nm	0,2	128	50mV	90°	11

Dataname	Image width	time/line	points/line	tip voltage	rotation	tip number	set point
grafit9_1	50nm	0,1	128	50mV	0°	12	
grafit10_1	4,1nm	0,1	128	50mV	0°	13	0,5nA
grafit10_2	4,1nm	0,2	128	50mV	0°	13	
grafit10_3	4,1nm	0,1	128	50mV	90°	13	
grafit10_4	4,1nm	0,1	256	50mV	0°	13	
grafit10_5	2,05nm	0,1	128	50mV	0°	13	
grafit10_6	2,05nm	0,03	128	50mV	0°	13	
grafit10_7	13,8nm	0,1	128	50mV	0°	13	
grafit10_8	4,15nm	0,1	128	50mV	0°	13	

List of Figures

References

[1] Dieter Ritzmann, *Einrichtung eines Versuchs: Rastertunnelmikroskopie für das Fortgeschrittenen Praktikum 2*, Fakultät für Physik, Albert-Ludwig-Universität, Freiburg i. Brg. 1994

[2] Wolfgang Nolting, *Grundkurs Theoretische Physik 5/1: Quantenmechanik Grundlagen*, 8th edition, Berlin, Heidelberg: Springer Spektrum 2013

[3] M. Köhli, S. Röttinger, *Versuchsanleitung FPI Rastertunnelmikroskop*, Albert-Ludwig-Universität, Freiburg i. Brg. 2013