Design and Commissioning of a UHV-STM: Simplified Besocke Design for the Study of Nanowires

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To Grova
Abstract

Im Rahmen dieser Diplomarbeit wurde ein Rastertunnelmikroskop und das dazugehörige Ultrahoch-Vakuum(UHV)-System für die Untersuchung von Quantendrähten auf Halbleiteroberflächen entwickelt und in Betrieb genommen. Das kompakte UHV-System besteht aus Präparationskammer und Rastertunnelmikroskopkammer mit Probeneinschleusung und Probentransfer. Es ist auf drei pneumatischen Isolatoren gelagert, wobei der Schwerpunkt des UHV-Systems im Schwerpunkt des dreieckigen Rahmens liegt, was zu einer hohen Stabilität führt.

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List of Unit Conversions and Acronyms

Å Ångström, 1 Å = 10\(^{-10}\) m
Foot 1’ = 304.8 mm
Inch 1” = 25.4 mm
Torr 1 Torr = 133.32 Pascal

AFM Atomic Force Microscopy
AWG American Wire Gauge
DVM Digital Volt Meter
HOPG Highly Oriented Pyrolytic Graphite
HV High Vacuum
KRIPES K-Resolved Inverse Photoelectron Spectroscopy
DOS Density of States
MBE Molecular Beam Epitaxy
PTCA Pin Terminal Carries Assembly (Sockets)
UHV Ultrahigh Vacuum
SPM Scanning Probe Microscope/Microscopy
STM Scanning Tunneling Microscope/Microscopy
STS Scanning Tunneling Spectroscopy
Chapter 1

Introduction

1.1 Historical Review

Binnig and Rohrer [1, 2, 3, 5] started off in autumn 1978 originally to do tunneling spectroscopy on a nanoscale but realized soon that vacuum tunneling with a positionable tip would also give topographic information. Three years later in 1981 they got first topographic of monosteps on CaIrSn$_4$ and attempted the Si(7x7) surface, which was at the time the most famous and intriguing surface reconstruction in surface science. But it would be on gold, Au(110), that they obtained the first atomic resolution images and performed the first spectroscopy experiments. When Binnig and Rohrer showed these images, few people believed them: “it just could not be that simple” [5]. Shortly after (in autumn 1982) they managed to get atomic resolution on Si(7x7), showing the top layer of the rhombohedral 7x7 unit cell in real space, and it turned out that none of the proposed models were right. But it took until 1985 that other groups got atomic resolution and with that scanning tunneling microscopy became accepted. With their invention of Scanning Tunneling Microscopy (STM), Scanning Tunneling Spectroscopy (STS), and Atomic Force Microscopy (AFM) a whole new dimension of science started: it enables us to see, touch, and manipulate atoms on surfaces.

The principles of scanning tunneling microscopy are simple and straightforward. It can be used for fundamental research in fields like physics and chemistry as well as for material research in industry. In only 18 years, scanning tunneling microscopy has become an indispensable tool for modern research and technology. The importance of the STM is reflected by the fact that Binnig and Rohrer were awarded the Nobel prize in 1986 for its invention.
1.2 The NanoPhysics Group

The NanoPhysics group of Professor A. McLean at Queen’s University investigates quantum wires on semiconductor surfaces. These are self-assembled nanowires with a highly correlated electronic structure. Their home-built k-Resolved Inverse Photo-electron Spectrometer (KRIPES) [8, 9], which gives momentum-resolved information about the empty states above the Fermi level, has a sensitivity six times better than conventional solid state detectors.

To allow further investigation of these unique nanowires, the NanoPhysics Group obtained an Equipment Grant from the Natural Sciences and Engineering Research Council of Canada (NSERC) in April, 1998, to construct a Besocke-type STM.

1.3 Nanowires

As electronic devices become smaller and smaller, properties of electronic systems on nanometer scale have become more and more important. Particularly interesting are one-dimensional systems.

One of these systems is the Si(111)-In(4x1) surface. It can be produced by evaporating indium on a Si(111) surface that is cut off under a small angle. The indium atoms reconstruct along the terraces of the Si(111). There exist seven overlayer phases depending on the coverage. The 4x1 phase appears by approximately 1.0 monolayers of indium, it reconstructs in single and three domain overlayers depending on the growth conditions.

Studies of the band structure perpendicular to and along the chains show the system is quasi-one-dimensional. A breakthrough in surface science was the discovery of a Fermi-level crossing in the Si(111)-In(4x1) system along the chains [10, 12], which means that the system is metallic. These quantum wires are the smallest existing wires and might be important prototypes for atomic scale interconnects. But so far there is still a debate about the atomic arrangement of the indium chains on the surface.

Using the electronic information obtained with KRIPES, the Scanning Tunneling Microscope can be used to selectively tunnel into the image state of the nanowires. These regions will be highlighted compared to the surrounding material, which leads to an elemental contrast [13]. Thus tunneling spectroscopy gives distinct images of the quantum wires on the surface.

1.4 The Adventures and Challenges of my Thesis

In the summer of 1998, Professor A. McLean and I spent two months looking at different arrangements of Besocke-type STMs: up side down, right side up, rotational, or lateral coarse approach, hanging from springs, or sitting on a damping stack. We
included and excluded a tip exchange (back and forth), developed a cooling stage, and varied the UHV system: one- or two-chamber system, spherical, cylindrical, square chambers, sample introduction from the side, from the back, and also the front. We finally came up with a compact and versatile solution.

While back in Germany I tried to get information about building a STM. The Physics Faculty in Stuttgart has several microscopes. The Surface Science Group of Professor R. Möller, where I had worked as a HiWi (lab assistant) for two years, had moved away. So I went to see them in Essen - they had just purchased a new Omicron STM. Just before I returned to Canada, I visited the Surfaces and Interfaces Group of Professor Dr. K. Wandelt in Bonn, which operates a variety of Besocke-type STMs.

In March, 1999, I arrived in the New World. Professor A. McLean had finally got a room in the basement with no windows: great for vibrational and noise insulation, but at times it felt like the burrow of a mole.

In the room was the major equipment: the ion pump in a big wooden box, the turbo pump, the rotary pump, three vibrational isolators, valves and the transfer arms for the UHV system, six piezoelectric tubes, the rack with the RHK controller, and a computer. After taking stock and organizing a chair and table to be able to sit down, I did not know where to begin. To start assembling the system we needed the right parts and tools, but to find out which tools and parts were needed, we had to start assembling!

To avoid ordering useless or unnecessary parts, I always tried to get all the information beforehand. This was sometimes a difficult task. Since this is the first STM at Queen’s University which operates in UHV, there was no other group with whom to share experiences. In addition, Scanning Tunneling Microscopy is such a recent topic with a lot of new developments in the last ten years that the few books on it held by the library were out of date. The Internet is a good resource for papers, but papers do not provide you with any information about all the pitfalls that should be avoided. When it came down to a certain tricky expertise - which might be trivial once you know how to do it - I needed advice from people who had built or tinkered with a STM before. Luckily, email is a fast and convenient medium to cry for help.

I also had to stay within the budget. Two thirds of it had been invested in the controller and the pumps. The last third went mainly towards the vacuum system where every little part is expensive. The rest of the money had to be spent very judiciously. By limiting the lab equipment to the essentials, we managed to build the STM for only half the price of a commercial one.

Last, but not least, the major challenge was to get it all working prior to the deadline of my thesis. This was possible only by staying focused and joining all our efforts towards the goal: a home-built scanning tunneling microscope.¹

¹Chapter 1.3. is not written in a strictly scientific manner but I think the only way to survive the stress of labs, research, a thesis, and to enjoy science is to look back at it with a smile.
Chapter 2

Principles of Scanning Tunneling Microscopy

2.1 Quantum Mechanical Tunneling

The quantum mechanical tunneling effect [14, 15] is illustrated in figure 2.1. We can derive the qualitative behaviour by solving the Schrödinger equation for a free electron in a time-independent one-dimensional potential \( V(z) \):

\[
-\frac{\hbar^2}{2m_e} \frac{d^2}{dz^2} \psi(z) + V(z) \psi(z) = E \psi(z), \tag{2.1}
\]

where \( \psi(z) \) is the wavefunction of the electron, \( m_e \) and \( E \) is its mass and energy, and \( \hbar \) is Planck’s constant divided by 2\( \pi \).

The potential \( V(z) \) can be divided into three regions around the potential barrier:

\[
V(z) = \begin{cases} 
0 & \text{for } z < 0 \\
V & \text{for } 0 \leq z \leq d \\
0 & \text{for } z > d 
\end{cases} \tag{2.2}
\]

Upon substitution of this potential \( V(z) \) into the Schrödinger equation 2.1, the ansatz for the wavefunctions \( \psi(z) \) in the three regions is:

\[
\begin{align*}
\psi(z) &= Ae^{ikz} + A'e^{-ikz} \quad \text{with} \quad k = \sqrt{2m_e(E - V)/\hbar} \quad \text{for } z < 0 \\
\psi(z) &= Be^{-\kappa z} + B'e^{\kappa z} \quad \text{with} \quad \kappa = \sqrt{2m_e(V - E)/\hbar} \quad \text{for } 0 \leq z \leq d \\
\psi(z) &= Ce^{ikz} + C'e^{-ikz} \quad \text{with} \quad k = \sqrt{2m_e(E - V)/\hbar} \quad \text{for } z > d
\end{align*}
\tag{2.3}
\]
Figure 2.1: Illustration of the Tunneling Effect:
In classical physics (top), an electron is a particle with a well defined position and momentum. The electrons in a metal are swimming in the Fermi sea with a maximum energy of $E_F$. They cannot penetrate into the vacuum region where the potential energy is higher than the Fermi energy $E_F$.
Quantum mechanics (bottom) includes the wave aspect of a particle. An electron is described by a wavefunction which describes probability densities of the position of the particle. In quantum mechanics, the electron has a nonzero probability of crossing a finite barrier; this is the so-called tunneling effect.
Since we are only interested in the electrons that are crossing the barrier and tunneling into the region $z > d$, we can reduce these equations to particle waves propagating in positive $z$ direction:

$$
\begin{align*}
z < 0 & \quad \psi(z) = Ae^{ikz} \quad \text{with} \quad k = \sqrt{2m_e(E-V)/\hbar} \\
0 \leq z \leq d & \quad \psi(z) = Be^{-\kappa z} \quad \text{with} \quad \kappa = \sqrt{2m_e(V-E)/\hbar} \\
z > d & \quad \psi(z) = Ce^{ikz} \quad \text{with} \quad k = \sqrt{2m_e(E-V)/\hbar}.
\end{align*}
$$

(2.4)

Solving these equations for the boundary conditions at $z=0$ and $z=d$, we get the solutions $B = A$ and $C = Ae^{-\kappa d}$; see figure 2.2. This leads to the following probability $p$ for an electron to be beyond the barrier $z \geq 0$:

$$p = |\psi(z)|^2 = |Ce^{ikz}|^2 \propto e^{-2\kappa d}.$$  

(2.5)

Now we look at the tunneling junction between the tip and the sample. The vacuum represents a potential barrier between two metals as shown in figure 2.3. For simplicity, we assume both work functions $\Phi$ to be the same. In the free electron model (Sommerfeld model), the states up to the Fermi energy are occupied by electrons and the states above the Fermi energy are empty. Electrons from both sides have a probability of crossing the barrier, but they tunnel back and forth so that there is no net tunneling current.

By applying a bias voltage $U$ between tip and the sample, electrons from the sample can now tunnel into the unoccupied states of the tip (or vice versa), as shown in figure 2.4. Looking at small voltages with $E \approx E_F$ it follows that:

$$\kappa = \sqrt{2m_e\Phi/\hbar}.$$  

(2.6)
Figure 2.3: Electron energies at a metal-vacuum-metal tunneling junction

Figure 2.4: The wavefunction of an electron with the energy $E$ at a metal-vacuum-metal tunneling junction with applied voltage $U$
Figure 2.5: By applying a voltage, electrons can tunnel into the free states of the sample, producing a net current.

The tunneling current $I$ is proportional to the probability of electrons crossing the barrier as derived in equation 2.5. But we also have to include the density of states of both metals. In a metal, the density of states is constant near the Fermi energy; this means the higher the voltage, the more electrons will be able to tunnel into free states (see figure 2.5). Therefore, the net current $I$ is proportional to the applied voltage and to the probability of electrons being beyond the barrier:

$$I \propto U e^{-2\kappa d}.$$  \hspace{1cm} (2.7)
Figure 2.6: The tunneling current depends on the density of tunneling states of the sample (as indicated with arrows).

### 2.2 Tunneling Spectroscopy

Tunneling spectroscopy is an important tool for investigating the electronic properties of surfaces. Varying the distance $d$ and measuring the tunneling current $I(d)$ gives information about the local work function. Particularly interesting for the characterization of semiconductors are $I(U)$ spectra. Here the bias voltage $U$ is varied or modulated at a constant distance over the sample. $I(U)$ curves give information about the local Density Of States (DOS) [16, 17] as is shown in the following.

The tunneling current $I$ depends on the density of states of the tip, the density of states of the sample, and the tunneling probability. The tunneling probability $p$ for electrons being transmitted through the barrier is derived in the last section (compare equation 2.5 and 2.6) as:

$$p \propto e^{-2\kappa d} = p(E, eU)$$

with $\kappa = \sqrt{\frac{2m_e \Phi}{\hbar}}$. \(^1\)

Assuming a constant density of states for the metallic tip the tunneling current can be approximated by:

$$I \propto \int_{0}^{eU} D(E)p(E, eU) \, dE$$

where $D(E)$ is the local DOS at electron energy $E$. This is illustrated in figure 2.6 for a fictitious sample.

\(^1p = p(E, eU)$ because the average barrier height $\Phi$ between sample and tip depends on the work function of the sample $\Phi_{\text{Sample}}$ and the tip $\Phi_{\text{Tip}}$, the energy state $E$ of the electron (relative to $E_F$) and the applied bias voltage $U$: $\Phi = \frac{1}{2}(\Phi_{\text{Sample}} + \Phi_{\text{Tip}}) - E + \frac{1}{2}eU$
Taking the derivative and normalizing, equation 2.9 leads to (after Feenstra [16]):

\[
\frac{dI/dU}{I/U} = \frac{D(eU) + Z(eU)}{N} \tag{2.10}
\]

where \(Z(eU)\) is a slowly varying background term and \(N\) is a normalization factor. Thus, varying the bias voltage \(U\) and measuring the tunneling current \(I\), subsequently taking the derivative with respect to the voltage \(U\), and normalizing this term with \(I/U\) gives information about the local density of states \(D(eU)\) of the sample. Figure 2.7 shows the \(I(U)\) spectra of a semiconductor (and a metal for comparison), and the normalized derivative (equation 2.10) which is proportional to the local density of states.
2.3 Origin of Atomic Resolution

To see atoms on a surface [6, 14], the imaging mechanism between sample and tip must have a lateral resolution of 2 Å. This interaction is the tunneling current which has an exponential decay length $l$ that follows from equations 2.6 and 2.7:

$$I \propto U e^{-2\kappa d} \propto e^{-d/l}.$$  \hspace{1cm} (2.11)

We can estimate the decay length $l$ assuming a typical work function $\Phi$ of 5 eV for a metal:

$$l = \frac{1}{2\kappa} = \frac{\hbar}{2\sqrt{2m_e\Phi}} = 1\text{Å}/\sqrt{\Phi(\text{eV})} \approx 0.5\text{Å}.$$  \hspace{1cm} (2.12)

Since the size of an atom is typically a few Ångströms, this means that mainly electrons from the front atom tunnel, as illustrated in figure 2.8. Due to the short decay length, a reasonably sharp tip (one atom is very likely to be the frontmost), at a very close distance to the sample, can image with atomic resolution.
2.4 Piezoelectric Effect

To image the atoms on a surface, the instrument has to be able to bring tip and sample into tunneling range, which is at a distance of only a few Ångströms, and to scan the surface with even smaller movements. This is made possible by so-called piezodrives.

The piezoelectric effect [14, 19, 18] was first discovered by Pierre and Jacques Curie in 1880. The distortion of a crystal which has no center of symmetry produces a dipole moment. The inverse piezoelectric effect describes the cause of stress by applying an electric field. The mechanism is demonstrated for a simplified quartz crystal in figure 2.9.

The piezoelectric effect can also be found in electrically poled ferroelectric ceramics composed of a mixture of PbZrO\(_3\) and PbTiO\(_3\). These lead zirconate titanate piezoelectric ceramics (PZTs) have the advantage that they can be shaped and electrically poled as required.

The most commonly used piezoelectric scanner (piezo) is the tube scanner. By applying different voltages to the electrodes of the piezo, it can be elongated in the x, y, and/or z directions. The principle is shown in figure 2.10. For tube scanners, the displacement \(\Delta x\) created by applying an equal and opposite voltage to the \(U_{X^-}\) and \(U_{X^+}\) electrodes can be calculated from the following equation:

\[
\Delta x = \frac{4\sqrt{2}d_{31}UL^2}{\pi(d_o - d_i)t}
\]  

(2.13)

where \(U\) is the applied voltage, \(d_{31}\) is a material property (strain per voltage), \(d_o\) and \(d_i\) are the outer and inner diameters, \(L\) is the length, and \(t\) the wall thickness of the piezoelectric tube.

Figure 2.9: Simplified quartz crystal: a voltage between the top and the bottom leads to deformation of the crystal.
The displacement $\Delta z$ for equal voltage at all four electrodes is:

$$\Delta z = \frac{d_{31}U L}{l}. \quad (2.14)$$

The values of our piezoelectric tubes [20] will give an idea of the motion range: $\Delta x$ is 78.6 Å per volt and $\Delta z$ is 25 Å per volt. By applying voltages between 1 mV and 100 V, the displacement can vary between a tenth of an Ångström and one micrometer.

2.5 Vibration Isolation

The STM is extremely sensitive to any external mechanical disturbances which can be transmitted from the ground or through the air. The corrugation of an atomic structure is typically only 0.1 Å. Therefore, the amplitude of the vibrations has to be less than 0.01 Å to get images with atomic resolution. The transfer function $Z$ for large vertical building vibrations of 1000 Å amplitude ($\hat{x}_{\text{Ground}}$) to the STM head ($\hat{x}_{\text{STM}}$) has to be smaller than:

$$Z = 20 \log_{10} \left| \frac{\hat{x}_{\text{Ground}}}{\hat{x}_{\text{STM}}} \right| \text{ (dB)} \leq 20 \log_{10} \left| \frac{0.01\text{Å}}{1000\text{Å}} \right| = -100 \text{ dB}. \quad (2.15)$$

The principle of vibration isolation [14, 21] can be demonstrated with the simple model of the STM in figure 2.11. The STM head and the table are coupled oscillators.
Figure 2.11: Schematic of the STM vibrational system

Figure 2.12: Transfer functions of a vibration isolator: coupled oscillators with very different eigenfrequencies (after Okano et al. [21])
which perform forced vibrations caused by external disturbances from the ground. If their eigenfrequencies are separated by more than two orders of magnitude, the STM head is vibrationally isolated from the ground. This is displayed in figure 2.12. Graph I is the transfer function of vibrations from the ground to the vibration isolator, with the resonant frequency $f_{\text{Table}}$; graph II is the transfer function from the vibration isolator to the STM head with a hundred times larger eigenfrequency. The overall transfer function from the ground to the STM head, curve III, shows that the two systems are almost decoupled. By including damping, the height of the peaks can be decreased.

Figure 2.13 shows the effect of damping; the more damping, the smaller the peaks at the eigenfrequencies, however the transfer functions become less steep. Here two similar plates were chosen where the first oscillator had only a slightly higher resonant frequency. The overall transfer functions were calculated for different damping constants. Graph I shows the case with no damping, graphs II - IV the cases with increasing damping constant.

The stability of the vibration system can be further increased by keeping the center of mass as low as possible and inside the damping support points. This prevents rolling modes which cause the system to sway with large amplitudes. A triangular setup of the damping points is preferable since three points define a plane.

The basic concepts of vibration isolation and stability lead to the following requirements for the design of the STM head: it should be very rigid and light to have eigenfrequencies higher than 10 kHz. It should also be small to avoid amplification of the vibration amplitudes due to leverage.

The vibrational isolator usually consists of two stages. The first stage is a big, heavy table which hangs from springs attached to the ceiling or is mounted onto
pneumatic suspended legs with resonant frequencies below 10 Hz. The second stage is either a spring-suspension with eddy current damping or a stack of heavy metal plates with Viton rubber\(^2\) pieces between them.

Important vibrational properties of the stack are: the heavier the plates, the higher the damping constant of the Viton pieces, and the more plates, the lower the resonant frequency of the stack. Figure 2.14 shows the latter by calculating the transfer function of a metal stack with 3, 5, and 7 equal plates.

In addition, care should be taken when choosing a lab for the STM. Building vibrations are smaller on the ground floor or close to the concrete beams. The location can be checked beforehand using an accelerometer.

---

\(^2\)Viton is UHV-compatible
Chapter 3

Design of the Scanning Tunneling Microscope

3.1 Design Requirements

This STM is built to investigate quantum wires on semiconductor surfaces. To keep the sample clean, the preparation and investigation have to be done under ultrahigh vacuum conditions with typical pressures of $10^{-11}$ Torr.

The preparation of nanowires is described in the following. After introducing the sample into the vacuum system, the semiconductor surface must be cleaned by flashing it with a high current on the heating stage. Then, indium or gold is evaporated onto the sample to form the nanowires. Now the sample can be transferred onto the STM stage.

To obtain similar sample conditions for the KRIPES and the STM systems we tried to keep the sample preparation (heating stage, evaporators, sample size, and sample transfer) the same with only minor changes.

This leads to the following requirements for this STM:

- UHV compatible
- sample transfer (after sample introduction and preparation)
- KRIPES compatible

The design of a UHV compatible STM must ensure not only that the materials of the STM are UHV suitable, but must also take into account that the access to and operation of the STM inside the UHV chamber is limited to wobble sticks, manipulators, and electronic control.

In general, the following properties are desirable for the STM head:

- versatile
Figure 3.1: Schematic of a classic Scanning Tunneling Microscope

- vibrationally stable (rigid, small, and light)
- temperature compensated (for low temperature applications)
- reliable
- simple (easy to build and handle)
- inexpensive

3.2 Coarse Approach and Sample Manipulation

Figure 3.1 shows the basic configuration of a classic STM. The main components are: base mount, coarse approach, scanner with tip sample, and sample manipulation.

The scanner is mounted facing the sample. A coarse approach mechanism is needed to bring the sample into the range of the tube scanner (from a few millimeters to a few nanometers). Common designs are electronic with piezo-driven motors or mechanical using micrometer screws. To access different areas of the surface sample manipulation is required.

The base mount size is about eight times the magnitude of the working range of the STM, which leads to complexity and vibrational instability of the STM.
3.2.1 The Besocke STM Design

The Besocke design [22] is simple and compact: all the parts are reduced to four
equivalent piezoelectric scanners mounted on a base plate. The three outer piezoelectric
tube scanners, which are capped with small metal or crystal balls, are in a triangular
configuration. The sample rests on these three legs; it is held down only by gravity.
The fourth piezo in the center of the triangle is the scanner. The small volume ensures
high eigenfrequencies and stability, and since the legs and the scanner are identical,
it is temperature compensated.

The initial coarse approach between the tip and the sample is done by lifting up
one of the legs with a micrometer screw to get the scanner in its range.

Figure 3.2 shows the sample manipulation. First, to avoid damaging the tip, the
sample is lifted up (1). Then, the piezos are lowered, moved to the side and lifted up
again. If this is a fast motion, the sample cannot follow because of its inertia and the
piezos arrive at position two. By slowly aligning them back into the start position
(3), the sample gets shifted to the right side. With this slip-stick walking motion, the
sample can be moved freely in X- or Y-direction.

3.2.2 The Frohn STM Design

In the Frohn design [23], the three piezo legs and the tube scanner are mounted onto
a disc; this unit is referred to as a tripod or beetle. This design uses Besocke’s idea of
a slip-stick motion for the coarse approach, as demonstrated on the left side of figure
3.3. First, the legs of the tripod are slowly bent and the disc shifts to the side (1 to
2). Then, the legs are straightened out fast and, due to the moment of inertia of the
disc, the tripod has walked one step (2 to 3) of a length of 100 to 2000 Å.

By walking down a ramp in a rotational motion, the scanner comes closer to the
sample, see figure 3.3 (right). The ramp consists of three 120° arcs, each 0.3 millimeter
3.2.3 The Wilms STM Design

In Wilms’s design [24, 25], the coarse approach is done by a lateral movement across a plane base plate. This is a further simplification of the Besocke-Frohn design. Figure 3.4 shows the new idea; as the tripod walks straight towards the sample, which is inclined at 5.7°, the scanner comes closer to the sample. The full walking range is 4 mm; the ratio of the walking motion to z distance is 1:10. The scanner is mounted perpendicular to the sample at the same angle of 5.7°.
3.3 Our STM Design

Our STM is a modified Besocke-type STM based on the Wilms design with several new design ideas and improvements. Isometric views of our tripod are presented in figure 3.5 and photographs in figure 3.6. A technical drawing of the whole STM inside the vacuum chamber is shown in 3.7. Here is a short description of the main new features:

- **The lateral coarse approach:**
  We are using Wilms’ design of the lateral coarse approach with two changes: The tripod is rotated by 30°. Instead of walking with the rear leg into the sample, all three legs are beside the sample, two on one side, one on the other. The range of the coarse approach is no longer restricted to the distance between the scanner and the rear leg, but is determined by the sample length, in our case 12 mm.
  We also simplified the angle from 5.7° to 6° because the scanner cannot be glued into the tripod with a precision of 0.1°, and this angle is easier to machine.

- **The tripod:**
  Our new design of the tripod is more versatile than the original design:
  In our design, the piezoelectric tubes for the legs are first glued onto pins. These are inserted into the tripod and secured with set-screws which makes the process of assembling the tripod easier. Furthermore, the leg units (piezo plus pin and wires) are height-adjustable, re-orientable, interchangeable, and re-usable.
• The wiring of the piezo legs:
  To avoid having fine, breakable wires attached to the piezo legs, we first glue thicker wires with Teflon shielding to their electrodes and guide these wires straight up and out of the way through each leg pin.
  Since the three legs always execute the same motion, we combine the thicker wires of the corresponding electrodes on top of the tripod disc. This way only 4 wires (instead of 12) are coming up from the piezo legs to the Teflon plate.
  To ensure optimum spacing between the wires and to avoid damaging them by hitting the shaft, the thicker wires are guided out to the side of the tripod through small holes. Here the fine wires are soldered to them or plugged onto with PTCA sockets.

• The wiring of the scanner:
  The wiring of the scanner is similar to the legs. Since the scanner is glued into the tripod, the thicker wires are guided through small holes in the tripod disc and then off to the side where the fine wires are attached.

• The tripod manipulator and the tunneling wire:
  We designed a new tripod manipulator to ensure that the tunneling wire is always electrically shielded and mechanically protected. The tripod manipulator centers the tripod over the sample and lowers it until it is decoupled from the manipulator and rests only on the sample table.
Figure 3.7: Cross-section through the STM, scale 1:2
In our design, the tripod manipulator consists of two V-shaped hooks which hang down the outside of the shaft. Two wings are attached to the tripod neck so that it can be picked up and centered from the outside. The neck of the tripod is long enough to reach directly into the tube shaft even after the tripod is decoupled. Thus the tunneling wire is always protected.

- **Vibrational damping:**
  
The design of the frame is optimized for stability. The frame, mounted onto three Newport pneumatic isolators, is triangular. Furthermore, the center of mass of the UHV system (the ion pump) is below the support points and located at the center of gravity of the triangle.

  The Viton stack consists of four stainless steel plates, each sitting on three Viton pieces [26]. The center of mass of the top plate is lowered by having a weight attached to its bottom side.

  By decreasing the total number of fine wires from 17 to 9, vibrations transmitted from the top flange to the STM head are reduced.

### 3.4 Assembly of the Tripod with Scanner

This chapter is written as a “How-To Build an STM Head” manual. Since the tripod will be used under UHV conditions it is important:

- to keep the tripod clean, especially from grease and fingerprints.

- to make sure that there are no air cavities that are difficult to pump on (this is equivalent to an air leak). This can be achieved by applying single glue points and adding strategically placed vent holes.

- to use only UHV suitable materials [27] like copper, stainless steel, sapphire, quartz, alumina ceramics, Macor (a machinable glass), Teflon (a plastic), Viton (a rubber), and metals or their alloys with very low vapour pressures (tantalum, tungsten, molybdenum, gold, nickel, beryllium, tin, silver, ...). Do not use any elements like zinc, cadmium, or antimony, whose vapour pressures are high enough to desorb in UHV at room temperature, but not high enough to be pumped out of the system while baking.

Technical drawings of tripod, leg pins, and jigs are included in the appendix.
### 3.4.1 The Leg Units

![Diagram of Leg Units](image)

<table>
<thead>
<tr>
<th>Description</th>
<th>Company</th>
<th>Part Number, Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric Tube</td>
<td>Staveley Sensors Inc.</td>
<td>EBL#2, .125”OD X .024”W X .500”L Nickel, (4) 90° Segment Electrodes</td>
</tr>
<tr>
<td>Ruby Sapphire Balls</td>
<td>Industrial Tectonics, Inc.</td>
<td>part# 1450005, .09375”</td>
</tr>
<tr>
<td>Copper Wire</td>
<td>California Fine Wire</td>
<td>part# CFW-156-010, .010” (AWG-30) Copper 99.99%, OFE, CDA 101 (.0003” gold-plated over Ni strike)</td>
</tr>
<tr>
<td>Teflon Tubing</td>
<td>Omega Engineering, Inc.</td>
<td>TF-W-30</td>
</tr>
<tr>
<td>Silver Epoxy</td>
<td>Epoxy Technology, Inc.</td>
<td>EPO-TEK H21D electrically conductive (cure 30 min at 160°C)</td>
</tr>
<tr>
<td>Nonconductive Epoxy</td>
<td>Epoxy Technology, Inc.</td>
<td>EPO-TEK H77, Lid sealing epoxy (cure 80 min at 160°C)</td>
</tr>
</tbody>
</table>

1. Glue piezoelectric tube to aluminum pin (see technical drawings in the appendix) with silver epoxy:
   Make single glue point, use jig. Check electrical connection from inside electrode of piezoelectric tube to pin (ground).

2. Prepare copper wires (.010”, 12 X 7cm) and Teflon tubing (W-30, 12 X 3.5 cm). Clean piezoelectric tubes with ethanol and let them dry thoroughly.

3. Glue copper wires to piezo electrodes with silver epoxy:
   Stick all four copper wires with Teflon tubing through holes in the pin. Twist another copper wire around the wires and the piezos to keep the wires fixed in their position. Apply epoxy and cure. (Misplaced drops can be wiped off right away with ethanol.) Check the glue points.
4. After the scanner is assembled:

Screw the leg units into the tripod and check again for good electrical connection from the inside electrode to the tripod (ground). Glue ruby sapphire balls onto the piezos with nonconductive epoxy.

3.4.2 The Scanner

1. Glue copper wire (6 cm) into stainless steel tube with silver epoxy.

2. Glue stainless steel tube into .5” long ceramic tube with nonconductive epoxy (glue point 1).

3. Be sure to use a piezoelectric tube with its inner electrode wrapped to the outside. This allows a ground connection to be made from an outside glue point (3) to the inner electrode.

4. Make a funnel from aluminum washer (using pipe flaring tool). Glue the funnel with nonconductive epoxy onto the piezo. Make one silver epoxy point so that the inside electrode (ground) of the piezo and funnel are electrically connected.
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Piezoelectric Tube</td>
<td>Staveley Sensors Inc.</td>
<td>EBL#2, .125&quot;OD X .024&quot;W X .500&quot;L, Nickel, (4) 90° Segment Electrodes</td>
</tr>
<tr>
<td>Copper Wire</td>
<td>California Fine Wire</td>
<td>part# CFW-156-010, .010” (AWG-30) Copper 99.99%, OFE, CDA 101 (.0003” gold-plated over Ni strike)</td>
</tr>
<tr>
<td>Stainless Steel Tube</td>
<td></td>
<td>Needle for Syringe, 21 Gauge .020&quot;ID, .032&quot;OD turned down to .028” (see technical drawings in the appendix)</td>
</tr>
<tr>
<td>PTCA Sockets</td>
<td>SPC Technology</td>
<td>Pin Terminal Carries Assembly Sockets gold-plated beryllium copper part# PTCA-16-01-L1 Newark stock# 46N6785</td>
</tr>
<tr>
<td>Ceramic Tube</td>
<td>Kimball Physics Inc.</td>
<td>part# Al₂O₃-TU-B-500 .061”OD, .030”ID, .500”L</td>
</tr>
<tr>
<td>Ceramic Tube</td>
<td>Kimball Physics Inc.</td>
<td>part# Al₂O₃-TU-B-1000 .061”OD,.030”ID, 1.000”L</td>
</tr>
<tr>
<td>Aluminum Washer</td>
<td></td>
<td>aluminum foil .010”, 9/32”OD, 1/16”ID (use hole puncher tool)</td>
</tr>
<tr>
<td>Silver Epoxy</td>
<td>Epoxy Technology, Inc.</td>
<td>EPO-TEK H21D, electrically conductive (cure 30 min at 160°C)</td>
</tr>
<tr>
<td>Nonconductive Epoxy</td>
<td>Epoxy Technology, Inc.</td>
<td>EPO-TEK H77, Lid sealing epoxy (cure 80 min at 160°C)</td>
</tr>
</tbody>
</table>

5. Glue the ceramic into the piezoelectric tube:

   Make one glue point (2) at the end of the piezo where the tip will be inserted. Align glue point 2 with glue point 1 of the stainless steel tube and one electrode of the piezo. This way the angle of the stainless steel tube, which will hold the tip, can be aligned with the angle of the whole scanner. Wrap aluminum foil around the other end of the ceramic to keep the ceramic in its position while gluing. (Remove the aluminum foil after gluing.)

6. Glue the 1.0” ceramic tube into the neck of the tripod. Make sure it does not get in the way of the scanner.

7. Glue the scanner into tripod at a 6° angle with the silver epoxy:

   Use the jig, align electrode and other glue points (1 and 2) with 6° angle, and make one glue point (3). Be careful not to get any glue inside the ceramics. Check connection between the inside electrode and the tripod (ground), and check that there is no connection between the stainless steel tube (tip wire) and the tripod (ground).
8. Glue copper wires (7 cm) with Teflon tubing (5 cm) onto scanner (see steps 2 and 3 from leg units).

9. Glue ground wire (copper wire, 5 cm long, with Teflon tubing) to top of tripod.

10. The tip is held in a PTCA Socket which is inserted into the stainless steel tube. To have a tight fit, the pin of the socket is slightly bent.

### 3.4.3 The Wiring

<table>
<thead>
<tr>
<th>Description</th>
<th>Company</th>
<th>Part Number, Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver Solder Alloy</td>
<td>Alfa Aesar</td>
<td>part# 41032, 1.6mm dia Ag:Sn 3.5:96.5 wt%</td>
</tr>
<tr>
<td>Kapton-coated Copper Wire</td>
<td>California Fine Wire</td>
<td>.0031&quot; (AWG-40), CFW-156-0031-HML copper 99.99%, OFE, CDA 101 H-ML = heavy polimide coating</td>
</tr>
<tr>
<td>Teflon Tubing</td>
<td>Omega Engineering, Inc.</td>
<td>TF-W-30, ID .012&quot;</td>
</tr>
<tr>
<td>Teflon Tubing W-18</td>
<td>Alpha Wire Company</td>
<td>part# TFT200-18-100, .042&quot;ID</td>
</tr>
<tr>
<td>Teflon Tubing W-13</td>
<td>Alpha Wire Company</td>
<td>part# TFT200-13-100, .076&quot;ID</td>
</tr>
<tr>
<td>Teflon-insulated Copper Wire</td>
<td>Belden Wire and Cable</td>
<td>part# 83000, type#MIL-C-17F stranded silver-coated copper wire with TFE Insulation</td>
</tr>
<tr>
<td>Coaxial Cable</td>
<td>Belden Wire and Cable</td>
<td>part# 83265 core: silver-coated copper covered steel with TFE Teflon insulation shield: silver-coated copper white FEP Teflon jacket</td>
</tr>
<tr>
<td>PTCA Sockets</td>
<td>SPC Technology</td>
<td>Pin Terminal Carries Assembly Sockets gold-plated beryllium copper part# PTCA-16-01-L1</td>
</tr>
<tr>
<td>Micro Pin</td>
<td>Keystone</td>
<td>part# 1218 key pin for .040&quot; socket contacts made of solid nickel silver</td>
</tr>
<tr>
<td>Female Crimp Pin</td>
<td></td>
<td>D-subminiature Contacts for .040&quot; pins</td>
</tr>
</tbody>
</table>

**The wiring of the tripod:**

1. Insert the leg units into the tripod, align the electrodes of the leg and tip piezos (use a foil jig), adjust the height, and tighten the set-screws.
2. Combine the wires of the corresponding electrodes \( (+X_{Leg}, -X_{Leg}, +Y_{Leg}, -Y_{Leg}) \):
   Start e.g. with \( +X_{Leg} \): twist two of the three wires together, then twist the third one to it with only two turns. Repeat for other electrodes.

3. Glue twists with silver epoxy for better electrical connection and cure. Cut off the end of the two-wire-twist and put a short piece of Teflon tubing (W-18) over connection knot. Shield the end of the remaining wire with Teflon tubing (W-30).

4. Guide all the wires (4 leg wires, 4 scanner wires, and ground wire) out to holes on the side of the tripod.

The tripod is now fully assembled: it is an interchangeable, compact unit. In the following is a description of the wiring from the tripod to the flanges.

**The wiring from the tripod to the 10 pin connector:** (compare figure 3.7)

- The wire from the 10 pin connectors to the Teflon plate is Teflon-insulated copper wire with female crimp pins on both sides. To avoid contact with other wires at the 10 pin, the female crimp pin is shielded with Teflon tubing (W-13).

- In the Teflon plate there are 9 micro pins.

- Nine very fine Kapton-coated copper wires (.0031") are connected to the nine thicker wires protruding from the side of the tripod. They are either soldered directly to the thicker wires or glued to PTCA sockets and plugged on. The other end of the Kapton-coated copper wires is glued or soldered to a female crimp pin which is plugged onto the male micro pin.

  The Kapton-coated copper wires are 4.5" long and .25" of the insulation on each end is stripped. The stripping of these very thin and breakable wires can be done mechanically by carefully sliding the wires between your finger and the sharp blade of a carpet knife.

- The silver solder requires 750°F and clean non-oxidized surfaces. It sticks well to gold-plated surfaces.

**Description of the wiring of the tunneling wire:**

- The tunneling wire is a Kapton-coated copper wire which is passed through a coaxial cable (from the BNC connector to the shaft) and then down the shaft. A PTCA socket is soldered to the end and plugged onto the thicker tip wire of the tripod.
3.5 Tip Preparation

Good resolution in a STM image depends on the tip. Therefore, it is important to find a reliable method to produce sharp tips. We are using two different types: platinum/iridium and tungsten.

The platinum/iridium tips are produced by cutting the wire (Pt/Ir 90/10, 0.25 mm, from Goodfellow) with a side cutter or scissors in a pull-cut motion [25]. Platinum/iridium tips have the advantage of great chemical inertness, but they are consequently difficult to etch.

The tungsten tips are electrochemically etched using a lamella drop-off technique [28, 29, 30]. Figure 3.8 shows the tungsten wire (0.25 mm) passing through the loop with the electrolyte lamellae. The loop is made from platinum/iridium wire (Pt/Ir 90/10, 0.010”, from California Fine Wire) and is about 7-8 mm in diameter. The electrolyte is 2 M KOH (or 2 M NaOH) solution. The etching is done by applying an 80-100 Hz square wave with 6-8 V peak-to-peak between the tungsten wire and the platinum/iridium cathode. After one minute the liquid should be renewed. After three cycles, the bottom of the tungsten wire is almost cut off. A square wave of 3.5-4 V peak-to-peak at 80-100 Hz is applied to polish the wire and to neck it. The bottom of the tungsten wire stretches under its own weight and drops off just before the etching is finished. The falling part is the new tip and must be caught safely. The shape (short, pointy, and sharp) of the tip is checked with a microscope before it is used in the STM.

Figure 3.8: Electrochemical lamella drop-off technique: the lamella (left) and cross-section through the tungsten wire during etching (right)
Chapter 4

Control Electronics of the Scanning Tunneling Microscope

We are using RHK SPM1000 control electronics [31, 32], which is of high quality, well designed, capable, and versatile, and offers all the features and tools we need. The SPM1000 control system consists of the SPM100 controller, SPM32 software (for data acquisition, visualization, and analysis), a computer interface board, and a two-stage current amplifier.

This chapter is written as an aid in understanding the basics of the control electronics. It explains the principles of the electronics [14, 33], including their application to our specific control electronics. The last section contains a brief overview of the software. A detailed description of the knobs and dials of the controller, which is essential to the optimum use of the STM, is given in Appendix B.
4.1 The Scanning

The actual image of the surface is obtained by raster scanning an area of the surface in one of the following two modes:

In constant height mode, the tip is kept at a constant height over the sample and the change in the tunneling current monitored.

In constant current mode, a feedback loop keeps the tunneling current constant and the change in the z position is monitored. This mode is more sensitive to the topography of the structure and is, therefore, the preferred mode. Its principle is illustrated in figure 4.1.

The raster is made by scanning adjacent lines. The direction of the scan lines can be done in the X- or Y-direction. Each line is scanned both ways, giving two images which are monitored separately - the forward and the backward scan.

Note that the tunneling current is sensitive to the local electronic structure of the surface and, therefore, images the atomic states and not the position of the atomic nuclei.
### 4.2 The Preamplifier

The preamplifier is essential for good performance of the STM. The current amplifier converts the low level tunneling current of typically 0.01 to 50 nA into a high level voltage.

We are using the two-stage system from RHK. The first stage is the RHK current amplifier IVP-200 with a gain of $10^8$, a minimum tunneling current of 0.005 nA and a bandwidth of 5 kHz. This stage should be located as close to the tip as possible to avoid picking up noise and, therefore, to keep the signal-to-noise ratio as large as possible. It is critical to totally shield the tip and the tip wire inside the vacuum chamber from the other electrical connections to the STM head.

The second stage is the RHK multi-gain preamplifier with programmable gain (x.1, x1, x10, x100), programmable low pass filter (none, 150 kHz, 50 kHz, 15 kHz, 5 kHz, 1.5 kHz, 500 Hz) and programmable signal input to correct for offsets (inverted, non-inverted).

Figure 4.2 displays the progression of a signal through the preamplifier chain. A bias voltage of 0.1 V is applied. The tunneling gap can be simulated with a 10 MΩ resistor which is equivalent to a tunneling current of 10 nA. This current is preamplified in the first stage current amplifier into a voltage of 1 V. The second stage is programmed to a gain of 10. This means a voltage of 10 V is fed into the controller. The Nano Amps DVM (Digital Volt Meter) reads 100 as the tunneling current. This method can be used to test and adjust the gain and the offset of the preamplifier.

Note that the tunneling current is converted into a voltage but still labelled as a current. Depending on the settings of the preamplifier, the Nano Amps DVM reading (and the current set point) is showing ten times the value of the actual tunneling current!
4.3 The Feedback Loop

4.3.1 Principles of the Feedback Loop

Figure 4.3 shows a schematic of the feedback loop. The tunneling current $I_T$ is first converted into a voltage $U_T$ by the Current Preamplifier and further amplified by the Logarithmic Amplifier to the voltage $U_L$. This tunneling voltage $U_L$ is compared with the voltage set manually at the Current Set Point $U_{CSP}$. The comparator (a high gain differential amplifier) gives an error signal $\epsilon$, which is fed into the Feedback Electronics.

The feedback is negative. If the current is higher than the Current Set Point, the scanner is withdrawn from the sample and the voltage $U_Z$ is negative. If the current is smaller than the Current Set Point, the scanner is extended and the voltage $U_Z$ is positive. The feedback loop circuit tries to keep the difference between the current set point voltage $U_{CSP}$ and tunneling voltage $U_L$ as small as possible, and the scanner stays in a mean position $d$ over the sample.

The raster scan (compare figure 4.1) is generated independently from the feedback loop. As the scanner scans a line, the contour of the surface changes; the feedback circuit keeps the tunneling current constant and the tip follows the contour of the surface. The $z$ position voltage $U_Z$ applied to the scanner is monitored as the topographic image of the sample.

4.3.2 The Feedback Electronics of the RHK Controller

Figure 4.4 illustrates the feedback electronics of the RHK controller. The tunneling voltage $U_T$ from the preamplifier is fed into the 9 Pin Preamp Input. The logarithmic amplifier can be switched on or off and the response of the feedback is linear. The signal is then compared to the current set point voltage and the error signal is fed into the feedback electronics. The feedback electronics consists of an amplifier with a programmable gain (0-2), an integrator with a programmable integration time con-
Figure 4.4: Simplified schematic of the feedback electronics of the RHK controller.

The computer monitors the z position signal of the feedback after the integrator. It can be further amplified (gain 1-128) to give a good resolution at the A/D converter (see also chapter 4.6). This signal can also be looked at with an oscilloscope at the Monitor Output Z Position.

Fast response times and high gain settings are desired to get the most accurate image of the topography of the surface. The overall gain is the product of the gain of the tunneling current per volt of bias applied, the gain of the feedback electronics, and the piezo response per volt. The response time depends on the delay of the piezo (due to its mechanical inertia), the current preamplifier, and the feedback. All the delays in the circuit will make the system unstable for high gain settings where the signal starts to oscillate.

This can also be understood by looking at the capacitances. As each amplifier is comparable to a low-pass filter in which R is the source impedance and C is the capacitive load, the time constant is \( \tau = RC \). If there is more than one amplifier in the circuit, the signal can have a phase shift of 180° at a certain resonance frequency so that negative feedback becomes positive feedback. If the gain is higher than one, an oscillation starts. Since the capacitance of an amplifier increases proportional to the gain, high gains lead to long time constants.

The integrator works as a feedback amplifier frequency compensation. It constitutes a low-pass filter with a longer time constant, which then dominates the time constant (approximately 1-20 ms), and a high voltage amplifier to drive the piezo of the scanner with up to 130 V.
constant of the response of the whole system and damps upcoming oscillations. If the gain setting is too high or the integrator time constant is too short, the system still becomes unstable and starts oscillating. If the gain setting is too low and the time constant too long, the system is overdamped and the feedback control is too slow to follow the contour of the surface. The optimum is between these two extremes when the system is critically damped.

### 4.3.3 Test of the Feedback Loop

The feedback of the controller can be tested independently from the actual scanning. The setup of the test procedure is shown in figure 4.5. A $10 \, \text{M}\Omega$ resistor simulates the tunneling gap. The contours of the surface can be modulated with a square wave, which is fed into one of the Z Position Modulation Inputs. It is important to test with which settings the feedback loop is critically damped to ensure optimum performance of the controller during a real scan. The tunneling current at the Tunnel Current Monitor Output, the modulation signal from the function generator, and the z position signal at the Z Position Monitor are monitored with an oscilloscope.

If no modulation is applied, the tunneling current is a constant voltage at the
Figure 4.6: Oscilloscope graphs during feedback loop testing
value of the current set point voltage; e.g. for a current set point value of 1 (nA), the voltage is 0.100 V. The resonant oscillations occur for very high gain settings and very short time constants, even if no modulation is applied.

The response speed of the system can be found by injecting a square wave pulse of about 10 mV (noise < 2 mV) at 500 Hz into the Z Modulation Input #1 (or #2). Figure 4.6 shows the modulation signal, the tunneling current, and the z position for three different gain and time constant settings. A long time constant and low gain result in an overdamped signal, graph I. For ideal settings of the time constant and the gain, the system is critically damped and the z position signal produces a little overshoot, as seen in graph II. For a short time constant and high gain, the system starts to oscillate (it is ringing), graph III.

In real scanning, the oscillations will occur earlier (for longer time constants and lower gain settings) than in the simulation, but this testing shows the characteristic behaviour of the controller.

### 4.3.4 Comparator Test

The comparator test, as shown in figure 4.7, is a simple test to check the comparator and the feedback electronics. A voltage (e.g. from the Bias Output to SPM) is applied
to the BNC Preamp Input and compared to the Current Set Point. The Z Position Integrator Meter swings from one side to the other as the applied voltage $U_T$ crosses the set voltage $U_{CSP}$. A Current Set Point of 1 (nA) is equivalent to a voltage of 0.100 V. The pointer of the Meter can be slowed down and centered by carefully adjusting the bias voltage to exactly 0.100 V, but, with time, the pointer always drifts to one side.

### 4.4 The Configuration of our STM head

The RHK controller can operate different types of STM heads, including AFM. Each configuration can be set with internal jumpers. Figure 4.8 shows the configuration of our tripod (left) and the electrical connections to the rear panel of the controller (right). The leg piezos are used for the coarse approach and for the X- and Y-offset. The scanner is used for the X-, Y-, Z-scan, and Z-offset.

In this configuration the X- and Y-offset, which moves the origin of the scan to different areas of the sample, is separated from the X- and Y-scan. The Z-scan signal gets summed into the X- and Y-scan signals. The Z-offset adjusts the height of the tip over the sample. The inner electrode of the scanner is grounded, which has the advantage that the tunneling wire is electrically shielded.

### 4.5 The Coarse Approach

The coarse approach is a slip-stick walking motion as shown in figure 3.3 (left). This motion is achieved by applying a sawtooth voltage. While the voltage slowly increases to its maximum value, the tripod bends and leans to the side. The voltage then falls rapidly to zero and the tripod abruptly straightens out its legs.
Figure 4.9: Schematic for the voltage cycle of the feedback controlled coarse approach

The software of the controller can generate this waveform; all parameters (waveform, amplitude, period, asymmetry) can be set in a menu. The voltage ramp is put out on the D/A output channel in the rear panel of the controller. A BNC jumper has to be set between the D/A output channel and the Inertial Input External Control to feed the signal into the electronics for controlling the motion of the leg piezos (+X, -X-offset). The controller only enables walking in the X-direction. To walk in the Y-direction, an external jumper can be switched to connect the Y-offset electrodes of the piezo to the X-offset outputs of the controller.

Once the tip has walked up very close to the sample, the fast approach (only walking) is stopped. Now the feedback controlled approach is started. This means that after each walking step the tip is extended to its maximum with the feedback loop active. If there is no tunnel current signal, the tip is retracted. Another step is taken, and the tip released and retracted again. This cycle goes on until a feedback signal is detected and the tip is within tunneling range (or crashed). The schematic for the cycle of the voltages for the last five steps is shown in figure 4.9: the tip is extended by applying an equal voltage to the \( +X_{Scan} \) and \( -X_{Scan} \) electrodes of the scanner. The time \( t_2 \) of extending the tip with feedback active is around 100 ms, depending on the time constant and gain settings.

The tip is extended approximately 1000 Å. With the ratio of step size to tip-sample distance of 1:10, the step length should be less than 10 000 Å, which is about the maximum step size of our piezos (for maximum sawtooth amplitude). If there is a huge roughness in the surface, or if the tripod jerks and slides (for too fast periods or very high voltage amplitudes), the tip can crash into the sample. A safe sawtooth period \( t_1 \) is 30 ms. The coarse approach takes approximately ten minutes.
4.6 Settings of the Controller

Appendix B gives a detailed description of the many knobs and dials of the controller, which is shown in figure 4.10. As many of the functions are independent and there are complex interactions between the settings, an in-depth understanding of the controller is required for optimum use of the STM.

The controller has a scan generator built in and can, therefore, be used stand-alone. The monitor outputs in the back of the controller allow the data to be displayed with an oscilloscope. This is a good tool for testing. In general, the data acquisition is done by the SPM32 software on the computer, which reads the settings and displays the data.
4.7 The Grounding

The grounding of the system is critical for the electronics. High performance of the controller is only possible with a low noise ground. The ground connection of the power outlet should have a good connection to the building ground. All the equipment (controller, computer, and UHV system) should be plugged into one single outlet so that it is referenced to the same power ground.

Improper grounding can lead to high noise levels. The electrical signals amplified by the controller are only a few nA and even noise at a fraction of this level induced into the feedback loop degrades the image. Noise characteristics can be tested by setting up the feedback loop test without an injected signal and watching the noise level at the Tunnel Current or Z Position Monitor Output. A schematic of the grounding of our UHV-STM system can be seen in figure 4.11.

The main aim of the careful grounding and referencing is to minimize ground loops. If the shield of the BNC output cables are tied together on both ends, it is likely to induce ground loops. Therefore, the braided shield should be cut back and disconnected on one side. It should be cut back far enough and covered with insulation so that it cannot short to the center conductor or to adjacent cables, see figure 4.12.
4.8 The SPM 32 Software

The SPM32 software permits data acquisition and display as well as image processing, visualization, and analysis. It also generates the waveform needed for the coarse approach. The software runs on a personal computer under DOS or Windows.

For running experiments with the STM, it is important to configure the software for our STM head and our coarse approach. During scanning, the SPM32 software acquires the settings of the controller and displays the data on the screen. The data is shown as an image in a scan window or as line scans. Two images are obtained: the forward and backward scan. A scan area display shows X- and Y-offsets. All the control parameters are stored automatically with the data. The most common mode is the constant current mode, which shows the topography of the surface. The constant height mode, the spectroscopy mode (I/U, I/Z, dI/dU, dI/dZ), and the lithography mode (for surface modification) allow further investigation of the sample.

For completeness and to give an idea of the capabilities of the SPM32 software, here is a short overview of the software visualization, image processing, and analysis features taken from the RHK brochure [34]:

The Interactive Visualization Tools permit rotation of the image to any angle or perspective, adjustment of the light source intensity and surface orientation, and different color maps.

The Image Processing offers several filters: Background, Smooth, Median, Interpolation, Laplacian Sharpening, Interactive Plane Subtraction, FFT Frequency-Domain Filtering, Autocorrelation, or customized filters.

The Analysis Tools provide Angle (thermal drift compensation), Cross-Section, 2-D FFT, Difference, Statistics, and Zoom analysis. Statistical Data analysis can be used to obtain Histogram, Area, Slope, RMS Roughness, Maximum, Minimum, Average, Standard Deviation, Integral, and Volume Above Plane information on the images.
Chapter 5

Design of the Ultrahigh Vacuum System

5.1 Principles of Ultrahigh Vacuum Technology

Figure 5.1 shows the basic setup of an Ultrahigh Vacuum (UHV) system [27, 35]. The surface preparation and investigations are all done inside a stainless steel vessel, the UHV chamber. The vacuum chamber has ports to attach the pumps, manipulators, pressure gauges, windows, and other peripherals. Valves are needed to close sections and to allow pressure differences between parts of the UHV system. The flanges of the ports are sealed by cutting into a copper gasket with a knife edge. The manipulator allows motion of the sample inside the chamber. Several pumps are needed to obtain the necessary pressure. The sample can be introduced in a load-lock port (‘Intro’).

Atmospheric pressure is 760 Torr. At least three pumps are needed to pump down to UHV: a roughing pump (e.g. a rotary pump), a turbomolecular pump (turbo pump), and an ion-getter pump (ion pump) or titanium sublimation pump (cryo pump). It is a tedious procedure to get the system from atmospheric pressure to UHV conditions. A typical cycle is described in the following:

- First all the nuts and bolts at each flange must be tightened down to seal the vacuum system.
- Then the rotary pump is turned on until an initial vacuum of $10^{-3}$ Torr is reached. This usually takes less than half an hour.
- At pressures below $10^{-2}$ Torr, the turbo pump is switched on.
- In addition, the ion pump is turned on at pressure of $10^{-6}$ Torr to get to high vacuum ($10^{-8}$ to $10^{-10}$ Torr).
- The ionization gauges can be switched on at pressures below $10^{-4}$ Torr. Only the Bayard-Alpert-type ion gauge can measure pressures below $10^{-8}$ Torr. (If
an ion gauge is turned on at atmospheric pressure, its filament blows.

- To get to pressures below $10^{-8}$ Torr, it is necessary to bake the system:
  After being exposed to air all the inner walls are covered with a water film which desorbs slowly. If the system is heated up to $150^\circ C$ to $180^\circ C$ for several hours, the water evaporates and can be pumped away. Since the pumps are not fast enough to pump all the water vapour away at once, the pressure rises. At pressures of $10^{-7}$ Torr, the baking should be stopped until the vacuum is pumped down to $10^{-8}$ Torr again. This cycle continues until there is so little water left in the system that the pumps are able to keep the pressure low during baking.

- Once the pressure is around $10^{-11}$ Torr, the turbo pump can be turned off and its valve closed. The ion pump stays on to maintain the UHV conditions against leakage from the wall or tiny hollow spaces (cavities resemble virtual leaks), diffusion from the wall or the sample, and desorption from materials used inside the system. The ion pump has no rotating parts and runs vibration-free so that it does not disturb investigations with the STM.

- To bring the system back up to atmospheric pressure, a valve is slowly opened in a dry nitrogen atmosphere; the adsorption of nitrogen prevents the water adsorption.
5.2 Design Requirements

This UHV-STM system is built to investigate quantum wires on semiconductor surfaces. After introducing the sample into the system, the semiconductor surface is cleaned by flashing a high current through the sample on the heating stage. Indium or gold are then evaporated onto the sample. The thickness of the sublimated layer is controlled with a quartz balance: the thickness monitor, which should be mounted close to the sample. After the preparation the sample is transferred onto the STM stage for the investigations. The pressure in the system should be UHV ($10^{-11}$ Torr). Since we want to compare the results obtained from KRIPES with the STM images, the sample preparation should be done under the same conditions. Therefore, we adopted the design of the heating stage, transfer system, evaporators, and sample size from KRIPES with only minor changes.

This leads to the following requirements for the UHV system:

- sample introduction, transfer, and manipulation,
- sample preparation,
- sample investigation with the STM,
- UHV conditions (during sample preparation and investigation), and
- KRIPES compatible.

5.3 The Compact Solution

We decided to use a small, two-chamber system consisting of a preparation chamber and a STM chamber. The smaller the volume of the system the faster it is to bake and pump. The advantage of a two-chamber system is that each chamber can be modified independently and that the sample preparation, which spoils the vacuum while cleaning or evaporating, is separated from the investigation stage. A technical drawing of our UHV-STM system can be seen in figure 5.2. The preparation chamber has ports for the evaporators, the thickness monitor, the heating stage, the sample introduction, the ion pump, a projector light bulb for heating the chamber from inside, and several windows. It is a recycled chamber from the KRIPES system, only slightly modified. The STM chamber is purpose-designed and -built for our STM. Figure 5.3 shows a photograph of the UHV-STM system.
Description of the ports of the STM CHAMBER:
1 - Linear transfer, STM head
2 - Viton stack, thermo couple, bias
3 - Window
4 - Tip conditioning
5 - Transfer
6 - Turbo pump, rotary pump
7 - Cooling stage
8 - Wobble stick
9 - Window
10 - Spare
11 - Wobble stick
12 - Window
13 - Spare

Description of the ports of the PREPARATION CHAMBER:
A - Window
B - Valve, reducer 8"-6", ion pump
C - Projector light bulb
D - Gauge
E - Thickness monitor
F - Spare
G,H - Evaporators
I - Manipulator
J - Heating stage
K - Transfer to STM
L - Introduction with manipulator, turbo pump port

Figure 5.2: Technical drawing of the UHV-STM system, scale 1:14
Figure 5.3: Photographs of the UHV-STM system
5.4 The STM Chamber

Before we could start on the design of the STM chamber, we had to decide roughly on the design of the STM head. The aim was to make the system versatile and include the possibility of different STM designs, changes, or later add-ons. The STM should also be easy to access and handle inside the chamber; a good view of the tripod and the sample is essential for its use. Due to the complexity of the design we built a model to simulate sample-handling and operation of the STM, and to realize conflicts between port functions or other restrictions. So we ended up building a model to simulate the typical operations.

Figure 5.2 shows the top view and the side view. In the front is a large window providing a full view of the tripod and the sample. A drawing of the STM inside the chamber is shown in figure 3.1: the top flange contains the linear manipulator with the tripod and the wire feedthroughs; the bottom flange holds the Viton stack. The whole STM is only mounted onto these two ports.

The other ports are for two wobble sticks (for moving the tripod and for sample transfer onto the STM stage), the tip conditioning stage, the turbo pump, and a low temperature stage, which might be added later. The valve between the prep chamber
Figure 5.5: Principle of the transfer system (left) and the sample table with tripod (right)

and the STM chamber can be closed during sample preparation or during tip exchange when the top flange of the STM chamber has to be opened. The technical drawings of the STM chamber are presented in Appendix A. The chamber shown in figure 5.4) was built by Johnsen Ultravac in Burlington, Ontario, Canada.

5.5 Sample Transfer

The sample transfer is based on the Phi concept. The sample is mounted onto a round sample holder and is transferred with forks that are attached to the end of the manipulators. Figure 5.5 (left) shows the transfer from one fork to the other. In our design, a sample table is mounted onto the sample holder so that the connection between sample and sample table is rigid. The tripod is resting on the sample table as shown in figure 5.5 (right).

The sample transfer procedure from the introduction to the STM stage is described in the following:

The prep chamber and STM chamber are at UHV conditions; the valve between the introduction arm and the prep chamber is closed. The sample is introduced onto the fork of the short transfer arm. This section is then pumped down to high vacuum with the turbo pump. Next, the sample is transferred into the prep chamber onto the main long transfer arm, and then the valve between the prep chamber and the introduction is closed again. The prep chamber is now at HV and must be pumped down to UHV. From the long manipulator, the sample is transferred onto the heating stage. There it is cleaned and the indium or gold are evaporated onto it. After the preparation, the sample is picked up with the main transfer arm again and the valve to the STM chamber is opened. The sample is now transferred onto the STM stage. A wobble stick is used to keep it in place while the fork is pulled back. After the
experiment, the same wobble stick is used to help pull the sample off the STM stage.

5.6 Tip Conditioning

It is important to clean the tungsten tip of the STM once it is inside the vacuum system. We are using the following methods:

**Ex-situ: field emission**: Voltage pulses between the tip (ground) and the sample (high positive bias voltage) are applied and field emission from the tip to the sample is induced thereby expelling spurious and protruding material. This process cleans and sharpens the tip. This can be done at any time during the experiment after moving the tip to a section away from the interesting region of the sample (since it gets damaged during the process) or onto the sample table.

**In-situ: high-field treatment**: The scan is done at high bias voltage (7.5 V) for a few line scans [14]. Afterwards, the bias voltage is reduced again. This method often improves the resolution due to tip restructuring mechanisms.

**In-situ: controlled collision**: On silicon surfaces the tip is crashed into the surface and picks up a cluster. This cluster may provide atomic resolution.

We are also planning a tip conditioning stage for **ex-situ electron beam annealing**. The tip is bombarded with electrons coming out of a cathode. This preferentially heats the outermost part of the tip and removes the contaminants and oxides. Here, the scanner is lifted off the sample and placed onto a tip conditioning stage. In low thermal power electron beam annealing [36], the scanner piezo is screened by a plate and only voltage pulses are applied to prevent the scanner piezo from overheating.

In the future, we would like to make it possible to exchange the tip of the scanner inside the vacuum system. Right now we need to bring the STM chamber up to atmospheric pressure to change the tip, but since our system is small with a large pumping capacity it takes only a day to get it back down to UHV.
Chapter 6

Conclusions

6.1 Representative STM images

After only five runs of tunneling on Highly Oriented Pyrolytic Graphite (HOPG) in air, the STM produced images with atomic resolution. Here is one of the first images (35 Å × 35 Å):
The HOPG crystal is ideal for testing the STM in air. It is a layered material which can easily be cleaved by removing the top layers with adhesive tape or by peeling them off with a pair of tweezers. It is an inert semi-metal with little contamination, flat net planes, and no surface reconstruction. The experiments are done inside the grounded vacuum chamber to have less air movements and thermal drift, which is one of the biggest problems when operating in air, and to provide electrical shielding for the STM head.

If not otherwise indicated, all scans are done at a tunneling voltage of 70 mV and a tunneling current of 2.5 nA. All images are an expanded area of the raw data without filtering which would improve the quality of the images.

The next figure shows a model of graphite to explain the observation of threefold symmetry rather than a sixfold symmetry. The atoms on the graphite(0001) surface can be distinguished into two types, the black dots resemble atoms with an atom underneath, the grey dots have no corresponding atom in the second layer. Only the black atoms are imaged with the STM and the structure appears hexagonal. The distance between the black atoms is 2.46 Å. This distance can be used to calibrate the lateral scale of the images: 1 Å in the figures corresponds to approximately 3.3 Å. (The lattice constant of graphite is 1.42 Å.)

The hexagonal structure expected for graphite can be demonstrated by taking the Fast Fourier Transform of the above first image of graphite:
The scans are reproducible at various resolutions. With raster scans oriented along the X- and Y-axes and for both the forward and backward directions, the scan images are essentially identical. After an initial settling period, the STM is very stable. The drift between successive images is of the order of one to two Ångströms on a 25 Å × 25 Å scale for a scan time of about 30 seconds. To enable the electronics to follow the corrugations of the surface, the scan speed should be around 500 Å per second.

Changing the extents of the scan produces images which are centered on each other. The following images show a zoom of a factor of 3.7:
The zooming can be continued to much finer resolution: the following shows the progression of the scale of graphite corrugation from approximately $50 \, \text{Å} \times 50 \, \text{Å}$ to $30 \, \text{Å} \times 30 \, \text{Å}$ to $7 \, \text{Å} \times 7 \, \text{Å}$:
Yet another image of graphite:

![Graphite Image]

We had a small mishap which produced the following fascinating picture of a nano-indentation from a tip crash on the graphite surface:

![Nano-indentation Image]

The vertical scale cannot be calibrated on graphite. Due to interactions between the tip and the sample the corrugations are enlarged (giant corrugations). Other testing materials in air are gold or silver and the first testing surface in UHV will be Si(111).
6.2 Summary

A holistic design approach has culminated in the successful commissioning of the STM. Proceeding from establishing a new lab to the first images in only nine months is the result of focused effort. Figure 6.1 shows a photograph of the STM lab.

Care had to be taken with each step of the design, assembly, testing, and commissioning. The attention to detail at every stage paid off when trying out the apparatus: after only a few runs, the STM was scanning with atomic resolution.

The STM is based on the Besocke and Wilms design but has several important innovations. The new design features include:

- The improved design of the manipulator ensures that the tunneling wires is always electrically shielded and mechanically protected.

- The $30^\circ$ rotation of the tripod legs allows a larger excursion while walking and better access to longer samples.

- The guiding of the wires of the piezos leads to an organized, tidy arrangement and makes the tripod a compact unit.
• The reduction of the number of wires from 17 to 9 improves the vibration isolation, makes the handling and assembly easier, and reduces electrical noise.

• The assembly of leg piezos as single units makes this design very versatile: the leg units are interchangeable, re-orientable, height-adjustable, and re-usable.

The tripod is small, light, and rigid, so that the resonance frequencies are high. The vibration isolator consist of two stages, a viton stack and a triangular frame which is mounted onto three pneumatic legs. The center of mass of the UHV system is at the center of gravity of the triangle, so that the system is optimized for stability.

The UHV system is compact, small, and modular. The system consists of a preparation chamber and a purpose-designed STM chamber; it includes sample introduction and transfer, as well as sample preparation for semiconductor surfaces. It can be pumped down to UHV within one day.

The whole STM is UHV-suitable. The assembly of the tripod, part numbers, technical drawings, and a detailed description of the electronics of the controller is included in this thesis which will serve as an manual for the use of this STM.
6.3 Prospects for Future Work

The STM built within the scope of this thesis is optimized for the investigation of nanowires on semiconductor surfaces. Initially it will be used to investigate the In(4x1) structure on Si(111). The reconstruction of this surface is complex and has not been solved yet.

Results obtained with inverse photoemission show an image state at 3.75 eV [10], approximately 0.67 eV below the vacuum level [11]. The image state is a hydrogenlike state of electrons bound outside the surface. The energies can be calculated with the Schrödinger equation for an electron in a one-dimensional potential barrier. Since the potential barrier is distorted by the field of the tip the image states are shifted (higher) in STS [4]. For materials with different local work functions, the resonance at the image state is at different bias voltage levels and leads to an elemental contrast [13] which might help resolve the atomic arrangement of the indium atoms on the surface. If the STM is operated at these high voltages, the tunneling is not in the neighborhood of the Fermi level but in the transition region between tunneling and field emission.

The In(4x1) system on Si(111) is the only known quasi-one-dimensional metal found in a 2D-material (interface, surface) and it should allow deep insight into low-dimensional systems. The electron-electron interactions in these systems are highly correlated. At low temperature this Si(111)-In(4x1) system changes into a semi-conducting phase [37] and exhibits a Peierls-like instability with a non-Fermi-liquid ground state. A charge density wave due to the coupling of the electrons and holes with the lattice vibration has been found and could clearly be seen as streaks in STM images.

The implementation of a low temperature stage will extend the capabilities of the UHV-STM system. Furthermore, single atom manipulation to build and change the wires is possible with this apparatus. Experiments in the area of nanowires and other low-dimensional systems on semi-conductor surfaces show a wide variety and diversity, and are unlimited in number. This research will become important in near future as electronic devices become smaller and faster and will soon be limited by fundamental phenomena. However, this STM can also easily be extended into other areas of interest.

This UHV-STM provides the basis for much exciting research in the field of nanophysics. It offers a wide range of applications and experiments, and it will hopefully be used for many years and by many researchers.
Appendix A

Technical Drawings

1. Technical Drawing: Tripod
   - tripod basic body with the scanner in two different orientations: the Wilms design and the $30^\circ$ rotated Wilms design,
   - glue jig for scanner piezo,
   - leg pins,
   - glue station for the wires of the leg units.

2. Technical Drawing: Extras
   - wings for the tripod neck
   - leg piezo glue jig,
   - tripod holder,
   - dimensions of the piezos,
   - stainless steel tube for scanner.

SS TUBE FOR SCANNER
(made from 21 gauge needle)

Scale 5:1

DIMENSIONS OF THE PIEZOS

TRIPOD WINGS

A - diameter .123 (G7 for 0.125 tripod neck)
B - tapped hole for 0.80 setscrew
C - diameter .25 H7 for leg pins
D - 20 gauge needle SS tube

Tiltle: Extras
Drawn by Antje Lucas
Date: 22.10.99
Material: Aluminum
All dimensions are in inches.
Appendix B

Settings of the controller

The RHK manual is particularly useful once the controller is understood. It explains the concepts and their influences on the settings for different types of Scanning Probe Microscopes (SPM).

This appendix provides a concise summary of each of the dials and knobs based on the controller manual and our experiences with our STM.

The following abbreviations are used: DVM for Digital Volt Meter, dial for 10 turn potentiometer, and LED for Light Emitting Diode. A photograph of the controller front panel is shown in figure 4.10.
X Column

- **X Offset DVM**: displays the applied X-offset voltage,
  - e.g. $21.3 = +21.3$ V
  - $-107.7 = -107.7$ V

- **X Range DVM**: displays the applied X scan voltage range set with the X & Y Scan Range Dial,
  - e.g. 8.67 means the voltage at the +X electrodes is sweeping from -8.67 V to +8.67 V.

- **Offset Dial**: sets the X-offset,
  - Dial: 0 5 10
  - Offset Voltage: -130.0 V 0 V +130.0 V

- **Slope Compensation Dial**: a proportion of the X scan voltage gets summed into the Z scan voltage to correct the slope if the scanner is not perpendicular to the sample,
  - Dial: 0 5 10
  - Slope correction: -X 0 +X

- **$x1$, $x0.1$, $x0.01$ Scan Range Switch**: multiplies the value of the X & Y Scan Range Dial.

- **X & Y Scan Range Dial**:
  - Dial: 0 10
  - Scan Range Switch $x1$: 0 V 130.0 V
  - Scan Range Switch $x0.1$: 0 V 13.00 V
  - Scan Range Switch $x0.01$: 0 V 1.300 V

NB: Z-offset and Z-scan are summed into the X- and Y-scan range, therefore, high Z-offset or, if the tip is out of tunneling range, the feedback loop will saturate the X- and Y-scan range!
Y Column

- **Y Offset DVM**: displays the applied Y-offset voltage,
  
  e.g. 21.3=+21.3 V  
       -107.7=−107.7 V

- **Y Range DVM**: displays the applied Y scan voltage range, set at the X & Y Scan Range Dial (if ganged) or Y Scan Range Dial (if separate),
  
  e.g. 8.67 means the voltage at the +Y electrodes is sweeping from -8.67 V to +8.67 V.

- **Offset Dial**: sets the Y-offset,
  
  Dial 0 5 10
  Offset Voltage -130.0 V 0 V +130.0 V

- **Slope Compensation Dial**: a proportion of the Y scan voltage is summed into the Z scan voltage to correct the slope if the scanner is not perpendicular to the sample,
  
  Dial 0 5 10
  Slope correction -Y 0 +Y

- **Ganged, Separate Switch**:
  
  If the switch is set to ganged, the X- and Y- scan ranges are the same (square image) and the Y Scan Range Dial is not used.

  If the switch is set to separate, the X- and Y- scan ranges can be set independently.

- **Y Scan Range Dial**:
  
  Dial 0 10
  Scan Range Switch x1 0 V 130.0 V
  Scan Range Switch x0.1 0 V 13.0 V
  Scan Range Switch x0.01 0 V 1.300 V

  NB: Z-offset and Z-scan are summed into the X- and Y-scan range, therefore, high Z-offset and out of tunneling range will saturate the X- and Y-scan range!
Z Column

- **Z Offset DVM**: displays the applied Z-offset voltage,
  e.g. $21.3=+21.3\ V$  
  $-107.7=-107.7\ V$

- **Z Range DVM**: displays the applied Z scan voltage range. This is controlled only by the feedback loop.

- **Coarse Offset Dial**: sets the coarse Z-offset to move the tip closer and farther from the sample to bring the feedback loop into its dynamic range,
  Dial  0  5  10
  Offset Voltage  -117.0\ \text{V}  0\ \text{V}  +117.0\ \text{V}  

- **Fine Offset Dial**: sets the fine Z-offset to move the tip closer and farther from the sample to bring the feedback loop into its dynamic range,
  Dial  0  5  10
  Offset Voltage  -13.0\ \text{V}  0\ \text{V}  +13.0\ \text{V}  

  **NB**: The dynamic range of the feedback loop can be checked with the Z Position Integrator Meter. A high Z-offset value saturates the X-, Y-, and Z-Scan range. Therefore, adjust the Z-offset before starting a scan and if necessary do another coarse approach step.

- **Out of Range, In Range, Crash LED**: show the position of the Z scanner, not the tunneling current.
  If the Out of Range LED is lit, the Z piezo is extended more than 95% of its total motion.
  If the Crash LED is lit, the Z piezo is retracted more than 95% of its total motion.
  The In Range LED is lit in between.

- **Inertial Approach Filter Switch**: is a low pass filter to remove the highest frequency components of the inertial approach waveform, which could excite harmonic resonances of the tripod. The highest bandwidth (19 kHz) is set by turning completely counterclockwise.
Feedback Column

- **Z Position** Analog Integrator Meter: displays the relative position of the tip within the dynamic range of the feedback loop. If the pointer is pegged to one side, the feedback loop is saturated. For best results, the pointer should swing centered from the left to the right.

- **A/D Output** Integrator Meter: displays the relative position of the tip within the dynamic range of the A/D converter (not the feedback loop), see also Z Position Gain. If it is pegged to one side, the A/D converter is saturated. If the pointer swings over the whole range from the left to the right, the gain setting is optimized.

- **Gain** Dial: sets the gain of the feedback loop. Higher gain means faster response times (see Chapter 4.3).
  
  \[
  \begin{array}{ccc}
  \text{Dial} & 0 & 10 \\
  \text{Gain} & 0 & 2 \\
  \end{array}
  \]

- **Time constant** Dial: sets the time constant of the feedback loop. Higher value means longer time constants (see Chapter 4.3).
  
  \[
  \begin{array}{ccc}
  \text{Dial} & 0 & 10 \\
  \text{Typical time constant} & 1 \text{ ms} & 20 \text{ ms} \\
  \end{array}
  \]

- **Log, Linear** Switch: turns the logarithmic amplifier on and off (linear).

  NB: If the log amplifier is turned on, the current set point value changes as the set point is now compared to the log of the tunneling current $U_T$. The following values are obtained with the differential comparator test:

  \[
  \begin{array}{ccc}
  \text{current set point} & \text{linear } U_T & \text{log } U_T \\
  10.0 \text{ nA} & 1.00 \text{ V} & 0.78 \text{ V} \\
  7.5 \text{ nA} & 0.75 \text{ V} & 0.22 \text{ V} \\
  5.0 \text{ nA} & 0.50 \text{ V} & 0.07 \text{ V} \\
  2.5 \text{ nA} & 0.25 \text{ V} & 0.023 \text{ V} \\
  \end{array}
  \]

  Linear feedback mode has faster scan rates; the logarithmic mode images better at very low currents.

- **Reset, Reset Mom.** Switch:

  The Reset Switch turns off the feedback loop and sets it to the center of its range.

  The Reset Mom. Switch sets the feedback loop to the center of its range.

- **Z Position Gain** switch:
The computer images the topography of the sample by plotting the voltage applied to the Z piezo (see chapter 4.1 Constant Current Mode). An A/D converter board in the computer converts the analog signal (voltage) into a digital number proportional to its amplitude with 12 bit resolution (4096 steps). If the surface is smooth, the resolution at a gain of 1 might not be good enough and a flat image is shown on the computer. The following table shows the resolution for different gain settings:

<table>
<thead>
<tr>
<th>Gain (Voltage/Gain)</th>
<th>Voltage Range (V/G)</th>
<th>Z Piezo Extension (Å/V)</th>
<th>Monitored Motion Range (Å)</th>
<th>Resolution of the A/D Converter (Å/bit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130/1</td>
<td>25</td>
<td>3250</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>130/2</td>
<td>25</td>
<td>1630</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>130/4</td>
<td>25</td>
<td>813</td>
<td>0.2</td>
</tr>
<tr>
<td>8</td>
<td>130/8</td>
<td>25</td>
<td>406</td>
<td>0.1</td>
</tr>
<tr>
<td>16</td>
<td>130/16</td>
<td>25</td>
<td>203</td>
<td>0.05</td>
</tr>
<tr>
<td>32</td>
<td>130/32</td>
<td>25</td>
<td>10</td>
<td>0.02</td>
</tr>
<tr>
<td>64</td>
<td>130/64</td>
<td>25</td>
<td>5</td>
<td>0.01</td>
</tr>
<tr>
<td>128</td>
<td>130/128</td>
<td>25</td>
<td>2.5</td>
<td>0.006</td>
</tr>
</tbody>
</table>

If the setting of the resolution is too high, the pointer of the A/D Output Integrator Meter is pegged to one side and the A/D converter is saturated. The software monitors no further extension of the piezo, even though the feedback loop still controls the motion of the piezo. The A/D converter is in its optimal range if the pointer swings over the whole Integrator Meter from the left to the right.

NB: The inertial approach needs a gain setting of 1.

NB: Further increase of the gain is programmable with the software.
Tunneling Column

- **Bias Volts** DVM: displays the bias voltage,
  e.g.  Bias Adjust Dial 1 = .100 V in 1 V range
  Bias Adjust Dial 1 = 1.00 V in 10 V range

- **Nano Amps** DVM: displays the value of the tunneling current (the refresh rate is only a few Hz)

- **Current Set** Dial: sets the current set point for the feedback loop,
  Dial 0 10
  Current Set Point 0 nA (0 V) 10.00 nA (1.000 V)

- **Bias Adjust** Dial: sets the bias voltage,
  Dial 0 10
  Bias Voltage 0 1.000 V with Range Switch at 1 V
  Bias Voltage 0 10.00 V with Range Switch at 10 V

- **1 V, 10 V Range Switch**: sets the range of the bias voltage to 1 V or 10 V.

- **+,- Polarity Switch**: changes the bias voltage polarity.
Scan Control Column

- **On, Off Power Switch.**

- **Scanning Rate LED:** active in Computer and Local Mode.
  The Scanning Rate LED is lit whenever the controller is scanning.

- **Free Run, Single Frame Switch:** only active in Local Mode.
  Free Run starts a continuous raster scan. Center position stops free run.
  Single Frame starts a single raster scan.

- **Stop Switch:** only active in Local Mode.
  The Stop Switch halts the raster scan Single Frame.

- **Computer, Local Mode Switch:**
  In Computer Mode, the raster scan is controlled by the SPM32 software of the computer with data acquisition to the monitor.
  In Local Mode, the raster scan is controlled by the controller. The data can be acquired with a storage oscilloscope. This mode is good for testing purposes.
  NB: In both modes, the raster scan operates independently from the feedback loop.

- **Reset Switch:** only active in Local Mode.
  The Reset Switch moves the tip slowly back to the origin.

- **1, 10, 100, 1K Multiplier Switch:** active in Computer and Local Mode.
  The Multiplier Switch sets the coarse scan rate.

- **MS Per Line Switch:** active in Computer and Local Mode.
  The MS Per Line Switch sets the fine scan rate. The total scan speed can be set in 36 steps and is equal to Multiplier times MS Per Line:
  \[
  \begin{array}{lcccc}
  \text{MS Per Line Switch} & 1 & 2 & \ldots & 9 \\
  \text{Multiplier 1} & 1 \text{ ms} & 2 \text{ ms} & \ldots & 9 \text{ ms} \\
  \text{Multiplier 10} & 10 \text{ ms} & 20 \text{ ms} & \ldots & 90 \text{ ms} \\
  \text{Multiplier 100} & 100 \text{ ms} & 200 \text{ ms} & \ldots & 900 \text{ ms} \\
  \text{Multiplier 1K} & 1000 \text{ ms} = 1 \text{ s} & 2 \text{ s} & \ldots & 9 \text{ s}
  \end{array}
  \]
  The smaller the scan area and the smoother the surface, the faster the scan time can be chosen.
  If the switch is set straight down, the raster scan is halted.
• **Lines Per Frame Switch**: active in Computer and Local Mode.

The Lines Per Frame Switch sets the resolution of the raster scan.

E.g. 128 means 128 scan lines with 128 data points. Data is taken in both directions of the scan. The smaller the resolution, the smaller the data files and the faster the scan.

NB: In the SPM32 software, switching the frame resets the raster scan and begins a new frame.
Bibliography


[20] Staveley Sensors Inc, EBL Piezoceramic Tube Characteristics (1994), EBL #2: \(d_0 = 0.125"\), \(t = 0.024"\), \(d_1 = 0.077"\), \(L = 0.35"\)


[26] The Viton rubber (diameter 0.313") was purchased from Seals Unlimited, Mississauga, Ontario.


[28] Thanks to Jörg Schneider, Institut für Physikalische und Theoretische Chemie, Universität Bonn, for sending us their recipe for etching tips


[34] RHK Technology, Advanced Scanning Probe Microscopy Solutions, SPM Control & Visualization Systems, Brochure (1996)


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