

Scanning Tunneling Microscopy

The new eyes and hands of the scientists

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Abstract— The scanning tunnelling microscopes have become the eyes of the scientists, a necessary and essential tool in the laboratories of education and research for the characterization of nanoscale. This article presents the basics of a tunneling microscope that have allowed scientists the visualization and modification of nanoscale surfaces. A methodology for the correct visualization and characterization of surfaces is described using the implemented instrument, reaching the bidimensional quantification of characteristics. This methodology, determined experimentally, takes into account critical parameters for stabilization of the tunnel current, such as the scanning speed and the geometries and dimensions of the microscope needles.

Keywords—*STM, scanning tunnelling microscope, tunnel effect*

I. INTRODUCTION

The control of matter at the atomic scale is one of the most important scientific challenges of the last 30 years. This control makes necessary the appropriate development of tools that allow to observe and quantify the modifications at small scales. Visualization and characterization have been the tasks in which the scanning microscopes have been concentrated, especially the scanning tunneling microscope (STM).

The development of the tunneling microscope had an advance in 1971 from the work of Russel Young and collaborators in the "National Bureau of Standards", with the invention of the so-called "topografiner" [1]. But the STM operation was introduced by Binnig and Rohrer later in 1982 [2], and its importance was recognized when in 1986 they received half of the Nobel Prize in Physics for their design of the scanning tunneling microscope [3]. Also thanks to the atomic-scale description of a structure of Si(111) 7x7 using the microscope at the IBM Zurich Research Laboratory [4].

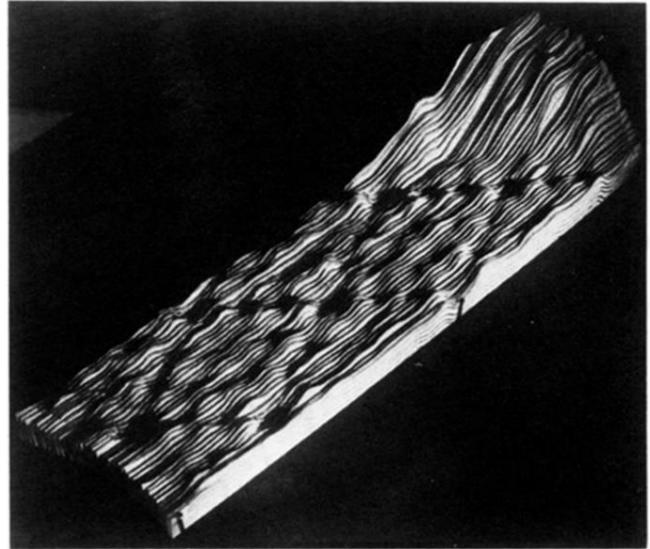


Figure 1: Relief of two complete 7 x 7 unit cells in 1982 [4]

The need for an instrument to perform local spectroscopy at the nanoscale was the main motivation that finished with the development of the STM. Its versatility became evident when this and other techniques such as potentiometry and scanning lithography were performed using the same instrument. The STM is mainly used as a surface characterization tool with atomic resolution; However, their experimentation has demonstrated the possibility of manipulating and creating nanoscale structures, thus giving the opportunity to manufacture useful patterns and geometries in the subsequent design of electronic devices [5].

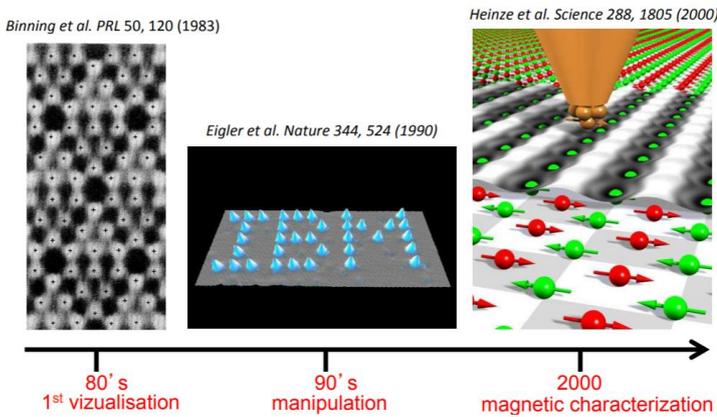


Figure 2: Chronological developments of STM [6]

The technological advance demands the familiarization and experimentation of the techniques of scanning microscopy in science and engineering programs. This article gives a brief description of the basic operation and physical principles of a tunnel scanning microscope.

Researches in the field of nanomagnetism made by Heinz using the STM allowed the magnetic characterization of surfaces in the atomic scale. This new observation of local magnetic phenomena down to atomic scale was crucial for the understanding of complicated magnetic configurations of nanomagnets. [1]

II. DISCOVERY ENVIRONMENT OF STM

One of the most motivating readings I did during the writing of this paper was "The tunneling microscope - from birth to adolescence", written by its own inventors Heinrich Rohrer and Gerd Binnig [7]. This reading tells the historical aspects of the development of the scanning tunneling microscope, were carried out. In the words of their own authors: "Our narrative is by no means a recommendation of how research should be done, it simply reflects what we thought, how we acted and what we felt. However, it would certainly be gratifying if it encouraged a more relaxed attitude towards doing science" [7]. Therefore, I would like to start by paraphrasing this reading, from which we can draw two fundamental attitudes that we should preserve during the development of any kind of project, motivation and perseverance.

It all started at the end of the '70s, when a team led by Binnig and Rohrer designed a novel microscope capable of operating at low temperatures, which they installed in a specially designed chamber where it was possible to achieve pressures lower than 10^{-9} Torr (conditions of

ultra high vacuum). Among other advances, this chamber had the necessary equipment to perform surface treatments on the samples with which it was going to work, as well as a novel superconductive levitation system that allowed to isolate the entire microscope from external vibrations. However, and despite all the details considered in its design, this microscope was very complicated and never worked properly. They had been very ambitious in their first attempt, only 7 years later and after the effort of many groups of researchers it was possible to operate a tunneling microscope at low temperatures.

After this failure they decided to considerably lower their pretensions and agreed to use an old desiccator that was thrown in the laboratory as a vacuum chamber, a lot of "Scotch"-tape, and a primitive version of superconducting levitation to isolate the microscope from external vibrations, which wasted 20 L of liquid helium per hour. With this rustic equipment they undertook the preliminary tests and after much effort, during a night measurement they managed to obtain the first curve that showed the exponential dependence of the current with the separation distance between the tip and the sample, fundamental characteristic of a current originated by tunnel effect. This moment is described by Heinrich Rohrer with the following words: "It was the portentous night of March 16, 1981. Measuring at night and hardly daring to breathe from excitement, but mainly to avoid vibrations. Our excitement after that March night was quite considerable." [7]. After 27 months of hard work the tunneling microscope was born. It was such an environment that was lived in the laboratory that they felt it was the right time to make their discovery public. So, they were encouraged to send their first job to a specialized magazine, but... that work was rejected.

Far from being discouraged, they decided to improve their results. For this, they managed to build a microscope operating under UHV conditions (this time without "Scotch"-tape), with a camera where it was possible to prepare the samples by heating and sputtering. With this new design in the fall of '82, they managed to observe the beautiful 7×7 reconstruction of the surface of the Si (111). "I could not stop looking at the images. It was like entering a new world" Binnig commented. After this important step, they decided to take a few days in St. Antönien, a charming village in the Swiss Alps, where they wrote another paper about the birth of a new microscope, which allowed for the

first time to observe in real space the atoms of a metal surface [7].

They made a second attempt to publish in a major magazine. This time, after reading and analyzing the work, the referee answered the following: "... *The paper is virtually devoid of conceptual discussion let alone conceptual novelty... I am interested in the behavior of the surface structure of gold and the other metals in the paper. Why should I be excited about the results in this paper?...*" he got the answer a few years later. Innumerable experimental and theoretical publications, crowned with the Nobel Prize in Physics less than four years after that response, marked the birth of a technique that has become our "eyes" and "fingers" in the nanoworld [3].

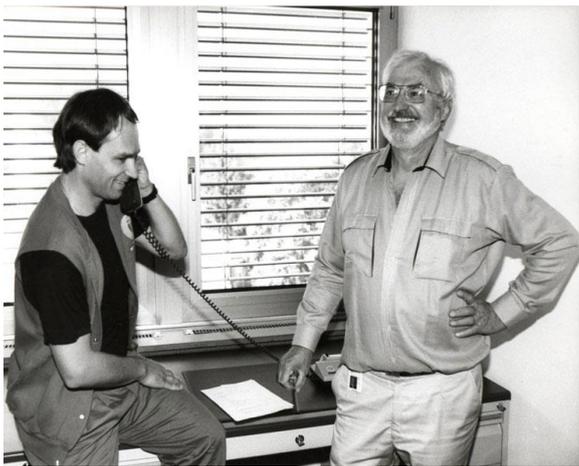


Figure 3: Binnig and Rohrer giving a telephone interview after being awarded with the Nobel price in 1986 [8]

III. BASIC THEORY OF AN STM

The STM basically consists in controlling (scanning) a very fine conducting needle on the surface of the sample at a constant tunnel current, as shown in Figure 4 [2].

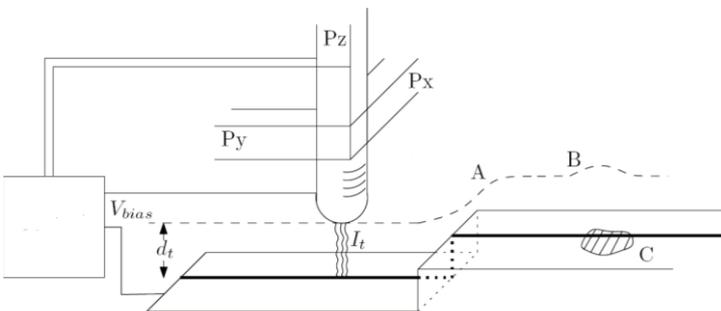


Figure 4: Principle of operation of a STM [8]

The physical principle of operation of the microscope is the tunnel effect. If a potential difference V_{bias} is applied through a potential barrier (two electrodes separated by a distance d_c , there is a tunnel current I_t proportional to the separation distance and the electronic structure of the electrodes [9].

$$I_t \propto e^{-2kd_t}$$

where:

$$k^2 = \frac{2m(V_{bias} - E)}{\hbar^2} \cdot e^{2kd_t}$$

For example, for $\frac{\sqrt{2m}}{\hbar} = 1.025 \left(\frac{1}{\hbar\sqrt{d}} \right)$ using the mass of the free electron as it is for the case of vacuum, and a potential barrier of a few eV, a monatomic change $\sim 2-5\text{\AA}$ in the tunneling distance produces a change in the current of up to 3 orders of magnitude [8].

A combination between tunnel current control and sweep tip displacements, given by the voltages applied to the piezoelectric elements (Px, Py and Pz in Figure 4), generates a detailed map of iso-currents that in the case of the conductors corresponds to a topographic map of the surface of the sample [9]. Figure 5 illustrates the necessary basic components of which there is an STM.

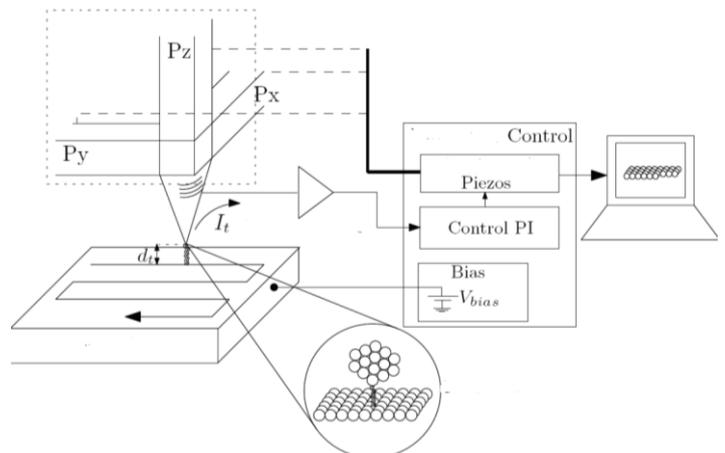


Figure 5: Basic block diagram of STM [8]

Given the exposed elements, it is necessary to take into account the following conditions under which this type of equipment operates:

$d_t \sim 1nm$, which implies sufficient mechanical vibration isolation to keep the tunneling distance stable, and a very precise position control of the tip.

$I_t \sim 1nA$, which requires a fairly high amplification stage and extremely delicate signal processing.

All the images produced by STM are grayscale, with optionally added colour in post-processed to visually emphasize important features. The resolution of an image is limited by the radius of curvature of the tip of the STM. In addition, if the tip has two points instead of one, irregularities can be observed in the obtained image; this leads to “double-tipped images”, a situation in which both points contribute to the tunnel effect and in which a duplicated image is perceived. It has therefore been essential to develop processes to consistently obtain sharp and useful points. Recently, carbon nanotubes have been used for this purpose. [10]

The tip may be made of tungsten or platinum-iridium, although gold is also used for it. Tungsten tips are usually manufactured by electrochemical etching, and platinum-iridium tips are manufactured by mechanical cutting.

Due to the extreme sensitivity of the tunnel current to the height, proper vibration isolation or an extremely rigid STM body is imperative to obtain useful results. In the first STM of Binnig and Rohrer, magnetic levitation was used to keep the STM free of vibrations; now spring or gas springs are often used. In addition, mechanisms to reduce eddy currents are sometimes implemented.

By maintaining the position of the tip with respect to the sample, the scanning of the sample and the acquisition of the data are controlled by computer. The computer can also be used to improve the image with the help of digital image processing As well as to perform quantitative measurements.

IV. OPERATION MODES OF THE STM

The first form of operation developed for STM is known as constant current mode. The control loop sends a signal proportional to the difference between the measured value and the pre-set value to the control unit of the central piezoelectric, which moves the tip in the “z” direction, making the measured current tend to the predetermined value. Once the tip-sample distance has stabilized, the lateral scan begins. The control unit, following the orders that arrive from the computer, moves the tip in the “xy” plane along adjacent parallel lines until covering a square region of the sample. The feedback loop is responsible for keeping the tunnel current constant at all times and the displacements of the tip along the z axis are recorded in the computer as a function of the position in the “xy” plane.

There is another way to acquire STM images, known as constant height mode. In this mode, the tip-sample distance is kept fixed and the tunnel current is recorded as a function of the position in the “xy” plane, and the resultant maps $I(x, y)$ are referred to as current images at constant height. Both methods have their advantages and disadvantages. The constant current mode was the first to develop historically and is used mostly for surfaces that are not atomically flat, since the tip moves in the “z” direction, being able to overcome obstacles present on the surface of the sample without hitting the same. On the other hand, the constant height mode is characterized by a much higher sweep speed, and is usually used to observe atomically flat areas. By working with a much higher sweep speed, the thermal drift that produces abrupt changes in the piezoelectric length is reduced, and by not using the feedback loop, the errors that could derive from it are also suppressed.

V. APPENDIX



Figure 6: *The IBM Zurich Laboratory soccer team. On October 15, 1986, the soccer team of IBM Zurich Laboratory and Dow Chemical played a game which had been arranged earlier. To everyone’s surprise, a few hours before the game, the Swedish academy announced the Nobel Prize for Gerd Binnig (right, holding flowers) and Heinrich Rohrer (left, holding flowers).*

Newspaper reporters rushed in for a press conference. Towards the end of the press conference, Binnig and Rohrer said that they must leave immediately because both were members of the laboratory soccer team. The reporters followed them to the soccer field. A photographer for the Swiss newspaper Blick took this photograph before the game started. At the center of the photograph, holding a soccer ball is Christoph Gerber, responsible for building the first scanning tunneling microscope as well as the first atomic force microscope. [11]

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