

1.10 Scanning tunneling microscopy

Prerequisite knowledge:

- Quantum tunneling effect (tunneling of electrons between two metals separated by a vacuum barrier).
- Piezoelectric effect.
- Setup and modes of operation of scanning tunneling microscopy.
- Principle of a feedback loop control.
- Atomic and electronic structure of a graphite surface (particularly HOPG).

List of References

[1] R.J Dwayne Miller, H.A Mizes and, A. Samsavar. Intructional Scanning Tunneling Microscope, Workbook, Burleigh Instrument, (1992).

→ Instruction book of the experimental set-up with additional information on history and basic working principal of the STM + some exemplary case of STM investigation including HOPG.

[2] E. Mayer, R. Bennewitz, H. J. Hug, Scanning Probe Microscopy: the lab on a tip, 2nd ed., Springer (2021).

→ Basic concept and technical application of scanning tunneling microscope, Theory of tunneling effect and it's application to STM. (Chapter 1 and 2) .

[3] C. Kittel: *Introduction to Solid State Physics*, 4th ed., Ch 14

→ Piezoelectricity

[4] G. Binnig, H. Rohrer, C. Gerber, and E. Weibel, Phys. Rev. Lett. **49** (1982) 57

→ First demonstration and publication of the scanning tunneling microscope.

[5] Sang-Il Park and C.F. Quate, Appl. Phys. Lett. **48** (1986) 112

[6] F. Atamny, O. Spillecke and R. Schögl. *Physical Chemistry Chemical Physics*, 1(17), 4113-4118 (1999)

→ STM studies on HOPG

Goal of the experiment

The main objective of this experiment is to understand the operating principles of scanning tunneling microscopy (STM). First, you will investigate a sample with a well-defined surface

structure consisting of a micrometer-scale gold grating. This sample serves to verify the x-y calibration of the instrument and to explore how the various adjustable imaging parameters affect the measured topography.

In the second part of the experiment, you will examine a sample of highly oriented pyrolytic graphite (HOPG). By optimizing the experimental conditions, you will aim to achieve atomic resolution and image the characteristic atomic lattice of the graphite surface.

Course of the experiment

1. Prepare the measurement tip by cutting a Pt/Ir wire and mounting it onto the appropriate tip holder
2. STM Investigation of the calibration sample which consists of a gold coated grating (2400 line/mm).
 - a) Scan the sample in constant current mode over a large scanning area ($4\text{ }\mu\text{m} \times 4\text{ }\mu\text{m}$) to image the parallel line structure of the grating. Determine the grating period from the topographic image and verify the x-y calibration of the piezo scanner. Typical scanning parameter are 1nA, 1V, CI feedback: 0.0005
 - b) Record topographic images using different scan velocities, tunneling current, voltage, feedback loop parameter. Choose a scan area between $0.5\text{ }\mu\text{m} \times 0.5\text{ }\mu\text{m}$ and $1\text{ }\mu\text{m} \times 1\text{ }\mu\text{m}$ that contains clearly identifiable surface features. Describe how each imaging parameter influences the quality and appearance of the recorded images.
 - c) Without changing the imaging parameters, record several consecutive topographic images of the same surface area. Use a scan size similar to that of part (b) and the imaging conditions that produced the best results. Compare the successive images to identify possible measurement artefacts and discuss their likely origin.
3. STM investigation of the freshly cleaved graphite (HOPG) sample.
 - a) Scan the sample over an area of approximately **100 nm × 100 nm** and locate step edges corresponding to different graphite layers (you may need to investigate several regions before finding suitable steps). Measure the step heights using line profiles and compare the results with the expected interlayer spacing of HOPG. For improved accuracy, determine the average step height from several different steps.
 - b) Reduce the scan area to approximately **3 nm × 3 nm** and select a flat terrace free of step edges. Optimize the imaging conditions to obtain atomic resolution. From the resulting image, determine the lattice constant of HOPG. For improving the x-y resolution change the magnification on the electronic controller to X50 and the X-Gain and Y-Gain in the software to 0.04.

Hint: Adjusting the tunneling current, sample bias, and feedback loop parameters may help achieve atomic resolution. In addition, post-processing techniques such as image filtering can improve the visibility of the atomic lattice.

Evaluation of the experiment

The measurement data are provided in a binary type format specific to the measuring software. For data analysis, the free software **Gwyddion** is recommended and can be downloaded from <http://gwyddion.net/download.php#stablewindows>. However, any other suitable data analysis software may also be used.

Several analysis instructions are given with the experiment task above. However, the precise relevant quantitative analysis will depend of the result of the experiment.

A qualitative assessment of your results must be included in the discussion section of your laboratory report.

Questions and exercises for preparation

Tunneling effect and its application to STM:

1. What is the tunneling effect and how does the electron wave function evolve when passing through a potential barrier?
2. How is the tunneling effect exploited in a scanning tunneling microscope, where a metallic tip and a conducting sample are separated by a vacuum gap? Which physical parameters determine the magnitude of the tunneling current between the tip and the sample?
3. By what factor does the tunneling current change if the tip–sample distance is reduced by $3 \text{ \AA}$? Assume that both the tip and the sample have a work function of 5 eV . Why does this strong dependence of the tunneling current on the tip–sample distance enable atomic resolution in STM?

Technical operation of scanning tunneling microscopy:

4. Describe the basic design of a scanning tunneling microscope and identify its main components.
5. Explain the physical principle of the piezoelectric effect. How is it used in the piezoelectric scanner of an STM?
6. What are the two main operating modes of the scanning tunneling microscope and how the associated feedback loop works with these operating modes?

Highly oriented pyrolytic graphite (HOPG):

7. What is the atomic structure of HOPG within a layer and between layers, and what are the associated atomic bonds?

8. How the particularity of the atomic structure of HOPG influences what do you “see” in STM imaging.

Beyond the experiment:

9. Why are scanning tunneling microscopes most often operated under ultra-high vacuum (UHV) conditions?
10. STM is frequently associated with scanning tunneling spectroscopy (STS). What is the principle of the STS and what information about the surface can be obtained?