Scanning Tunneling Microscopy and Spectroscopy of the GaSb(111)B surface

Author: Pontus Littow

Supervisor: Prof. Anders Mikkelsen

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Department of Physics

Division of Synchrotron Radiation Research

Lund University, Sweden

LUND
UNIVERSITY

Abstract

In this thesis the III-V semiconductor material GaSb (111) was studied using Scanning Tunneling Microscopy and Scanning Tunneling Spectroscopy. To characterize the surfaces of semiconductors has become more relevant in today society. When semiconductors become so small that they are in the micro scale the surface must be taken into consideration.

The sample is first placed in the cleaning chamber to clean the surface using atomic hydrogen. When the sample is clean the sample is placed in measurement chamber and a tip is brought within a couple of Angstroms from the surface. A bias is applied and electrons tunnel between the tip and the sample. From this an image is obtained of the surface of the sample.

In the project the temperature needed to make a clean surface of GaSb (111) was determined to be about 515 °C however droplets have started to form on the surface. What reconstructions the surface had after the different cleanings could not with absolute certainty be stated. This is partially due to the distance between the atoms calculated has a large uncertainty for values taken from the second cleaning and also the third cleaning values not being close to other known distances in other reconstructions.

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Introduction

Motivation

Every day there is progress in every branch of science. One of the topics that come to mind in today's society is the new innovations in technology. It impacts our everyday life with telephones, computers and new energy sources etc. With these new technologies comes research in the materials used. One kind of material has been shown to display a wide array of applications, semiconductor materials. Semiconductors have been around for a while (e.g. silicon) but in the last decade a new type of semiconductors, III-V materials, has been developed. The III-V semiconductors have become of interest of researchers all over the world for their use in, for example, light-emitting diodes [1] and high-performance electronics [2].

The advances in technology come alongside an ambition of creating even smaller and more powerful devices. Transistors as an example are getting smaller in every object that contains an electronic chip.

In a macroscopic object the surface has no major impact on the properties of the material simply because the surface makes up a very small part of the material. When the object reaches microscopic dimensions the surface makes up a large fraction of the material and the surface properties becomes more relevant. The surface can have different electronic properties compared to the rest of the material. These properties can generate unwanted results. In case of for example nanowires and graphene, sometimes every atom is a surface atom and thus controls for instance the conductivity.

Therefore it is crucial to understand the surfaces of materials and learn about their properties. By doing so it might be possible to engineer devices that utilize the surface electronic properties rather than rendered useless by them.

There are different methods to study the surface but in this thesis Scanning Tunneling Microscopy (STM) and Scanning Tunneling Spectroscopy (STS) were used. STM obtains a good image of the surface with atomic resolution. While other methods used in today's research have their advantages, they cannot produce an image of the surface the way STM does.

The sample used in this experiment is GaSb(111), which has not been studied using STM and STS before. Before the experiment can start the sample must be clean and in this experiment atomic hydrogen is used in the cleaning process. This type of cleaning process has been used before on other materials but not on GaSb (see method section). The cleaning process is done on a flat surface due to it being an easier starting point than a nanowire to see how effective the process is on GaSb.

The structure of GaSb is similar to another material, GaAs. This material has been studied more than GaSb and was used as a starting point for the cleaning process.

Theoretical Background

In the theoretical background the physics behind the experiment is presented. First the tunneling is explained as it is an important part for the STM and STS. After this come the parts concerning the semiconductor: what is a semiconductor, the semiconductor used in the experiment (GaSb) and reconstructions on the surface.

Tunneling

When working with materials, such as Gallium Nitride, on the micro scale it is important to know that the physics is not the same as on the macro scale. Here the electrons follow quantum mechanical laws and not the laws of classical physics. STM and STS use a phenomenon from quantum mechanics called electron tunneling. An insulator between two materials creates an energy barrier between the materials. If a voltage is applied between the two materials, the Fermi levels of the materials changes so that the difference between the Fermi levels is the applied bias. There is now a driving force for the electrons to move across the barrier. This would not be possible in classical mechanics but quantum mechanics allows a finite number of electrons to traverse the barrier.

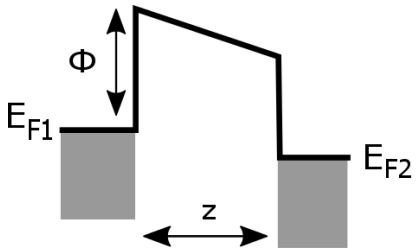

Figure 1. *Two materials separated by an energy barrier with width z where **Φ** is the work function.*

The work function Φ is how much energy is required to extract an electron from the material to infinity. If the bias U is lower in energy than Φ then the electrons have a defined probability to tunnel thorough the barrier.

If a barrier has a width *z*, see figure 1, the probability for an electron to tunnel the barrier is the tunneling current. This current decays exponentially with the barrier width as

$$I \propto e^{-2kz} \quad (1)$$

Where *k* is:

$$k = \frac{\sqrt{2m(V-E)}}{\hbar} \quad (2)$$

where *m* is the mass of the electron, *ħ* is the reduced Planck`s constant, *E* is the energy of the electron and *V* is the potential of the barrier [8, pp 8-9].

Scanning Tunneling Microscopy

Surface science took a leap when the STM was invented in 1982 by Binnig, Gerber, Rohrer and Weibel [3]. This was due to the STM having capabilities to image individual atoms on the surface of the material and individual localized electronic states.

The tip of the STM, usually tungsten, is brought within close range of the sample surface (around 1 nm). The coarse movement is done manually and for the fine movement close to the surface piezoelectric crystals are controlled by a software to get as close as possible to the surface. A voltage bias is applied across the tip and the sample. Electrons tunnel between the sample and the tip and a current is created. From here the STM can operate on two modes to produce the images, constant current mode and constant height mode [8, p 12]. In this project we used the constant current mode; the computer maintains a constant current (using a feedback loop) as well as a constant bias over the tip. These conditions require a constant sample-tip separation. The three directions the tip can move (x, y and z) are controlled by piezo-electric elements. When the tip moves in the x-y plane change in height, for example atomic steps, or change in density of states changes the current, so to maintain the constant current the tip alters the z-position (see figure 2). The imaged produced with constant current mode is a 2-D array of integers representing heights at a specific x and y position. The reason we use the constant current mode is because the mode gives images directly related to electron charge density profiles.

Depending on the voltage applied across the tip and the sample, different states contribute to the image (see figure 3). If the bias is positive the current goes from the tip to the empty states of the conduction band in the sample and are known as empty states imaging. If the bias is negative the current goes from the valence band in the sample to empty states in the tip and are known as filled states imaging.

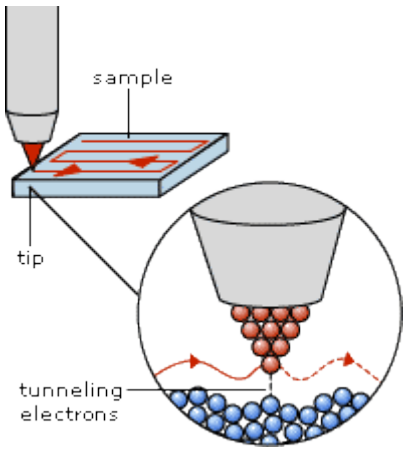

Figure 2. *The tip is brought within 1 nm of the sample. When the bias is applied across the tip and the sample the electrons tunnel thus creating a current. Reference [9]*

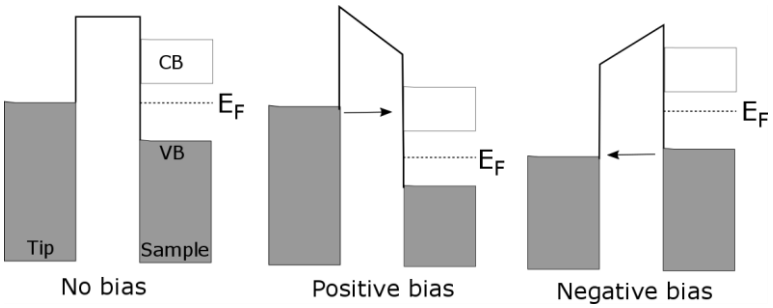

Figure 3. *How the current moves depending on the bias*.

Scanning Tunneling Spectroscopy

The STM gives a good image of how the surface looks like and from there it is possible to obtain information about the structure of a material. However to determine the electrical properties of a material STS is used. STS uses the STM tip and thus both methods are performed during the experiment, although not at the same time. The tip is placed at the area of interest and the tip-sample separation is kept fixed. The feedback loop is disengaged and the sample bias is scanned while the tunneling current is recorded. The resulting data obtained are so called current-voltage curves (IV-curves, see figure 4) and the electronic properties of the surface around the Fermi level are shown.

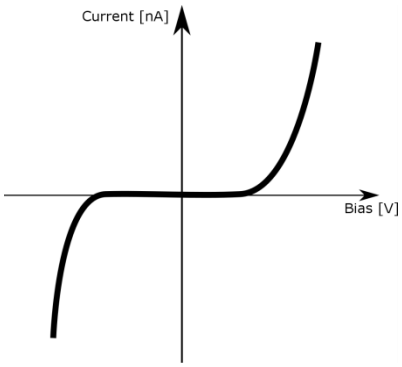

Figure 4. How *an I-V curve from a semiconductor might look like.*

If the STS is measured on a semiconductor the electronic properties around 0 V sample bias is non existing because it is in the middle of the band gap with 0 V being the Fermi level. If the semiconductor is doped the Fermi level position within the band gap will change. This will show in the I-V curve since the bands (valence and conduction band) will move closer or further away from 0 V sample bias depending on the doping.

Semiconductors

The difference between metals and semiconductors/insulators is defined as the density of states at the chemical potential (also known as the Fermi energy) at 0 K. If the density of states at the chemical potential at 0 K is 0 then the solid is a semiconductor or an insulator. This means the chemical potential is in the band gap of the solid. The band gap is a gap between the valence band and the conduction band (see figure 5). In the band gap there are no states so the electrons have to excite from the valence band to the conduction band in order for the semiconductor to be conducting.

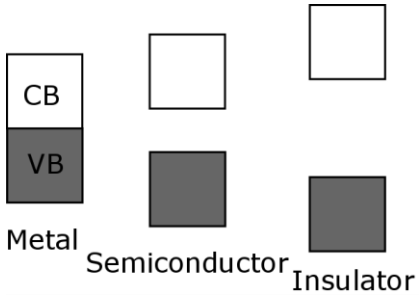

Figure 5. *The band gap in a metal, semiconductor and insulator*.

At room temperature the carrier concentration of the semiconductor is too low to give any appreciable conductivity. To get more carrier concentration an impurity is added, a process called doping. There are two types of doping; n and p doping. n-doping is when an atom with an extra electron is added. The extra electron is found in the outer orbitals and is thus loosely bound in the conduction band. The other type, p-doping, is instead an atom with one missing electron, thus creating a hole in the valence band. In this thesis we have worked with one such doped semiconductor: Gallium Antimonide (GaSb). The material belongs to the so called III-V semiconductor materials. III-V materials consist of group III and V atoms in the periodic table. The III-V materials are currently being used in new high performing electronics, LEDs and other new technologies. However the materials have a high production cost and thus only represent a small part of the semiconductor market.

GaSb

The atoms of the material have equal distance from each other and thus form a unit cell. For the whole material these unit cells form a repeating pattern called crystal lattice. The unit cell tells allot about the structure of the material and is a starting point when analyzing the material. The unit cells can have different shapes but the most simple one is the so called cubic structure where the atoms sit in the corners of the cube, each atom contributing with 1/8 of their volume resulting in a total of 1 atom in the unit cell. There are two other cubic structures: body centered cubic (bcc) and face centered cubic (fcc). The bcc unit cell is just like the simple cubic but with an extra atom in the center of the cube and fcc unit cell has an atom on the center of each side of the cube along with the atoms in the corner.

Since GaSb consists of two atoms the two atoms cannot be in the same point in the unit cell. The unit cell of GaSb is called zinc blende unit cell and consists of two fcc cells combined to

one cell (see figure 7). The lattice constant of GaSb is 6.095 Å [7] and can be used to calculate distances between the atoms in the unit cell. The band gap of GaSb is 0.726 eV [11].

The Miller indices are a notation system used for denoting the planes in the crystal lattice. The Miller indices of the planes will be different depending on how the planes are orientated. Miller indices have three integers (*h*, *k* and *l)* which denote the plane and are proportional to inverse of the intersection of the axis in the unit cell. This means if a plane does not intersect with one of the three axis, the integer is zero. In the case of this thesis GaSb (111) was used in the experiment.

The (111) plan will go through the unit cell (see figure 7) and determine which atoms will become the surface (see figure 6). However since GaSb is a zinc blende unit cell one plane will have Ga atoms and the next plane will have Sb atoms. The planes will alternate between the atoms throughout the material but the important planes are the first and the last planes. The first plane will have Ga atoms and the last Sb atoms. It is common to denote these two planes as the A side and the B side, where A is the first plane and B is the last plane.

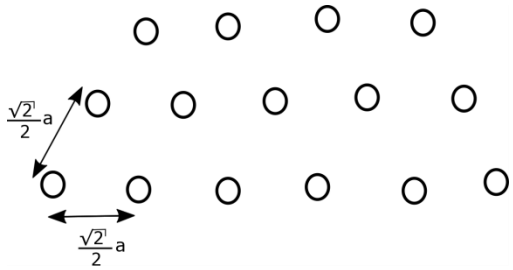

Figure 6. *The unreconstructed surface of GaSb (111) where* ***a*** *is the lattice constant of GaSb*.

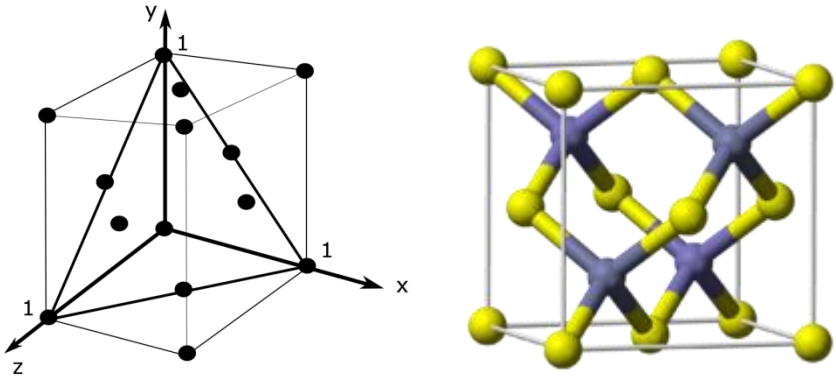

Figure 7. *The left image shows an face centered cubic unit cell with the Miller indices (111) drawn. The right image shows the zinc blende unit cell of GaSb [10]*.

Reconstruction

The surface of a material does not have energetically favourable bonds like the bulk does. The surface can then in many cases reconstruct to another structure with lower energy. Surface atoms can reconstruct differently, for example a vacancy at positions where atoms would be or atoms can form so called dimers, two atoms bound together. The reconstructed surfaces can be described using Woods notation, the new reconstructed unit cell is described in the basis of the unreconstructed unit cell in the bulk.

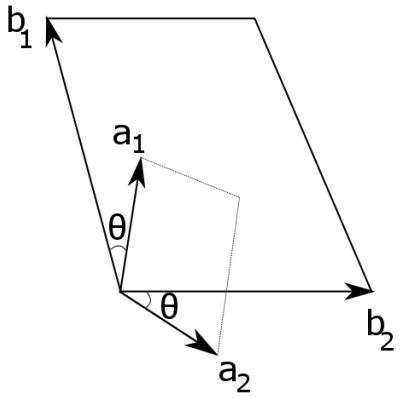

Figure 8. *Woods notation where the **b** vectors represents the new unit cell and the **a** vectors represent the bulk unit cell and θ is the angle.*

The expression for Woods notation will look like:

$$\left(\frac{b_1}{a_1} \cdot \frac{b_2}{a_2}\right) R\theta$$

Where the vectors ***b, a*** and θ are as seen in figure 8. The R means there is a rotation in the reconstructed unit cell with respect to unreconstructed unit cell in the bulk. If there is no rotation then $R\theta$ is omitted.

Different reconstructions on GaSb (111) have been reported, e.g. (2 x 2), (3 x 3). In the (2 x 2) case there is no rotation from the surface unit cell but atoms are missing, making the distance to the neighbor atom twice as large as in the unreconstructed case (1 x 1). For the (3 x 3) case it is almost the same but with three times the distance of the (1 x 1) case. If the lattice constant is known for the material then the distance between the atoms can be calculated theoretically. For the (2 x 2) reconstruction the distance between the atoms are the lattice constant times $\sqrt{2}$.

As mentioned before if the surface is not in energetically favorable bonds, like the bulk has, it can reconstruct but the circumstances leading to this happening can be different. For example when the material is cleaved the new surface looses the bonds and thus can reconstruct to be more stable. It could also be due to the cleaning process done during the experiment (see method section) when the sample is heated, allowing the surface to find a more energetically favorable structure.

Methods

In this section the experiment is explained as to what was used, when it was used and why it was used. To begin, the sample preparation is presented and followed by the experimental setup.

Sample preparation and Experiment setup

The GaSb sample is cut from a disc of GaSb(111) material with the B side of the disc was placed upward. To ensure that the B side is upward the A side is scratched to tell the sides apart. To hold the sample to the tray, indium is used as glue by heating the tray up and then placing the sample in the liquid indium and letting it cool down.

The machine, in which the experiment takes place, is pumped down to ultra high vacuum meaning the pressure is about 10^{-9} mbar (see figure 12). The chamber needs to be in ultra high vacuum to ensure that no new oxygen or other unwanted elements stick to the surface of the sample after cleaning. To achieve this low pressure three pumps are used. The first pump is an oil based pump which uses a rotor to gather gas and transporting into an outlet valve which then releases the gas to it is atmospheric pressure. The first pump will take the pressure down to about 10^{-3} mbar. The next pump is turbo pump which has a spinning fan rotor that hits the gas molecules towards the exhaust and the pressure is lowered even more. The third pump is an ion pump which ionizes the gas and has a strong electrical potential to accelerate the ions into a solid electrode. The ion pump will retain the low pressure so when the pressure is in the range of 10^{-9} mbar it will only require the ion pump to be active. The machine consists of two chambers: the cleaning chamber and the STM chamber. The two chambers are connected with a pipe and within the pipe an arm can move, in one direction, between the chambers.

In order to get the sample into the chamber a load lock is used (see figure 9). Before the sample is placed in the load lock the pressure must be pumped up to the pressure in the room. Opening the load lock without changing the pressure would be difficult due to the vacuum and the force required to remove the lid would be too high to remove it. While the sample is in the load lock the pressure is pumped down. Once the pressure is down to a reasonable level the sample is transferred to the cleaning chamber (see figure 11) using the transfer arm (figure 11).

Figure 9. *The load lock of the STM machine*.

The cleaning process used in the experiment has shown to be effective when cleaning III-V materials [4, 5, 6]. The sample is heated and at the same time molecular hydrogen is pumped into the chamber. The molecular hydrogen passes through a tungsten tube with a temperature of 1700 °C after which the hydrogen is cracked to atomic hydrogen. Atomic hydrogen is very reactive and will stick to the oxide layer on the surface of the sample. When the hydrogen is pumped in to the chamber the pressure changes. The chambers are closed off from each other with a wall so the hydrogen does not move to the STM chamber. Two displays are used to show the pressure in both chambers (see figure 12) and when the hydrogen is pumped down the wall is removed. The temperature of the sample varies depending on the material used. The temperatures of GaSb were measured with a pyrometer during the cleaning process and since the pyrometer was held by hand there is an amount of uncertainty in the values.

For our experiment GaAs was used as a reference sample to determine that the cleaning process is working because we know the settings that should clean the surface, however these settings does not say anything about the surface of GaSb. A method to see if the GaSb is clean or if it needs to go through the cleaning process again but with a higher temperature and longer time, is to scan the surface with the tip.

When the cleaning is done the sample tray is moved from the cleaning chamber to the STM chamber. The sample is placed in a holder that rotates the sample so it is upside down. If the indium does not have sufficient hold of the sample the rotation can cause the sample to fall off the sample tray and we would have to start all over with a new sample.

The tray is manually moved from the holder to the STM by a wobble stick that can be moved in *x*, *y* and *z* directions. When the sample ray has been moved to the STM (see figure10), the locking mechanism holding the platform in place is released and the platform is suspended by electromagnets. This is done so the machine is not affected by vibrations.

During the experiment, the voltage bias is changed. As was seen in figure 3 depending if the bias is negative or positive the current will move through the conduction or the valence band. The bias is also changed, in number of Volts, so more states in the given band will allow a greater current. This is seen in the results section were the STM pictures have different bias.

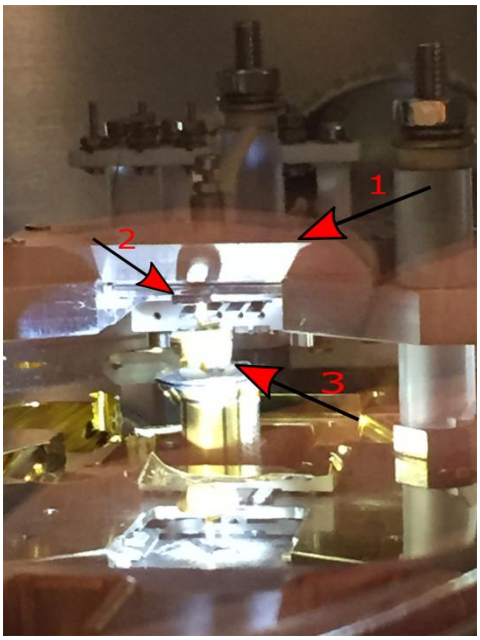

Figure 10. *The sample holder and the STM tip. The arrow labeled 1 is pointing to the sample holder, arrow 2 points to the sample tray and arrow 3 points to the STM tip although it is hard to see.*

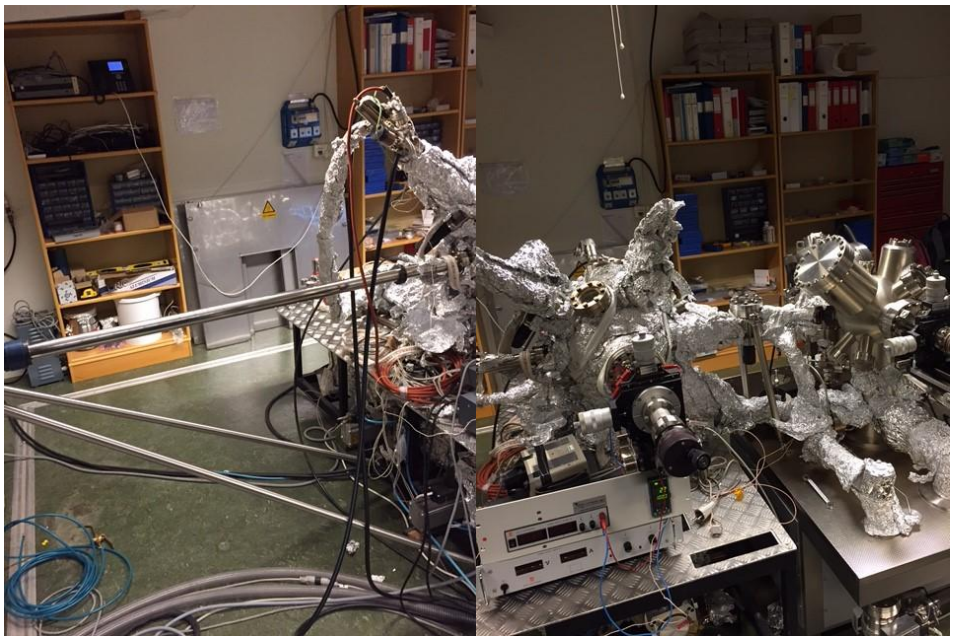

Figure 11. *The whole STM machine. The left picture shows the transfer arm that is used to transfer the sample between the two chambers. The right picture consists of three parts: the left part of the machine is the cleaning chamber, the right part the STM chamber and in the middle is the load lock.*

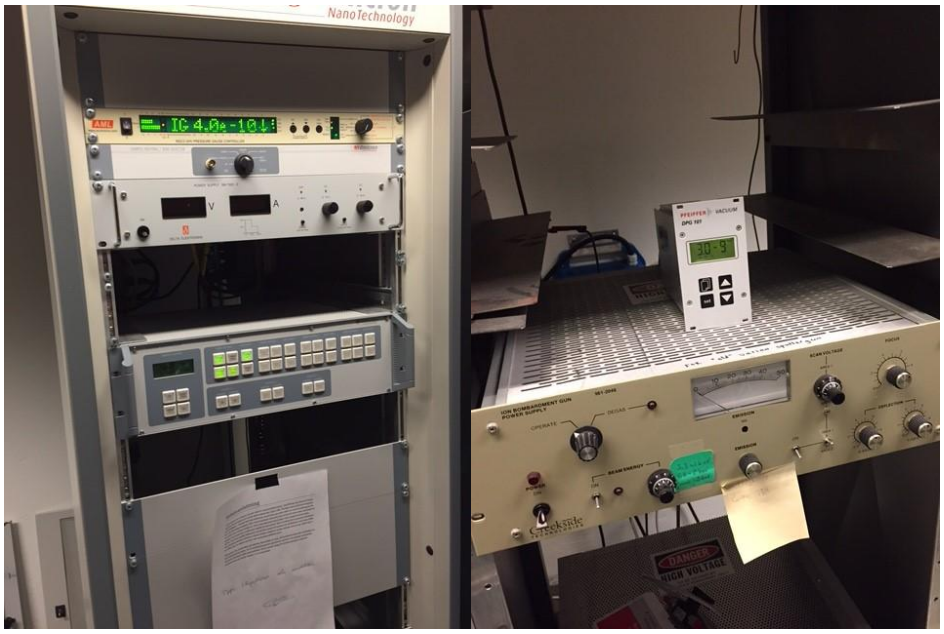

Figure 12. *Displays showing the pressures in the different chambers*.

Results

GaSb was cleaned at four different temperatures, 450-460 °C, 475 °C, 515 °C and 550 °C.

The results are categorized under which cleaning the pictures and data was taken from.

First Cleaning

The first cleaning process was heated to about 450-460 °C for 45 min. The pressure in the cleaning chamber was $2 \cdot 10^{-6}$ mbar. From this process the following STM pictures was obtained (see figure 13). The STM pictures have a color code, meaning the darker areas are the lowest points and the lighter areas are the highest points. The difference in height is shown to the right in the figures.

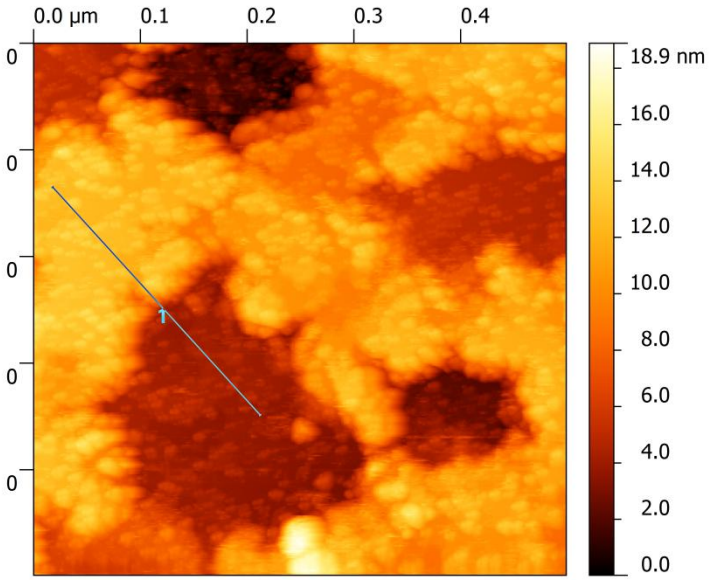

Figure 13. *STM picture after the first cleaning. The scan was made with a bias of-1.3 V, current of 150 pA and the area scanned was 500x500 nm. The line in the image is a profile line.*

From figure 13 we can see it is not very clean and atomic resolution was not obtained. From figure 13 the roughness of the unclean area is obtained by taking a profile line as seen in the figure. The profile line is shown in figure 14.

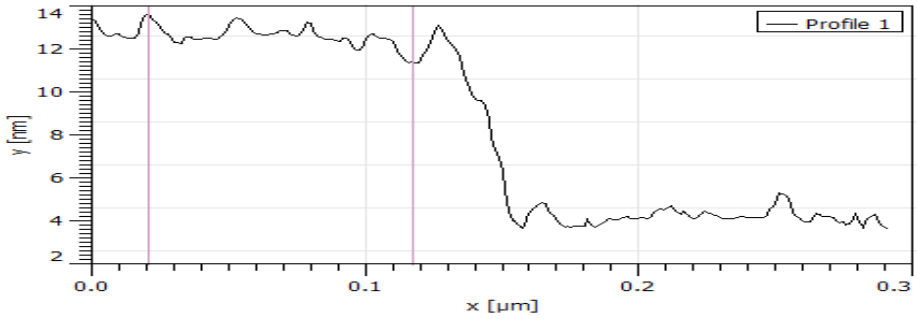

Figure 14. *Profile line from figure 13 from the unclean patch to the clean patch. The two vertical lines are made to determine the height difference between the two points that the lines intersects with the profile.*

From figure 14 the roughness of the unclean area is calculated by taking the height difference between the lowest point and the highest point and the result was 2.25 nm.

We can also see in figure 14 that the unclean area is about 8 nm high.

Second Cleaning

After the second cleaning, at 475 °C for 40 min with a pressure of $2 \cdot 10^{-6}$ mbar, figure 15 was obtained.

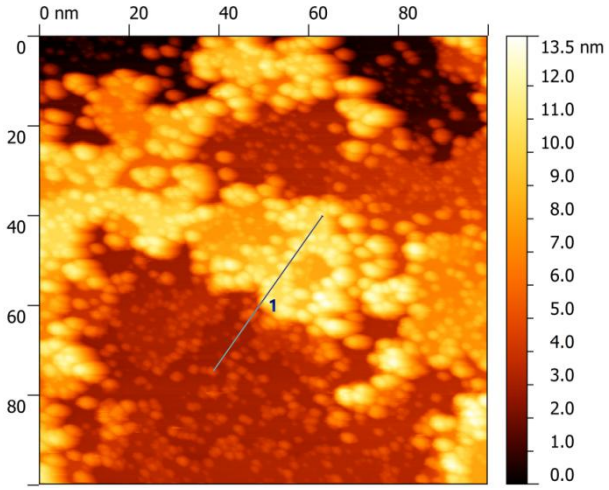

Figure 15. *STM picture after the second cleaning showing more of the surface of the sample. The settings used for this image was with a bias of -1.5 V, a current at 100 pA and the area scanned has the size of 100x100 nm. The line in the image is a profile line.*

Even though the surface is not completely clean, as seen in figure 15, we are now able to see atomic steps in the clean patches. The roughness of the unclean area is measured using the same method as was used in the first cleaning. The profile in figure 15 is shown in figure 16.

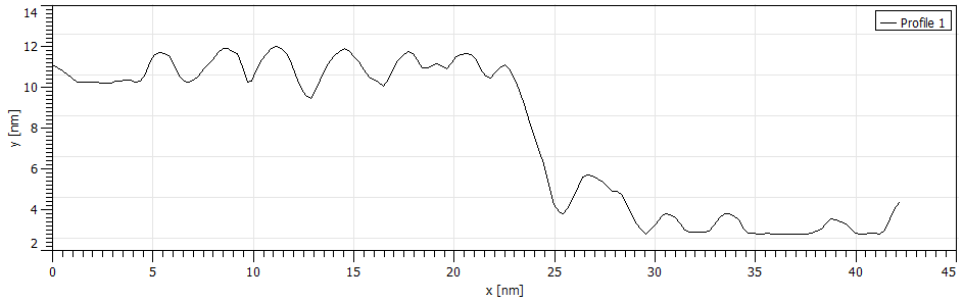

Figure 16. *Profile from figure 15 from the unclean patch to the clean patch.*

From figure 16 the roughness is calculated the same way as in the first cleaning. The roughness was calculated to 2.49 nm. The profile also shows the height of the unclean patch, about 7 nm.

Figure 17 is an area from figure 15 that shows the atomic step in the clean patch.

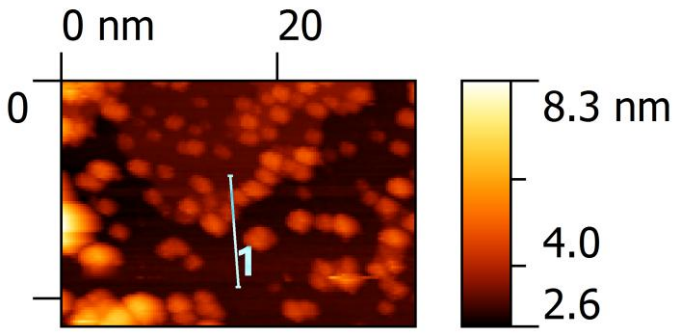

Figure 17. *Zoomed in from figure 15 showing atomic steps, a line represents the profile.*

Even though it is not atomic resolution figure 17 shows an atomic step. The profile line from figure 17 is taken from the higher step to the lower and is represented in figure 18.

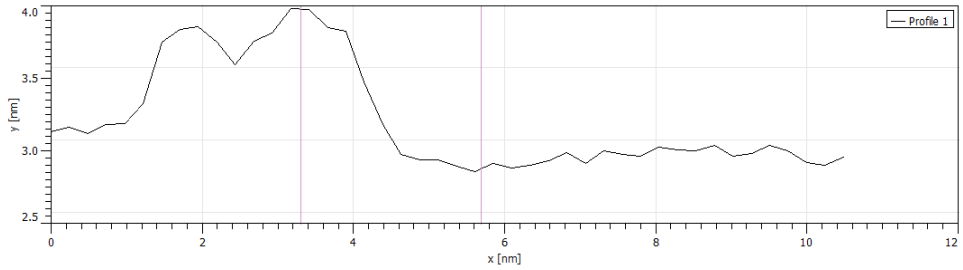

Figure 18. *Profile line over an atomic step. The two vertical lines in the profile give the height difference between the points the lines intersect with the profile.*

In the profile the height difference from the vertical lines was 1.102 nm. From the theory part we know that the lattice constant is 0.6095 nm. So we would expect the atomic step to be around 0.6095 nm but now we get 1.102 nm. However looking at figure 15 where the profile is taken there are atoms on top of the atomic step. So now two layers of atoms the distance should be theoretically 1.2 nm.

Zooming in on the clean patches and scanning an image with atoms, figure 19 was obtained but the resolution was not so good. It is still possible to try to calculate the distance between the atoms from the figure.

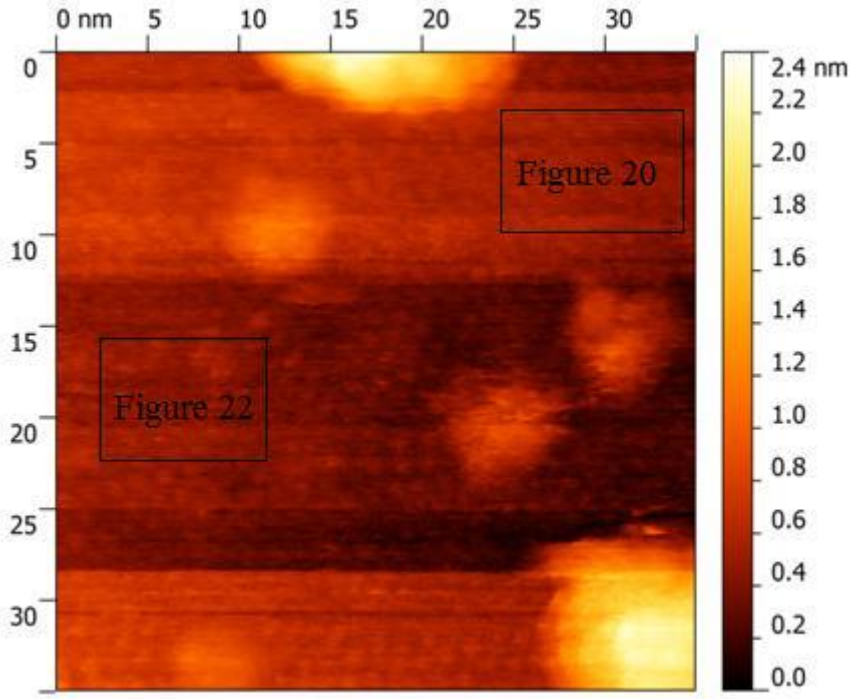

Figure 19. *STM picture with atomic resolution. The settings for the scan were: a bias of 0.8 V, current of 300 pA and the area scanned was 35x35 nm.*

In figure 19 two areas were extracted (see figures 20 and 22) to expand two rows of atoms in order to taken profiles from them and from the profiles calculate the distance between the atoms.

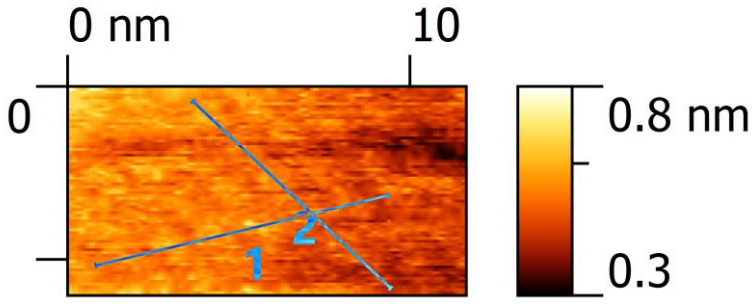

Figure 20. *An area zoomed in from the upper right area of figure 19 with two profile lines.*

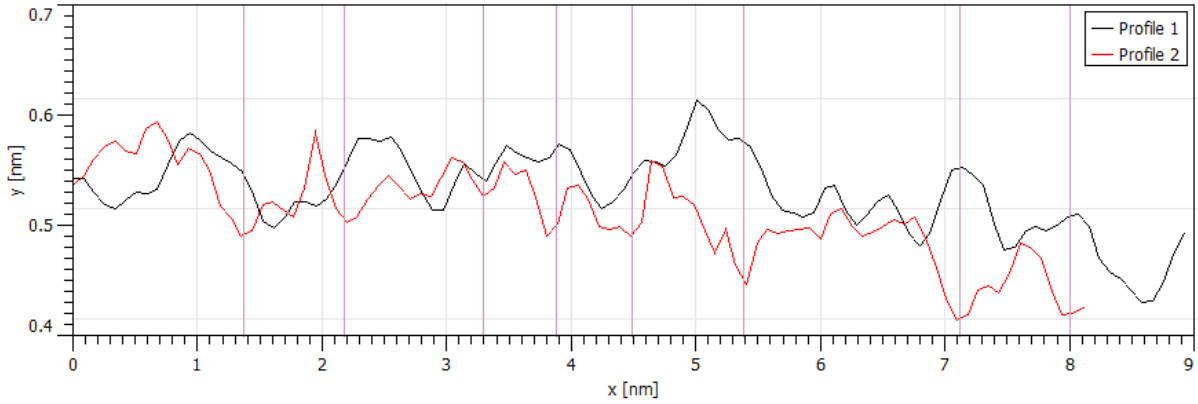

Figure 21. *Profile 1 and 2 are from figure 20.*

By taking a profile of a row of atoms, the distance between the atoms is obtained. From the different distances between the atoms a statistic average is made along with the error in the calculations. For figure 21 the distance between the atoms was calculated to: in profile 1 (1.16±0.29) nm and for profile 2 (0.95±0.36) nm.

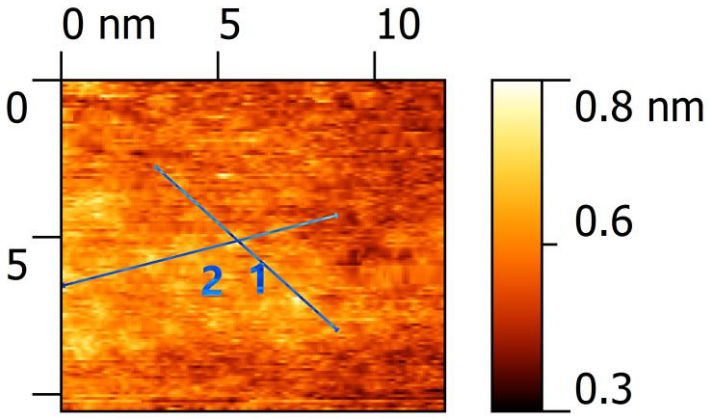

Figure 22. *Another area from figure 19 with two profile lines.*

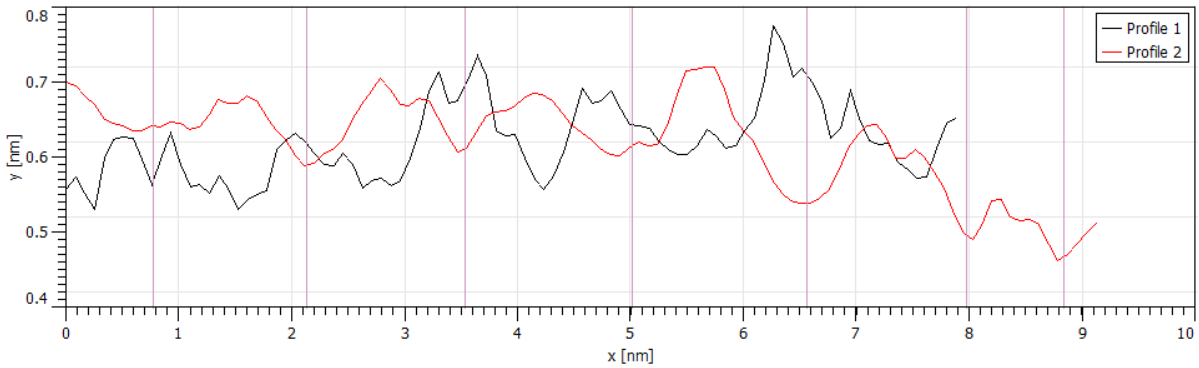

Figure 23. *Profile 1 and 2 from figure 22.*

Taking one measurement is not enough for one image so the same calculation was done on another part of the image, see figure 22. Now the distance between the atoms was calculated to: for profile 1 (1.22±0.22) nm and for profile 2 (1.34±0.23) nm.

Third cleaning

As was observed from the previous cleaning, the sample was not completely clean so the sample was cleaned again but this the time the temperature was raised with a larger step to 515 °C for 60 min with a pressure of 1.2 10^{-5} mbar.

Now the sample has become very clean and it was possible to produce an even better atomic resolution as seen in figure 24.

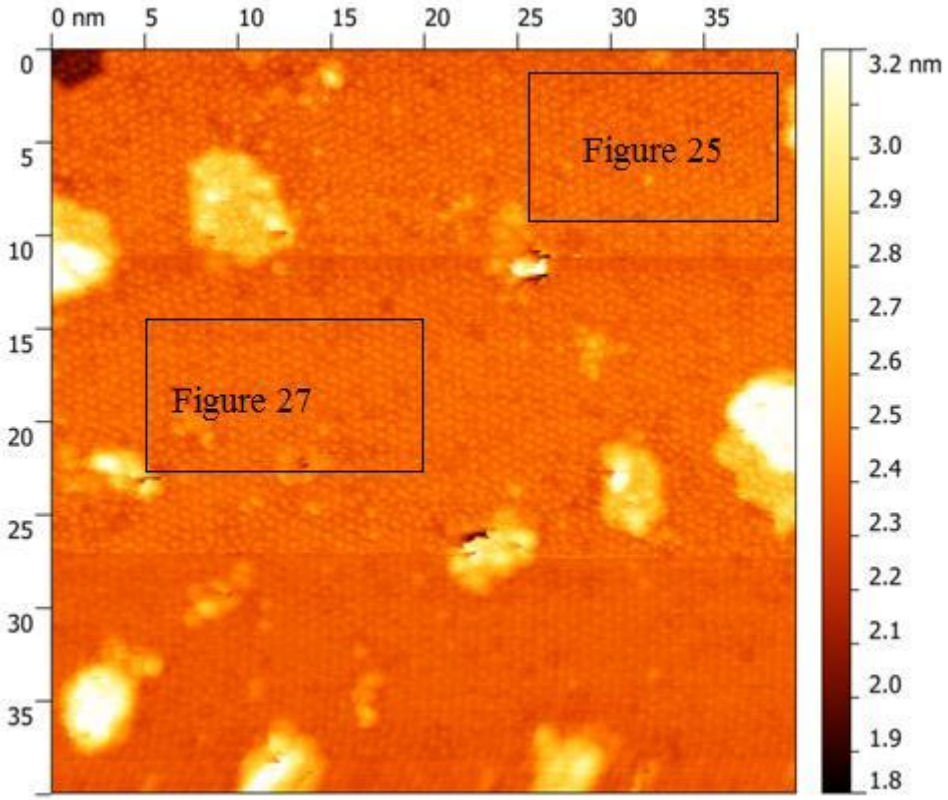

Figure 24. *STM picture taken after the third cleaning showing very good atomic resolution. The settings for the scan were with a bias of -1.5 V, a current of 400 pA and covering an area of 40x40 nm.*

The distance between the atoms is calculated the same way as it was done for the second cleaning. However, this time the resolution is much better making it easier to identify the atoms when drawing the profile over a row of atoms. Two areas of figure 24 were extracted (see figures 25 and 27) and profile lines were drawn to calculate the distance between the atoms using the same method as was done in the second cleaning.

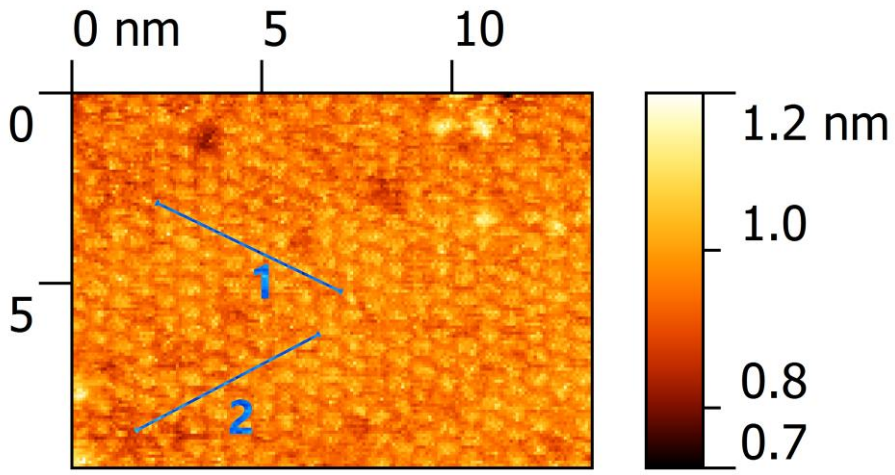

Figure 25. *An area of figure 24 extracted and the lines are the profiles.*

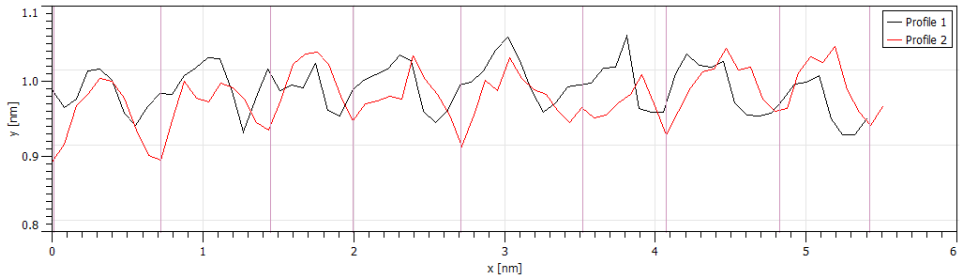

Figure 26. *Profiles from figure 25.*

The atoms from figure 25 are now easily identifiable compared to the figures from the second cleaning. From figure 25 two profile lines are drawn and are shown figure 26. The distance between the atoms was calculated to: for profile 1 (0.647±0.08) nm and for profile 2 (0.68±0.09) nm.

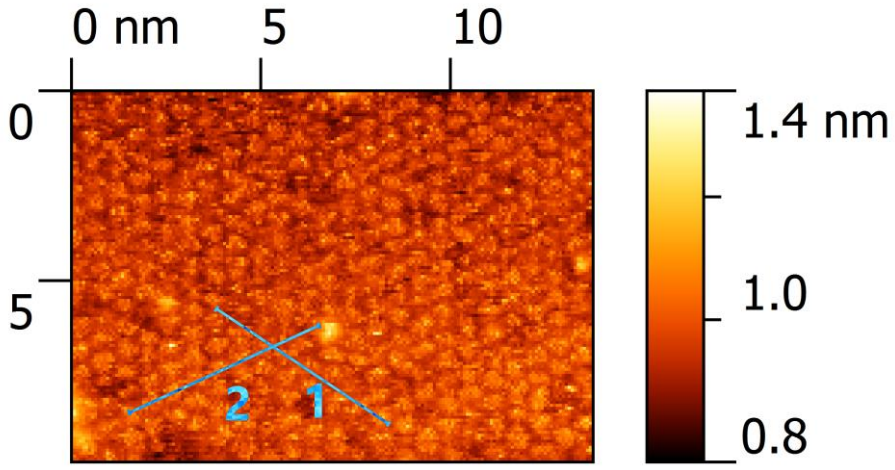

Figure 27. *The second area extracted from figure 24 with two profile lines.*

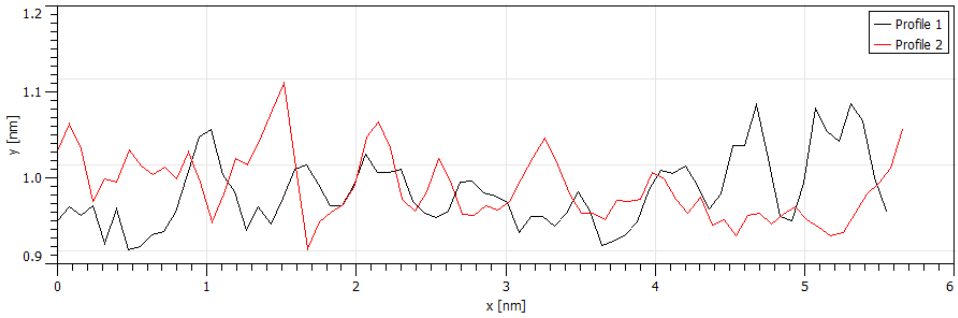

Figure 28. *The profiles from figure 27.*

The distance between the atoms, using the same method as before, in figure 27 was calculated to: for profile 1 (0.57±0.17) nm and for profile 2 (0.63±0.19) nm.

Fourth cleaning

The sample was also cleaned a fourth time at 550 °C to determine if the sample became really clean. After the cleaning process the surface was rendered unusable, the temperature was too high and so called droplets had formed [12]. These droplets are due to the Ga atoms underneath the Sb surface. At too high temperatures they lose their bonds and move up to the surface (see figure 29). From the figure 29, a lot of droplets over a wide area is observed. The sample has become unviable for performing measurements with. The droplets also seem to occur during the third cleaning but not to the same extent as they appear here.

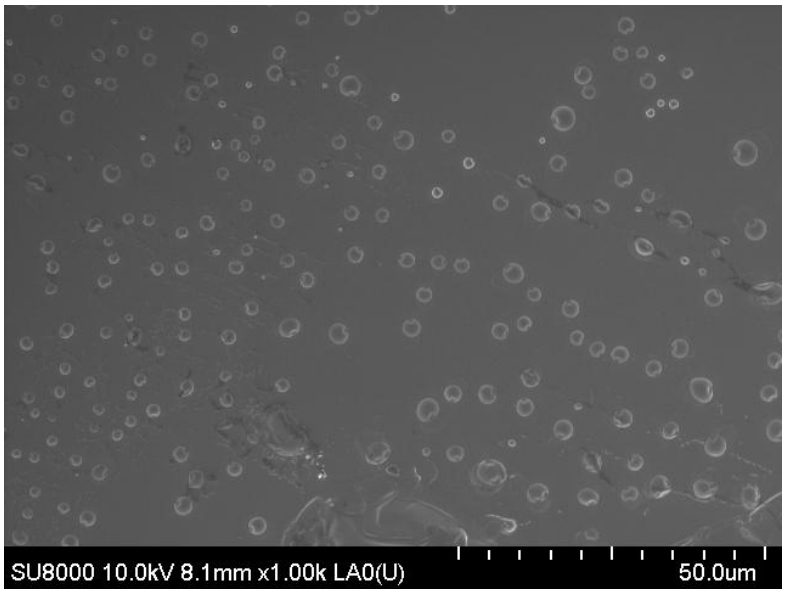

Figure 29. *SEM image of* d*roplets on the sample surface. Made by Sofie Yngman.*

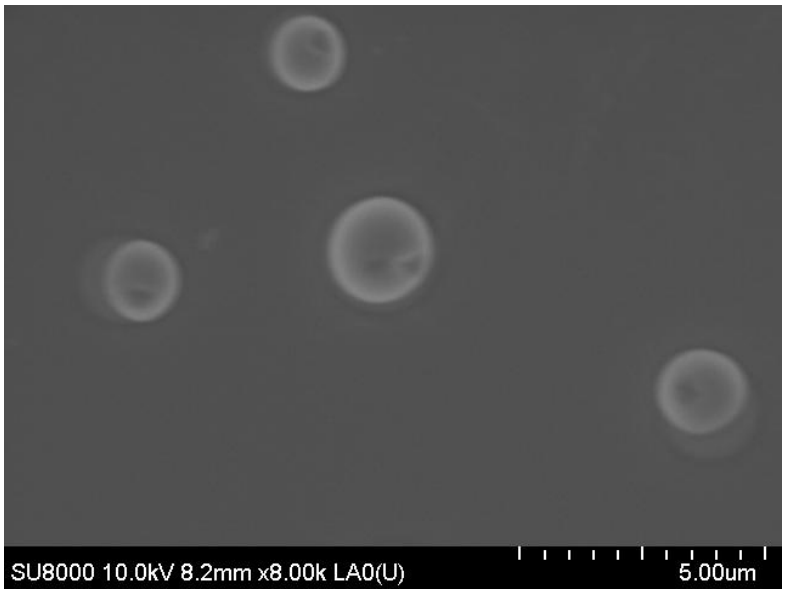

Figure 30. *A closer look at the droplets using SEM. Made by Sofie Yngman.*

Result Discussion

From the different cleanings it was shown at what temperatures the sample became clean. At 515 °C the surface became very clean (see figure 24), however we also noted droplets forming at this temperature so the optimal temperature for cleaning is between 475 °C and 515 °C.

The distance between the atoms was calculated using statistics of the several distances between atoms. For the second cleaning the resolution (figure 19) was not very good thus making it hard to find a row with several atoms. The values calculated have large errors so the correct atomic distance for the surface would be hard to say. For the third cleaning the atomic resolution (figure 24) was much better and thus is is easier to find rows with several atoms. The distance between atoms calculated from figure 24 were all around 0.63 nm but some of the values have higher errors than others. The method used to calculate the distance between the atoms was not the best method and if the experiment was redone another method would be better to use. With the uncertainty in the distance between the atoms being large it cannot be claimed with full certainty what reconstruction the surface has. However, for the case in the second cleaning the values are about three times larger than the unreconstructed case. An intuitive guess could then be made that the reconstruction is a (3 x 3). In the case of the surface in the third cleaning there is a reconstruction as the distance between the atoms is larger than the unreconstructed surface but what reconstruction the surface has cannot be said with certainty.

The STS results did not give any favorable data of the GaSb surface. Figure 31 shows an I-V curve taken on the surface of GaSb. From the STS theory, in the theoretical background, around 0 V in the I-V curve is the band gap of the sample. The band gap for GaSb is known (see headline GaSb) and the I-V curve should also give this value. However the I-V curve shows the band gap being over 2 eV which is a contradiction from the real value. In the figure there are nine repetitions on the same place on the sample, given they deviate from each other the results cannot be trusted.

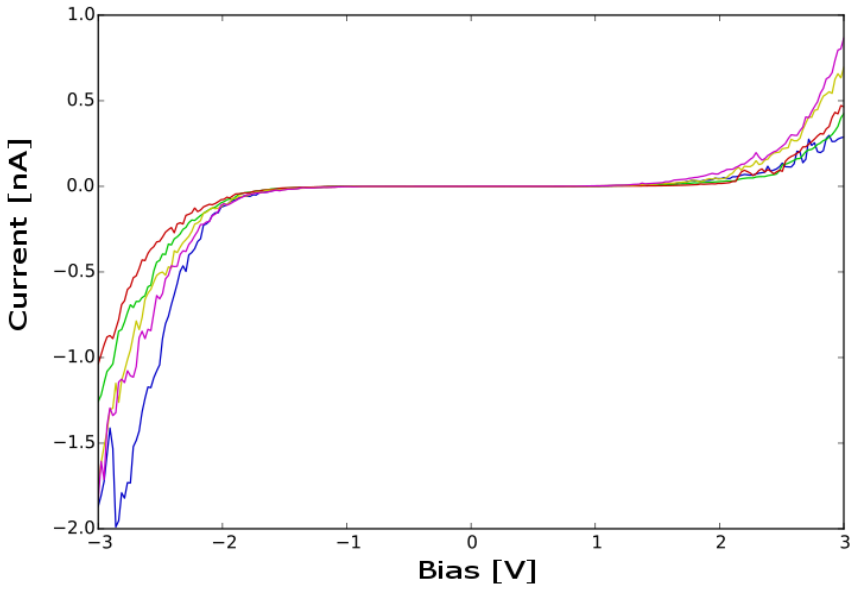

Figure 31. I-V curve *of GaSb. There were some conversion errors when the files were exported from the lab computer so the current values are maybe not completely correct. There are 9 repetitions in the figure all taken from the exact same place*.

Outlook

In this thesis the surface of GaSb was studied using Scanning Tunneling Microscopy and scanning Tunneling Spectroscopy. Before the measurements can be done on the surface, the sample must go through the cleaning process to remove the oxide layer and other unwanted elements on the surface. From the cleaning process it was shown that optimal temperature for cleaning GaSb sample was around 515 °C. At 475 °C the temperature was not high enough to get a clean surface and 550 °C was too high as droplets formed and the sample surface unviable to measure on. Although the sample was relativly clean at 515 °C, droplets were formed during the cleaning process. However, these droplets were small and did not occur as often as in the forth cleaning case. From the atomic resolution images obtained during the different cleanings the distance between the atoms was calculated but due to the uncertainty in some of the values and the method used to calculate them they are not completely reliable. Due to this fact the reconstructions on the surface cannot be stated with certainty what reconstructions the surface possesses. For the second cleaning, the distance between the atoms was around three times as large as the unreconstructed surface and thus an intuitive guess could be that it is a (3 x 3) reconstruction. For the third cleaning there is a reconstruction as the distances are larger than the unreconstructed surface but what reconstruction it is cannot be said with certainty.

Since the result in this thesis did not give an answer to the reconstruction the surface possesses, more measurements is required to find answers to this question. With the results from the thesis a researcher could apply them, as the temperature needed for a clean surface is known now. If the experiments are done again, another method for calculating the distance between the atoms should be used. It would also be useful to record the so called differential signal ($\frac{dI}{dV}$-curves) when performing the STS measurements.

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