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Building a low-cost STM

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1 Introduction

Scanning tunneling microscopy is one of the most recent developments in high-resolution microscopy. Although developed only 25 years ago, in 1981, by the physicists Binning and Rohrer, the technology is widely used today in many scientific fields.

1.1 Overview

A scanning tunneling microscope (STM) is a non-optical microscope with the capability of obtaining images at an atomic scale ($2 \cdot 10^{-10} m$). Because the device employs certain principles of quantum mechanics, only conductive surfaces can be examined.
It is even possible to manipulate single sub-atomic particles of the observed surface.

The microscope scans the sample by moving a very fine tip over it. As the stylus is moved over the surface, a voltage is applied between probe and sample. Depending on the voltage, electrons will jump (tunnel) from the tip to the surface. The result is a weak current, that is highly dependent on the distance between probe and surface. By measuring the current while moving the stylus over the sample a high resolution image of the material under study can be generated.

1.2 History

Physicist have been acquainted with the quantum mechanical principles employed by tunneling microscopes since the 1920's. Actually building the first working device took 60 more years, because micro-positioning systems had yet to be developed and the problem of damping such an assembly had been largely overrated. Furthermore the power of modern computers enables researchers to generate beautiful 3D images from the STM data.

The STM was not the first device that scanned a sample with a stylus. Systems involving contact between stylus and material, however, struggled with the resulting damage to the tip and the sample. The American physicist Russel Young at the National Bureau of Standards came up with a solution to these problems. He proposed maintaining a small distance between surface and stylus.
Young built an instrument that utilized the phenomenon of field emission to measure the distance between stylus and the sample. He also realised, that the resolution of his device could be greatly improved by using the quantum mechanical tunnel effect. Because of severe experimental difficulties Young could not realize this idea.

Gerd Binnig and Heinrich Rohrer at the IBM Research Laboratories in Zurich, Switzerland were the first to succeed in building a working scanning tunneling microscope. They took great care in the mechanical design and thereby eliminated all outside influence on the assembly. For perfect damping Rohrer and Binning placed their entire microscope on a free floating superconducting magnet.

In 1986 Binning and Rohrer received half ot the the Nobel prize in physics for their achievement. (The other half went to Ernst Ruska for the design of the first electron microscope.)

Figure 1: E. Ruska, G. Binning and H. Rohrer

2 Basics

2.1 Working principle of the STM

The STM scans the sample point by point with the tip of a very thin stylus. As shown in Figure 2 an image of the complete surface is generated in progressive stages.
Unlike the human eye, the STM can only 'see' one point of the image at a time. In figure 2 the size of the points is exaggerated. The principle used here is similiar to transmitting an image on TV.

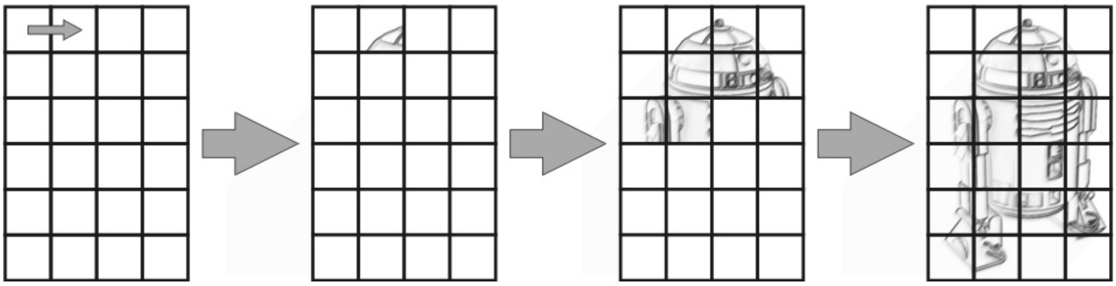

Figure 2: The STM scans the surface point by point

The STM scans the material with an extremely fine conducting stylus. Under ideal conditions there is only a single atom on the tip of the stylus. A smaller tip increases the resolution of the microscope.

A small voltage (bias) is applied between stylus and surface. This voltage can range upwards from a few millivolts to a volt. If the tip is far from the surface, there is no current. If the tip is brought very near to the surface ($10mn$- $1mn$), electrons from the stylus start to 'tunnel' to the probe. In other words, the probability density of the tip-electrons moving to the surface has a positive value.

The current value depends on the distance between tip and surface. This distance can constantly be altered while scanning the material to keep the tunnel current constant. The tip movement then corresponds to the height profile of the surface. This technique is called *constant current mode*.

There is also a *constant height mode* that is especially suitable for even surfaces. While scanning the distance between tip and surface is not altered. The change of the tunnel current is then used to derive an image of the surface.

2.2 Quantum mechanics

The theories of classical physics do not apply for very small objects (such as atoms). Quantum mechanics is a physical theory that replaces the classical laws of motion for very small objects. The theory predicts three basic phenomena that classical physics can not explain:

- quantization
- wave particle duality
- quantum entanglement

and explains the behaviour of systems that seem to contradict classical mechanics -for example the existance of stable atoms.

Quantum mechanics do not assign definite values to observables. Only predictions about their probability distribution are made. The probability distribution gives a probability for each possible outcome of a measurement.

Accordingly quantum mechanics describe the valence electrons at the tip of our scanning-stylus as a 'smeared' wavepacket. Schroedinger's law gives the equation of motion for such an electron:

$$i\hbar\frac{\partial}{\partial t}\psi(\vec{r},t) = \left(-\frac{\hbar^2}{2m}\Delta + V(\vec{r},t)\right)\psi(\vec{r},t) \tag{1}$$

where ψ is the wavefunction of the particle, m its mass and V its potential.

The electron tunnels from the tip to the surface if the probability distribution for the stay of the electron in the material of the surface has a positive value.

3 The STM

The device shown in figure 3 was designed and built in 2004 at the University of Hannover.

Figure 3: The complete STM-system

The goal was to compose a scanning tunneling microscope from low-cost components only. The STM had to be robust enough to be operated by students in a lab. The microscope has three main parts:

- the main component (containing the scanner and a pre-amplifier)
- the electronics (controlling the tip height)
- a computer (for data acquisition and interpretation)

3.1 Mechnical parts

The STM's main component consists of an upper part that stands on three points on the microscope's base plate. As shown in figure 3 the upper part holds the scanning head with the stylus (3), the screws for coarse height adjustment (2) and a micrometer (1).

Mounted on the base plate is a magifying glass (5) and a specimen holder (4).

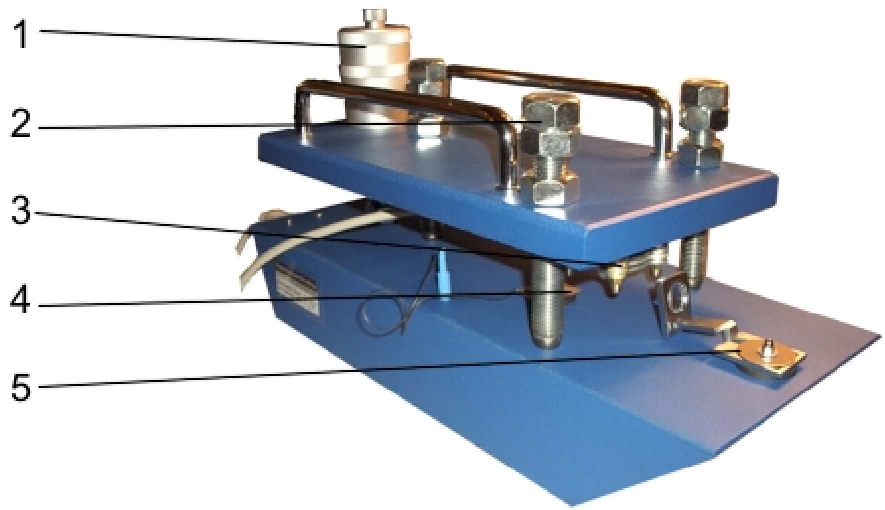

Figure 4: The STM's main component

Hardened steel globes are mounted on the end of the screws (2). The globes fit into the indents on the baseplate and thereby hold the upper part in place. The upper part can be easily removed from the base for maintainance.

3.1.1 Approaching the sample

A fundamental problem of STM construction is getting the stylus to approach the sample without touching it. The distance between tip and sample has to be adjusted in a range from a few centimeters to a few nanometers. Here the distance can be adjusted in three steps:

1. The tip is brought within a centimeter from the sample by turning the coarse adjustment screws.
2. With the micrometer the distance between tip and sample can then be reduced to 200 nm. The upper part of the STM serves as a single-sided lever and therefore transmits only $\frac{1}{20}$ of the micrometer movement to the tip.
3. A piezo crystal is used to cover the remaining distance. The crystal has a maximum devation of $2\mu m$

3.1.2 Scanning-Head

The scanning-head contains two central components: the piezo-scanner and the pre-amplifier.

Piezo-scanner and the amplifier are built into a metal case that eliminates any electro-

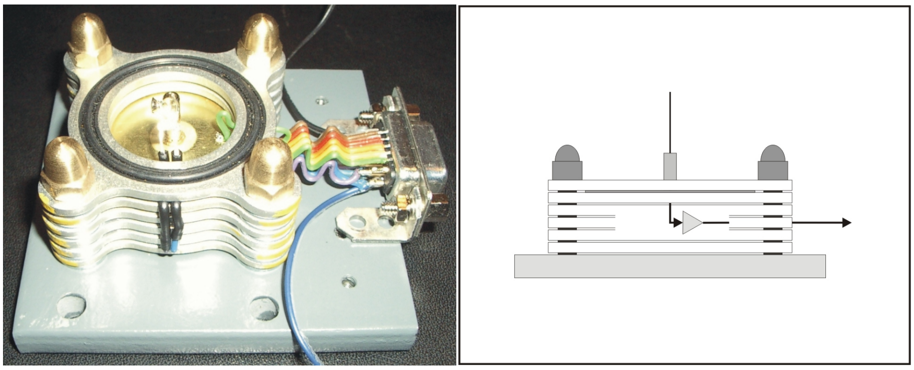

Figure 5: The scanning-head

magnetic outside influence. The closeness of scanner and amplifier reduces the outside influence on the tunnel-current even further.
The head is also equiped with an LED to illuminate the sample.

The piezo-scanner was made from a simple loudspeaker. It consists of piezo-ceramics glued onto a brass plate.
When a current is applied between ceramics and brass plate, the piezo-ceramics expands radially. Because crystal and brass are glued togehter the plate bends like a bimetal.

To make a piezo-scanner from the loudspeaker the upper electrode was cut into four pieces and the mount was glued to the middle. If the current flows through only one piece of the now divided crystal, the plate bends either into the X- or Y- direction.

3.1.3 Scanning-Tips

The STM is only as good as it's scanning-tip. Touching the tip will instantly lead to its destruction. There are two ways to produce the required extremely sharp tips:

- tearing apart a platinum-iridium filament
- corroding a wolfram filament

On the one hand making tips form platinum-iridium is much easier than corroding the wolfram filament. On the other hand the latter leads to better results and platinum-iridium filament is very expensive.

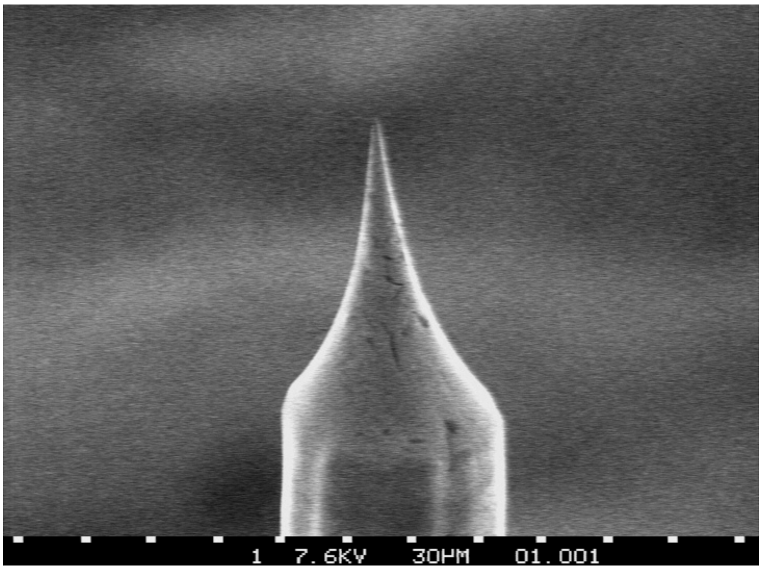

Figure 6: A scanning-tip made from a wolfram filament

3.2 Control electronics

The control electronics is composed of standard ICs. It accomplishes the following tasks:

- amplification of the tunnel current
- height-control for the tip
- communication with the computer
- power generation

As can be seen in figure 7, all controls are mounted on the front plate of the electronics housing. The rotary knobs in the upper left corner (1) are used to set the height control

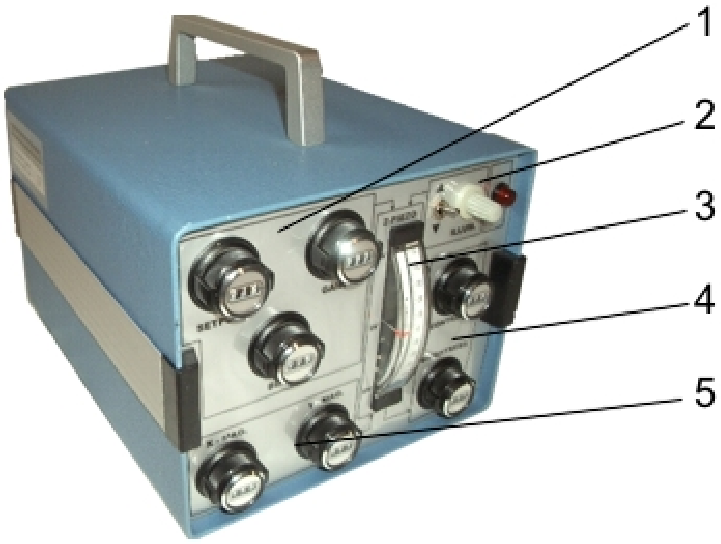

Figure 7: The control electronics housing

for the *constant height scanning* mode.
The switches in field (2) control the sample illumination. The gauge (3) displays the relative movement of the Z-piezo. When the probe is scanned, the amplitude variation corresponds to the sample's height-profile. Contrast and brightness of the resulting image can be manipulated (4). If the size of the scanned area is changed the magnification increases or decreases (5).

3.2.1 Main board

The main board converts the pre-amplifier signal into a control current for the Z-piezo. From this the setpoint-current is subtracted from the pre-amplifier output and then summed by an integrator. The resulting signal controls the tip's height. At the same time it is sent to the computer for further interpretation.
Small changes in the tunnel current that cannot be compensated by tip movement are extracted by another integrator. Theses changes will later be mapped as a texture on the 3D-height-model in the computer.

3.2.2 Amplifier

The amplifier is a Texas Instruments TLC2201 low-noise JFET operational amplifier. It converts the tunnel current of approx. $1nA$ into a direct voltage between $0V$ and $5V$. The amplifier is placed directly unter the piezo-scanner for noise reduction.

3.3 Data acquisition and processing

The computer is a normal laptop equipped with a National Instruments measurement card (pcmcia). The software for image generation was programmed in LabView 7.

3.3.1 Data acqusition

The card reads the height-signal and the texture-signal. It writes out the scan-current for the X- and Y-piezo.

3.3.2 Software

The software serves three basic purposes:

- It generates the scan-current to move the piezo in the $X-$ and $Y-$directions.
- It reads the measured values from the control electronics.
- It visualizes the measured data.

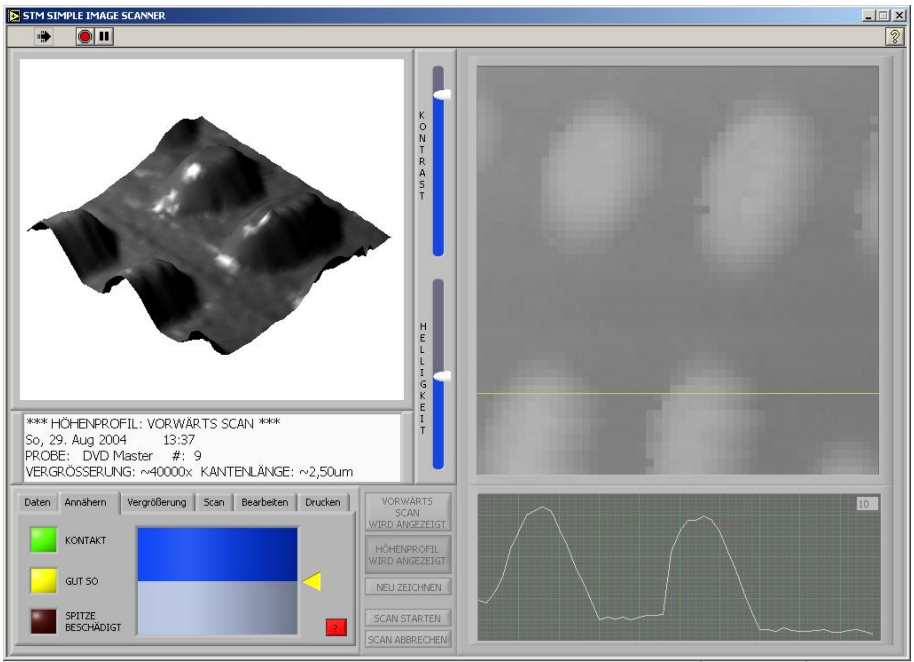

Figure 8: The STM software

As explained above there are two images to be processed. Each image is taken twice (forward- and backward-scan) to eliminate interferences. That makes a total of four images to be composed into a three dimensional view.

The 3D-representation is generated by interpreting the control current for the tip-height as height information and then mapping the changing of the tunnel current onto the resulting 3D-model.
As a final step the virtual surface is smoothed over to give a nicer impression.

4 Results

A dvd master is the stamp that is used to emboss a dvd. Advances on the stamp will become indents on the finished dvd. The STM shows the single bits on the master as clearly visible exaltations with a size of approx. $500nm$.

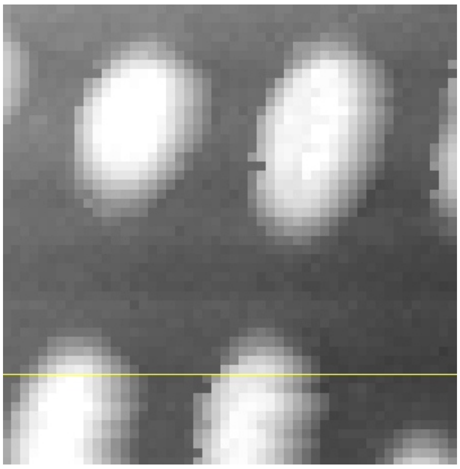

Figure 9: 2D image of a dvd master

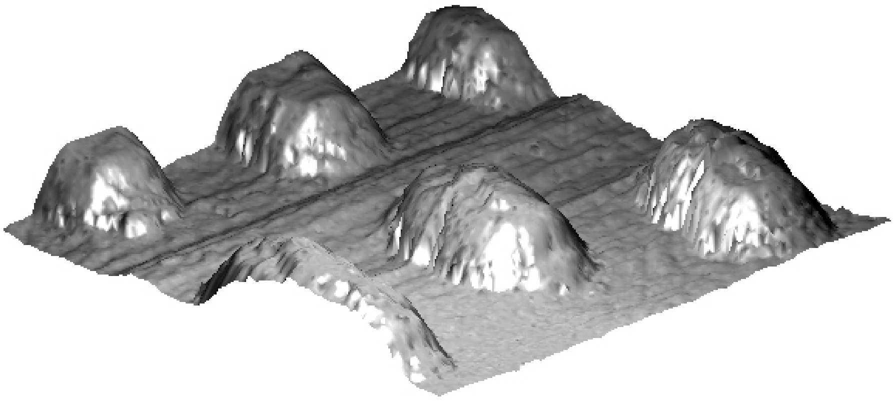

Figure 10: 3D image of a dvd master

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