Scanning Tunneling Microscope (STM)

Objective：

Imaging formation of scanning tunneling microscope (STM) is due to tunneling effect of quantum physics, which is in nano scale. This experiment shows how to obtain the sample image by operating STM individually. Students can manually control the distance between the sample and the needle in nano scale, observing the tunneling current and control it in order to fix the distance between the sample and the needle. By applying bias voltage to the piezomaterial, students can obtain image in nanoscale through needle scanning back and forth over the sample surface.

The sample used in this experiment includes grooves with 700 nm a period, gold particles in dozens of nanometer, and graphite terrace in few nanometers. Students can compare sample image with those observed through optical microscopy to experience the power of high resolution of STM.

Apparatus：

Nanovie STM Educa can be divided into three parts: main body, control box, and Nanovie STM Control Program. With extraordinary design, Nanovie STM Educa can be operated without vacuum system, extremely low temperature system, and suspension table. Students can obtain elaborate sample image under atmospheric temperature and pressure.

"Main body" is designed open-ended and is composed of scanner, needle base, sample base, scanning base, precision stepping motor, camera, and suspension components.

"Control box" is designed to control scanning components and record topographical data of sample, including I-gain bottom and G-gain bottom to control scanning rate and displacement separately. It connects to main body by network cable and SMA cable, the former provides bias voltage to control the needle, and the later records the tuning current between sample and needle. Also, it connects to CPU with USB cable, and then students can operate the the apparatus through the Nanovie STM Control Program.

"Nanovie STM Control Program" is designed to translate row data into topographic image, and then calculate any characteristic value for analyzing.

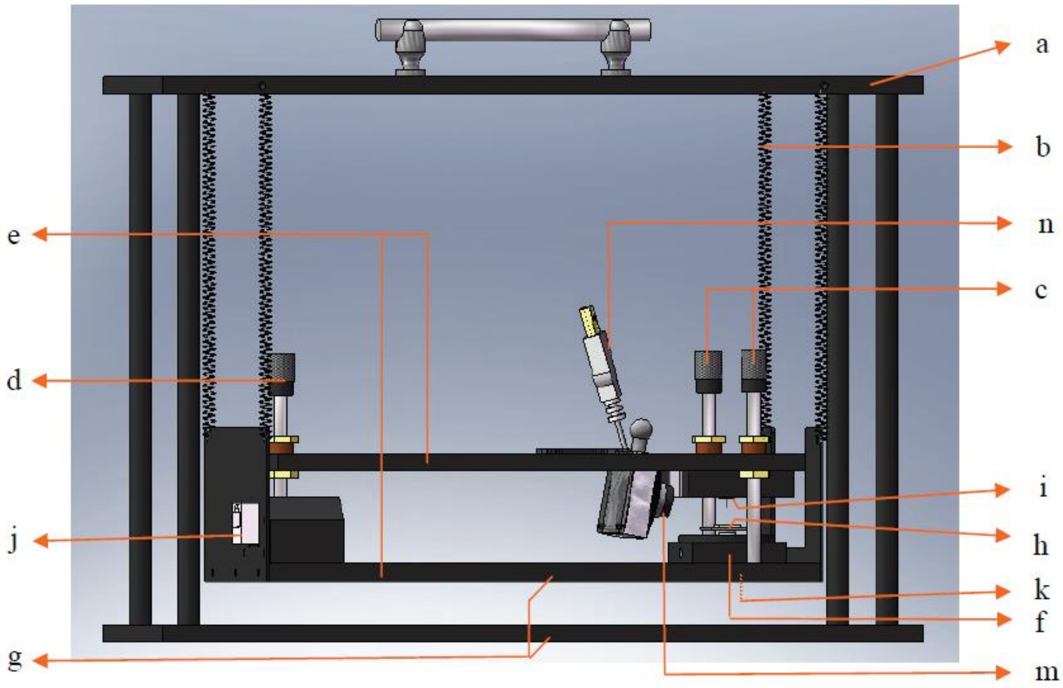


Figure 1. Nanovie STM Educa Main Body

No.	Name	No.	Name	No.	Name
a	suspension template	f	scanning component	j	network cable socket
b	suspension spring	g	installation screw	k	SMA cable socket
c	helix stepping motor	h	sample base	m	Camera
d	fine-tuning helix stepping motor	i	needle base	n	USB cable joint for camera
e	scanning upholder				

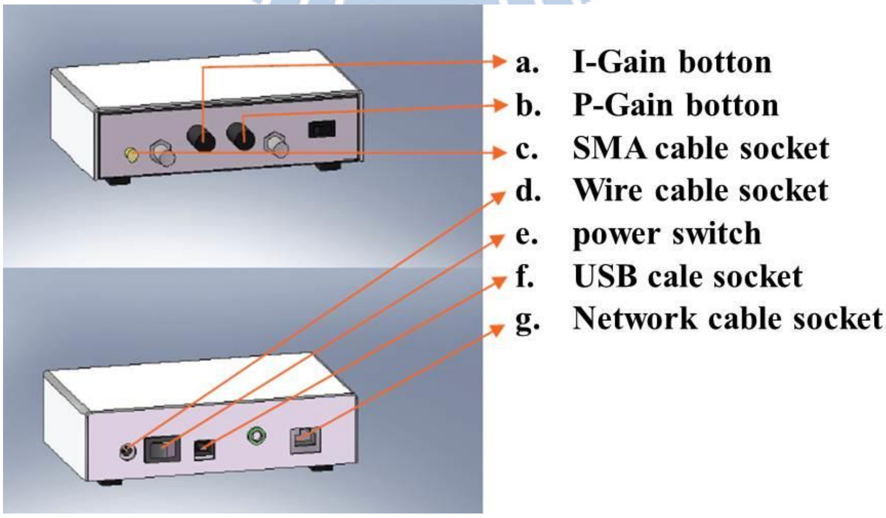


Figure 2. Nanovie STM Educa control box

Principle：

A. Origine of Scanning tunneling microscope (STM)

As shown in figure 3. Scanning tunneling microscope (STM) is an instrument for imaging surface at the atomic level. Its development in 1981 earned its inventors, Gerd Binnig and Heinrich Rohrer, the Nobel Prize in Physics in 1986. The STM is based on the concept of quantum tunneling. When a conducting tip (about ten to one hundred degree of curvature) is brought very near to the surface to be examined, a bias applied between the two can allow electrons to tunnel through the vacuum between them. The technology is used to observed nano structure of sample surface, reconstruction of crystal surface and the distribution of density of state.

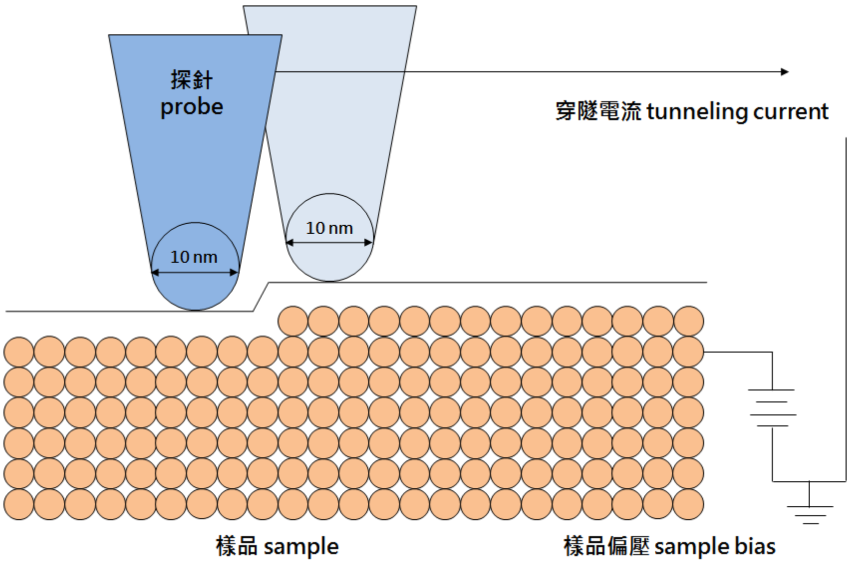


Figure 3. Diagram of tip and the sample surface

B. Theory of tunneling effect

In classical mechanics, when the energy E of a moving particle is lower than the potential energy of the barrier U, the possibility of tunneling through the barrier is zero.

In 1923, de Broglie proposed the hypothesis of matter wave which stated a moving micro-particle with energy E and momentum P showed the wave nature with wavelength λ and frequency v, and was so-called matter wave.

The relation between wavelength, momentum and energy of the particle can be expressed as

$$P = \frac{h}{\lambda} \qquad \& \qquad E = \frac{P^2}{2m}$$

where h is Planck`s constant ($h = 6.63\times10^{-34}$ J・S), m is the mass of micro particle.

In 1925, on the basis of hypothesis of wave matter, Schrödinger proposed wave equation which described the wave behavior of particle

$$-\frac{\hbar^2}{2m}\nabla_r^2\psi(r,t)+U(r,t)\psi(r,t)=i\hbar\frac{\partial}{\partial t}\psi(z,t)$$

In one dimension, assume potential energy U is time-independent, and then we can simplify it to one dimensional time-independent wave equation

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2}\varphi(z)+U(z)\varphi(z)=E\varphi(z)$$

Where $\varphi(z)$ is wave function of particle, $U(z)$ is potential energy of particle.

Assume the distance from a metal tip to a conductive sample is only few nanometer as showed in figure 4, the work function of both the tip and the sample are assumed Φ and set $\Phi \ll eV$, where V is bias voltage applied between tip and sample. Then the energy of electron in the sample (the highest energy of electron in metal is Fermi energy E_F) is higher than that in the tip as showed in figure 5.

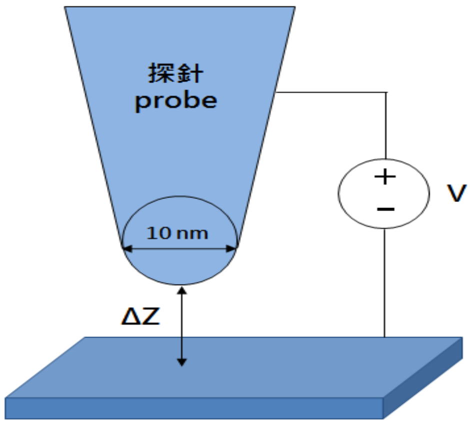


Figure 4. Bias voltage applied between sample and tip

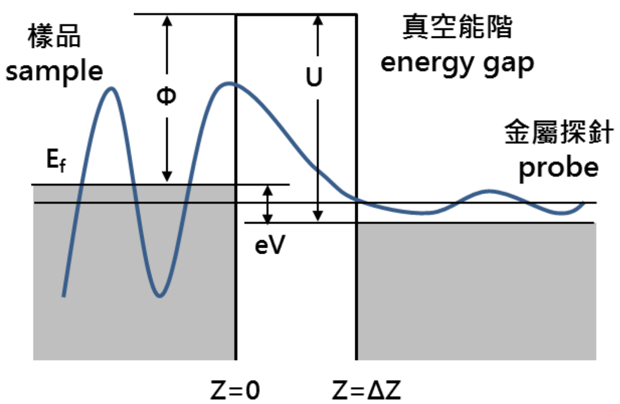


Figure 5. Energy diagram of electron tunneling effect

Divide energy diagram in figure 5 into sample, barrier, and tip regions, we can derive the wave functions of electron by taking the potential energy of sample, barrier,and tip into one dimensional time-independent wave equation

$$\varphi_{sample}(z) = Ae^{ikz} + Be^{-ikz}$$
$$\varphi_{barrier}(z) = Ce^{Kz} + De^{-Kz}$$
$$\varphi_{tip}(z) = Fe^{ikz}$$

After working hard to solve equation, we can get the possibility of tunneling from sample to tip of electron

$$T = \frac{F^*F}{A^*A} \cong 16\frac{E}{U}\left(1-\frac{E}{U}\right)e^{-2K\Delta Z} \propto e^{-2K\Delta Z}$$
$$k = \frac{\sqrt{2mE}}{\hbar}$$
$$K = \frac{\sqrt{2m(U-E)}}{\hbar}$$

Where k is wave factor of incident wave, K is wave factor of transmitted wave, ΔZ is the width of the barrier, A, B, C, D, and F are the amplitude of the wave in sample, barrier, and tip regions.

From above, it is clear that although the energy gap between the sample and tip regions is smaller than the energy of the potential barrier, the possibility of tunneling from sample region to tip region for electron still exists, and that is so-called tunneling effect with tunneling current resulted during tunneling.

When the total energy of electron is constant (that is, the applied bias voltage is constant), then the tunneling current decreases rapidly as width of the barrier ΔZ increases

$$I \propto e^{-2K\Delta Z}$$

C. Piezoelectric effect

Applying bias voltage on top and bottom of the piezoelectric ceramic chip, then the distortion occurs as showed below

(a) Here is the side view of piezoelectric ceramic chip. Applying forward bias voltage on top of the chip will make the chip bending upward.

(b) Without applying forward bias, that is, electric field is uniform through the chip, distortion does not exit.

(c) Once applying backward bias voltage on top side, the chip will bend downward.

By controlling the bias voltage, relative shift occurs in nano scale in vertical orientation(Z axis). To control the shift in nano scale in horizontal orientation(X and Y axes), we have to individually apply bias to X and Y axes.

D. Principle of STM

When a tip about ten to one hundred degree of curvature comes close to the smooth surface around 1 nm, tunneling current with few nano amps exists due to bias voltage between tip and sample. The tunneling current is smaller than the contact current between sample and tip, and is also much smaller than the working current through tunneling junction in the range of micro scale. With the feedback of tunneling current, tip can keep fixed distance from the sample surface when scanning back and forth. The displacement through Z axis is the height of sample surface. Scanning along X-Y plane, we can obtain the surface image in nano scale.

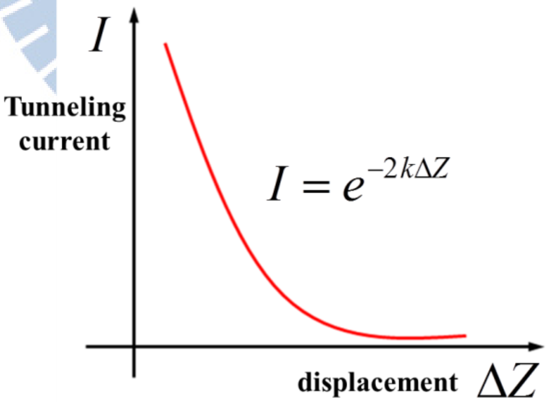


Figure 6. Relation between displacement and tunneling current

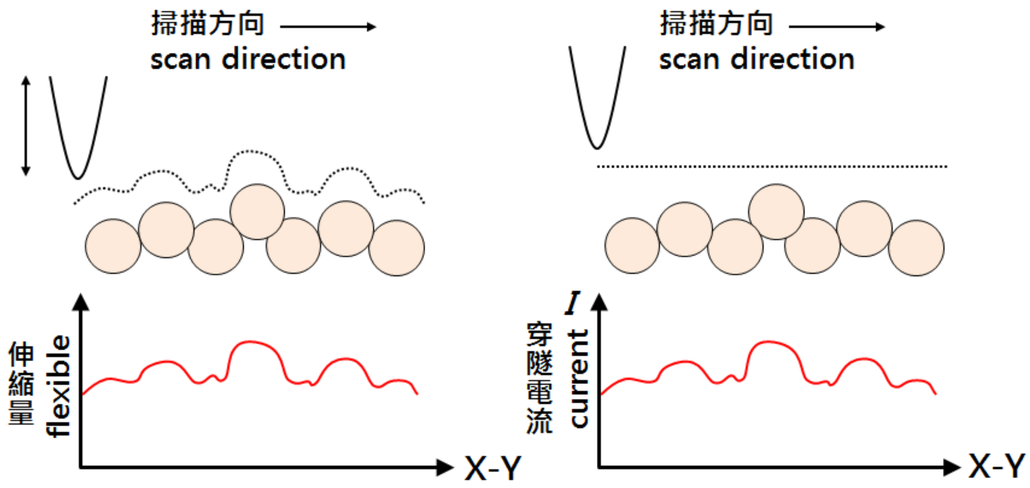
E. STM scanning mode

(a) Constant Current Mode：

By using a feedback loop the tip is vertically adjusted in such a way that the current always stays constant. As the current is proportional to the local density of states, the tip follows a contour of a constant density of states during scanning. A kind of a topographic image of the surface is generated by recording the vertical position of the tip.

(b) Constant Height Mode：

In this mode the vertical position of the tip is not changed, equivalent to a slow or disabled feedback. The current as a function of lateral position represents the surface image. This mode is only appropriate for atomically flat surfaces as otherwise a tip crash would be inevitable. One of its advantages is that it can be used at high scanning frequencies. In comparison, the scanning frequency in the constant current mode is about 1 image per second or even per several minutes.



(a) Constant Current Mode (b) Constant Height Mode

Figure 7. STM scanning mode

Remarks：

1. Before taking out or putting in the sample base, needle base and the scanning tip, rotate the precision screw clockwise until there is enough space between sample and tip.
2. When withdrawing or putting in the sample base, needle base and the scanner, avoid component crash due to powerful magnet. You must move those components horizontally then pull in
3. Make sure I-Gain and G-gain are in maxima on the control box before insert the needle, and then rotate counterclockwise to the end.

Procedure：

A. Setup main body

1. Remove the shielding.
2. Make sure scanning template is hook on suspension string.
3. Make sure helix stepping motor and fine-tuning helix stepping motor is horizontal and "tip-out".
4. Make sure needle and needle base locate appropriately.
5. Make sure sample is placed on the template.
6. Connect camera to CPU with USB cable.

B. Setup control box

1. Connect control box to main body with network cable.
2. Connect control box to main body with SMA cable.
3. Connect control box to CPU with USB cable.
4. Connect control box to socket with transformer specified for STM Educa.

C. Tip-in training

Choose unsound needles and hundred-nanometer-scale groove to practice. Until obtaining clear image of sample without sample or needle damaged. Qualified students will get new needles to start experiment.

D. Needle base setting

1. To withdraw the needle base, please rotate helix stepping motor clockwise until enough safety margin between sample and needle.
2. To avoid shaking during operation, fix the bottom board of scanning base and the top board of suspension template with screws, and then turn over the top board of scanning.
3. Withdraw the needle base with folder horizontally. Through magnetic force, withdraw the sample base from the disc of scanner carefully. Avoid drag it vertically or obliquely, otherwise, it causes sample and needle damaged.
4. When placing the needle base with holder, push the inner edge of needle base near to the outer edge of magnetic sample template slightly obliquely. After contact the base gently, push the sample base to appropriate position horizontally. Do not place the base vertically or let down the sample base during the process. Crash due to powerful magnetic force will cause damage to instruments.
5. Place the top board to the original place aligned with the position of precision screw.

E. Replace the needle

1. Before replacing the needle, refer to (D) to withdraw the needle base from scanning base.
2. Loosen the screw on both side of needle base, and clip the used needle with folder.
3. Loosen the screw on the needle storage, and clip new needle with folder.
4. If needed, check condition of the needle by using optical microscopy.
5. Place new needle into the needle hole with folder, and fix screws on both side of needle base until needle does not shake.
6. Following (D) to put the needle base back. Avoid needle damaged or needle bass loss.

F. Sample setting

1. To withdraw the sample, please rotate helix stepping motor clockwise until enough safety margin between sample and needle.
2. To avoid shaking during operation, fix bottom board of scanning base and top board of suspension template with screws, and then turn over the top board of scanning base.
3. Clip the sample from sample storage with folder and avoid touching the sample surface.
4. Withdraw the sample base with folder horizontally. Through magnetic force, withdraw the sample base from the disc of scanner carefully. Avoid drag it vertically or obliquely, otherwise, it causes sample and needle damaged.
5. 開When placing the sample base with holder, push the inner edge of sample base near to the outer edge of disc slightly obliquely. After contact the base gently, push the sample base to appropriate position horizontally. Do not place the base vertically or let down the sample base during the process. Crash due to powerful magnetic force will cause damage to instruments.
6. Place the top board to the original place aligned with the position of precision screw.

G. Preparation for needle-in

1. Scan the top board to make sure it is horizontal.
2. In order to avoid crash when you fine-tune needle-in, rotate counterclockwise I-Gain and P-Gain buttons of the control box to maxima.
3. Turn on the camera program, if needed; adjust the focus of camera to observe clearly the needle.
4. Turn on STM Control program and make sure status bar of needle is black and normal.

H. Tune the needle-in

1. Helix stepping motor is composed of two precision screws, rotate in the same orientation and in the same degree with both hands. Rotate counterclockwise for needle-in.
2. When tune the needle-in, stare at the screen. Stop tuning until the distance from tip to the reflection image of tip from sample surface is small than 0.5 mm.
3. Withdraw the USB cable for camera from the scanning base after tuning the needle-in.

I. Fine-tune the needle-in

1. Before fine-tuning the needle-in, withdraw the USB cable for camera from the scanning base, and then loosen the screw to make scanning base suspended.
2. Fine-tuning helix stepping motor is composed of one precision screw, rotate it with one hand slowly and steadily, and hold the scanning with another hand. Rotate counterclockwise for needle-in.
3. When fine-tuning the needle-in, stare at the status bar of needle on the screen. Stop fine-tuning the needle temporarily when feedback signal shows, and then tune it until status bar is about 50%.
4. Turn down I-Gain to lower reaction rate of needle until status bar becomes stable.
5. Turn down P-Gain to lower reaction rate of needle until status bar becomes stable.
6. Fine-tune the needle and turn down both I-Gain and P-Gain repeatedly until status bar is stable in the middle of the bar.

J. Pre-scanning

Choose low resolution (100×100~200×200 pts), short dwelling time (2~5 ns), and then press Scan bottom to get partial image. Check the quality of the image and then decide whether tune I-Gain and P-Gain again. Also check the condition of the needle tip.

K. Start scanning

1. Set “Bias, Dwelling time, Scan Area, Scan Position, Image Size, and Set current”, check scan mode is right (large range or high resolution), press Scan botton, and then press Save bottom to record data.
2. Auto Contrast is recommended, that distinct image could be present instantaneously.
3. If saving data is needed during scans needed, choose Continuous Mode before scan.

L. Change parameters instantaneously

During scanning, User can change "Set current and Dwelling time" and tune I-Gain and P-Gain in order to improve quality.

M. Repair the needle instantaneously

When low quality of image contributes to poor condition of the needle, press the Pulse bottom to applied high bias voltage in order to change the interaction between needle tip and sample, therefore, it is possible to repair the needle tip to get better image.

<u>Questions</u>：

1. What is piezoelectric effect? Please explain.
2. What are the possible reasons for slight difference between images obtained from the same sample scanned by the same instrument each time? Please explain.
3. Could you observe the sample surface through optical microscopy? Please explain.