

Scanning Probe Microscopy

Lecturer: Prof. Randall M. Feenstra
Scribe: Mahim Mishra

History of Scanning Probe Microscopy(SPM)

- 1982: Scanning Tunneling Microscope (STM), developed at the IBM Research Lab, Zurich. Gerd Binnig and Heinrich Rohrer shared the Nobel Prize in Physics of 1986 for this discovery (the 3rd laureate that year, Ernst Ruska, had designed the first electron microscope).
- 1986: Atomic Force Microscope (AFM)
- ... (other methods)
- 1992: manipulation of individual atoms

Agenda for the lecture

1. Instrumentation
2. STM
 - uses tunneling
 - can also be used for spectroscopy
3. AFM
 - uses atomic forces
 - can be used for biology
4. Manipulation of atoms

Instrumentation

A. General idea

Use a (very) sharp tip, bring it close to the surface of the sample, have electric current between tip and sample, and scan the tip (see Figure 1). The atomic configuration that the STM obtains is showed in Figure 2.

There is vacuum between the tip and the sample.

Separation $s \approx 10 \text{ \AA}$ ($1 \text{ \AA} = 10^{-10} \text{ m}$, and is the typical atomic radius)

Precursors to the STM

The *topografiner*: Developed at the National Bureau of Standards, USA in 1972, this used the same principle as the STM. However, it was bulky, and did not give a very good resolution (a later paper by the developers outlined how resolution could be improved by using tunneling effects, the exact same principle on which the STM is based).

Field electron/ion microscope: This was the first to see individual atoms, for a specific class of materials.

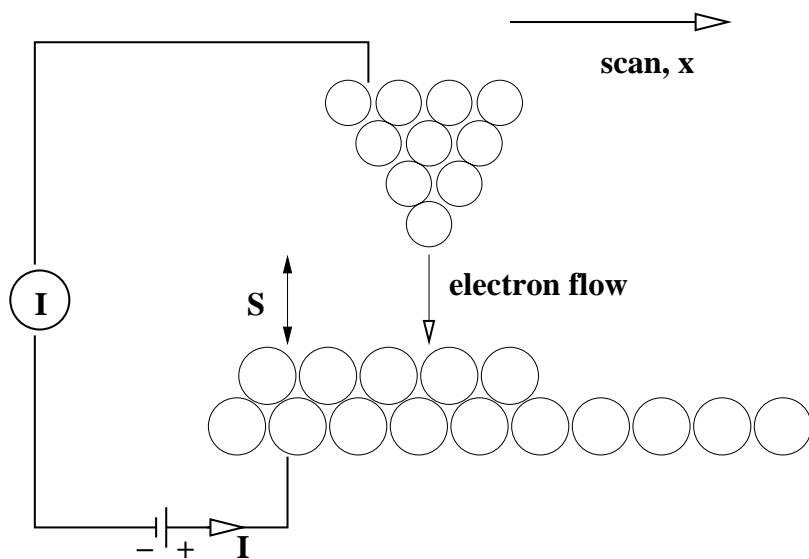


Figure 1: A schematic representation of how the STM can be used for scanning

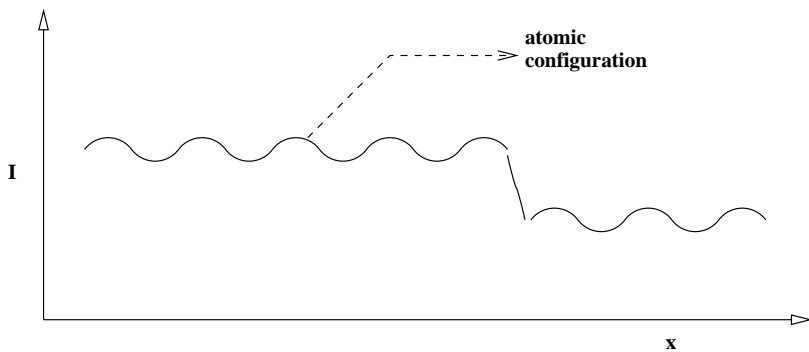
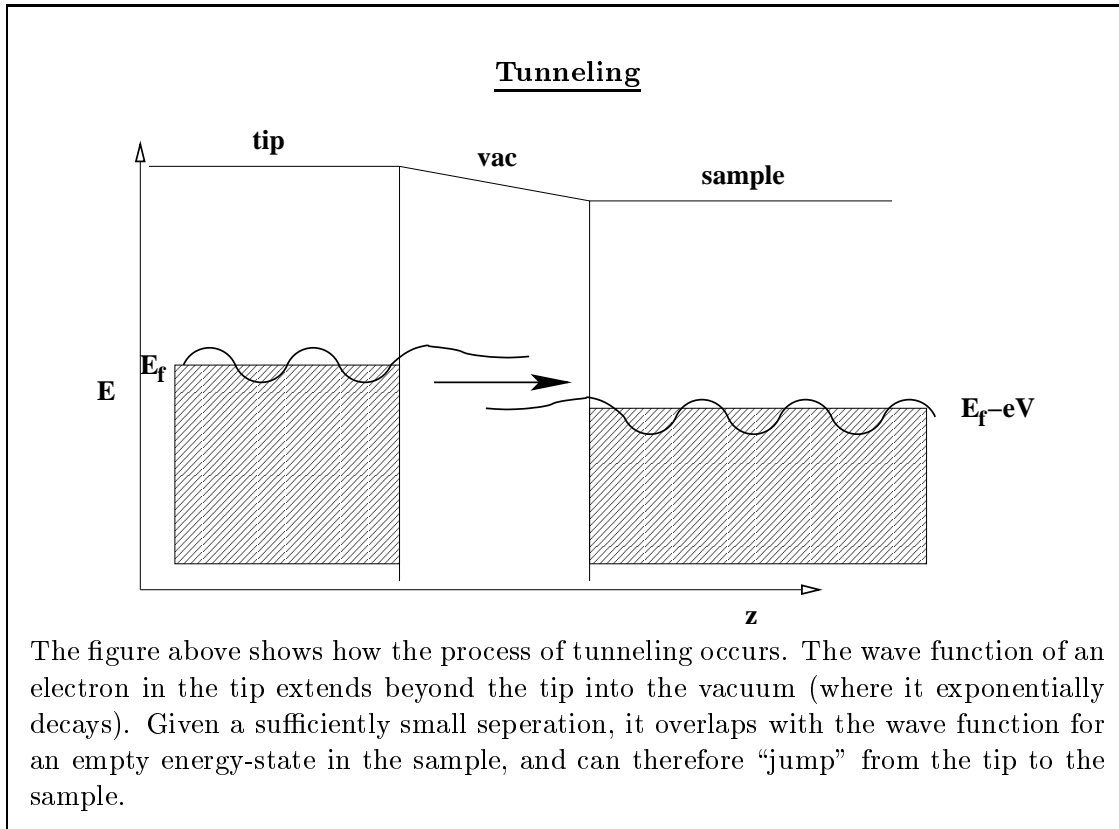


Figure 2: The atomic configuration that the STM detects



Current $I \propto e^{-2\kappa s}$

where $\kappa = \sqrt{\frac{2m\phi}{\hbar^2}} \approx 1.1 \text{ \AA}^{-1}$

This implies that 1 \AA change in s causes $e^{-2.2} \approx 10$ change in current I . The current I is usually maintained at 1 nA.

- The current flows from tip to sample using a process known as tunneling (see box). This flow takes place through vacuum.
- Contact between the tip and the sample has to be prevented. This is usually done by using a feedback loop to adjust the height of the probe tip, so that the current flowing is kept constant (this gives the most common type of STM image) (see Figure 3).
- The speed of the scan is limited by the feedback loop, which is in turn limited by the mechanical resonances in the system.
- Resolution achieved:
 - vertical: $\approx 0.01 \text{ \AA} = 1 \text{ pm}$
 - lateral: $\approx 4 \text{ \AA}$

Of course, this depends on the atomic resolution of the tip!

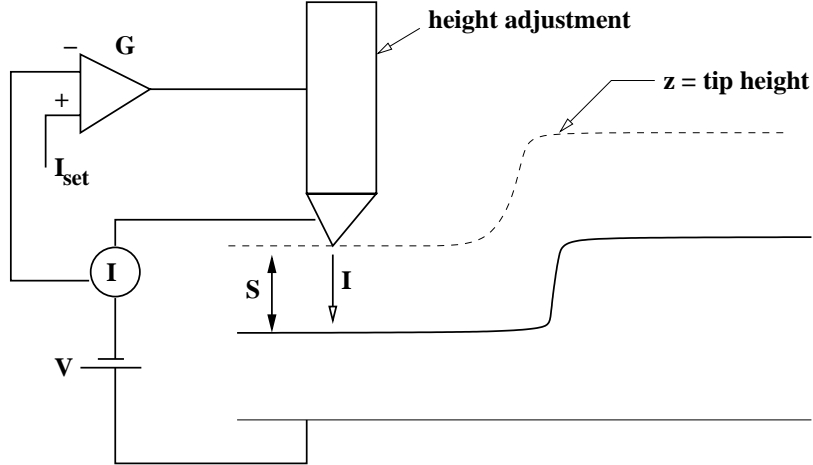


Figure 3: This figure schematically represents the feedback loop to adjust the height of the STM tip.

B. Components

i. fine motion

This is used for fine movements in the z -direction and for scanning in the x - and y -direction. The resolution required varies from 0.01 \AA to about a 1000 \AA .

The motion is achieved using piezo-electric materials (usually commercially available ceramics), which deform when a voltage is applied across them (see Figure 4(a)). The deformation is about 10 \AA per Volt of applied voltage.

To achieve motion along 3 axes, two alternative arrangements of the piezo-electric material are used:

1. As a tripod, as shown in Figure 4(b): this requires 3 rods of the material.
2. A single hollow cylinder, as shown in Figure 4(c): the electrodes that produce motion in the x and y directions are along the outside of the cylinder and perpendicular to each other. Electrodes for producing z motion are along the inside. A single cylinder is able to achieve all 3 directions of motion.

ii. coarse motion

To approach tip to the sample without crashing into the sample. To achieve this, these mechanisms have to achieve sub- μm resolution. Two major mechanisms are in use:

1. Piezo-electric motors, such as the *inchworm* (see below)
2. Mechanical, such as through screws and reducing levers.

The inchworm (see Figure 5) consists of two metal sections at the end which are clamped, and a piezo-electric section in between which expands and contracts. By clamping one end and unclamping the other, extending (or shortening) the piezo-electric section, reversing the clamps and reversing the motion of the

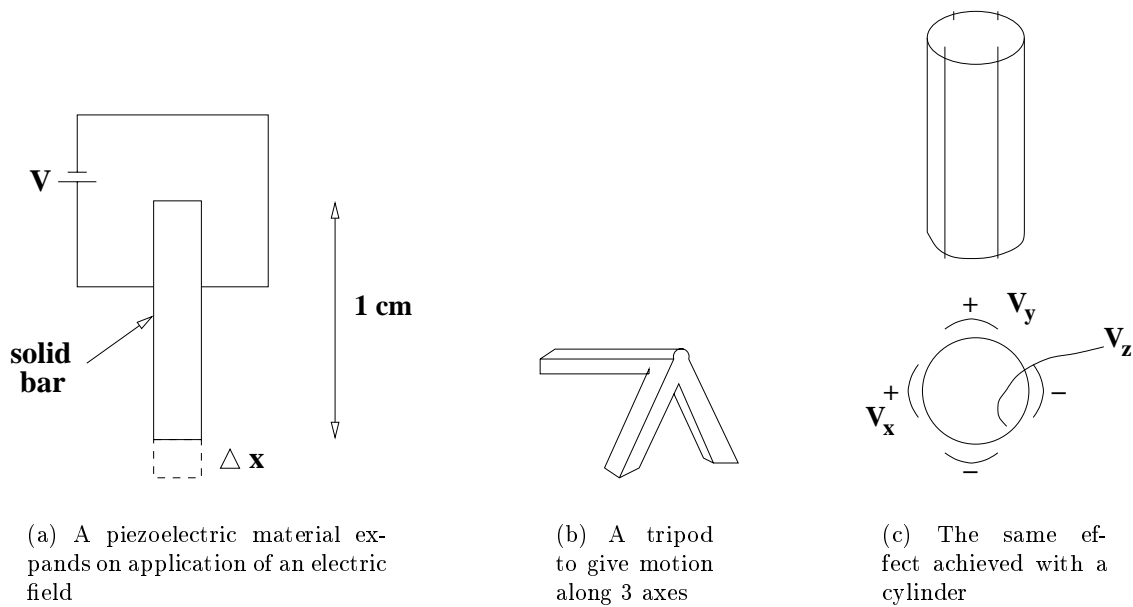


Figure 4: Achieving fine motion

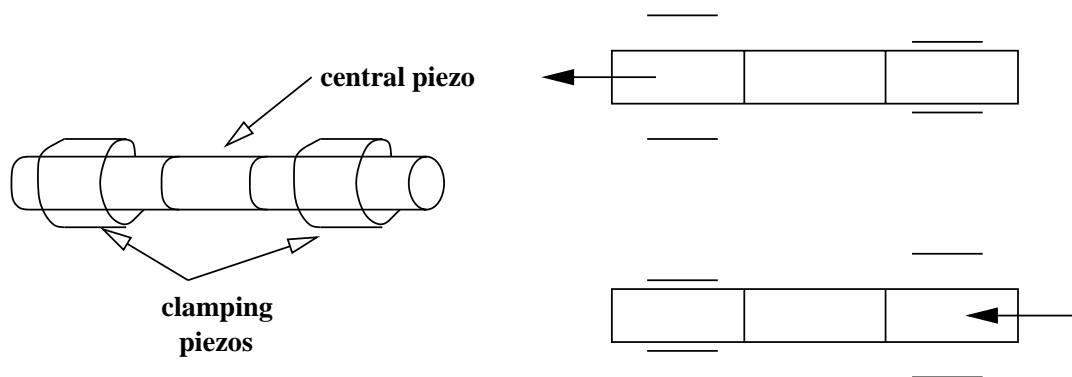


Figure 5: A schematic representation of an inchworm is shown on the left. On the right is a sequence of actions that let the inchworm move forward.

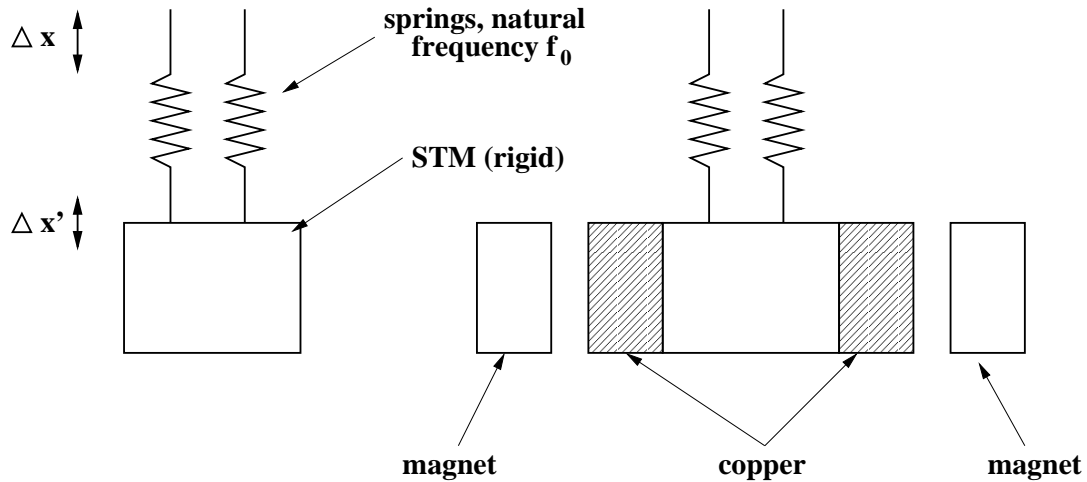


Figure 6: The springs help eliminate high frequency vibrations. The magnets and conductor arrangement on the right eliminates low-frequency vibrations

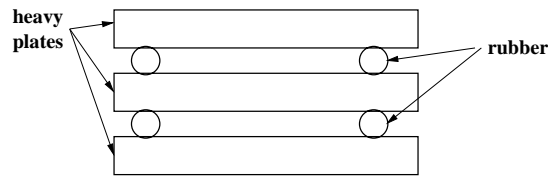


Figure 7: This arrangement is also used to dampen vibrations

piezo-electric, a small forward motion can be achieved; this can be repeated to move the tip forward in an inchworm-like manner.

The tip is carefully approached to the sample using this mechanism, while monitoring the tunnel current.

iii. vibration isolation

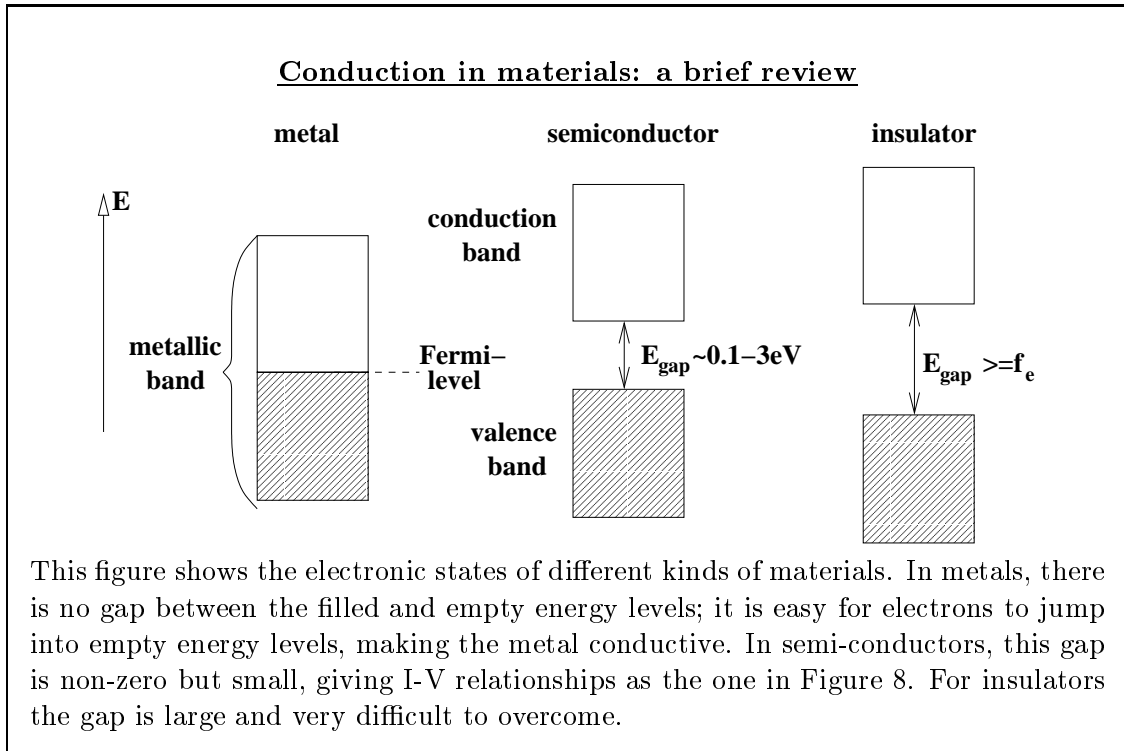
It is essential that the STM be isolated from the vibrations in the environment. This is achieved using a setup as in Figure 6. The (rigid) STM is suspended with springs which have a natural frequency of vibration f_0 . We shall now relate the displacement $\Delta x'$ of the lower end of the spring when the upper end is displaced Δx by an external vibration of frequency f .

- $f \gg f_0$: $\frac{\Delta x'}{\Delta x} \sim \frac{1}{(f/f_0)^2}$.

Therefore, we want f_0 to be low, and typically choose it to be 1 Hz.

- $f \approx f_0$: an arrangement similar to the right side of Figure 6 is used. The motion of the magnets induces current in the copper conductor, which dampens the motion of the spring.

Sometimes, a stack of plates as in Figure 7 can also be used to dampen out external vibrations. The STM is placed atop the top plate.



STM

A. Imaging

The STM is used in constant-current mode for imaging. The most important early images were of *reconstructions* on the surface of silicon (see lecture slides).

B. Spectroscopy

This is done by fixing x , y and z co-ordinates of the tip, fixing potential difference V between the tip and the surface, measuring current I and obtaining an I-V relationship. This allows the exploration of electronic states within a few eV of the fermi-level of the sample atoms.

The plot obtained depends on the nature of the material (see sidebar); for semiconductors, the plot would look something like Figure 8. The measurements are carried out at an extremely low temperature to improve the resolution.

AFM

An AFM has a very light probe mounted on an extremely light cantilever arm with a small spring constant (or, in other words, a *leaf spring*) (Figure 9). The tip is brought close enough to the surface so that atomic forces between the tip and the surface atoms come into play. These forces can be measured by measuring the deflection of the leaf spring. From this, the force that must be acting on the tip can be inferred,

Limitations of STM

- need conducting sample (also, current has to be carefully maintained: high current can destroy the tip or sample, while low current is susceptible to noise. Usually, $I \approx 1$ nA.)
- tunneling is sensitive to surface composition: need ultra-high vacuum or inert atoms
- speed of scan is limited ($f_{scan} < f_{resonance}$)

Also, the image obtained is always “high resolution”; resolution cannot be traded off for scanning speed.

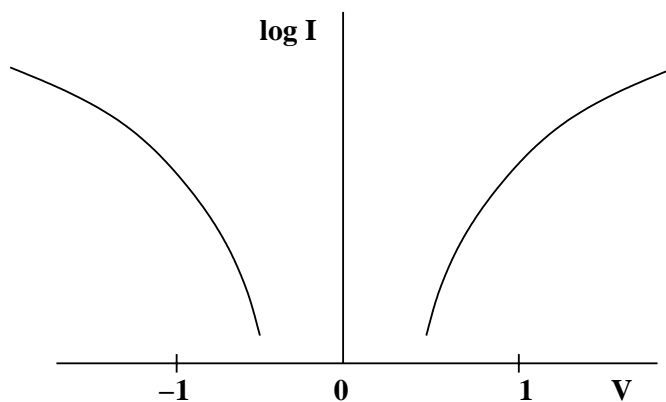


Figure 8: An STM can be used to obtain I-V curves of this nature

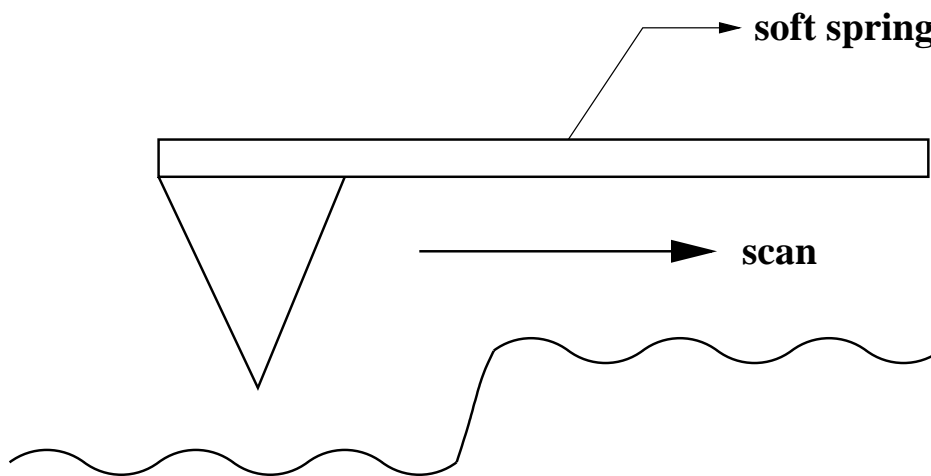


Figure 9: Schematic of an AFM

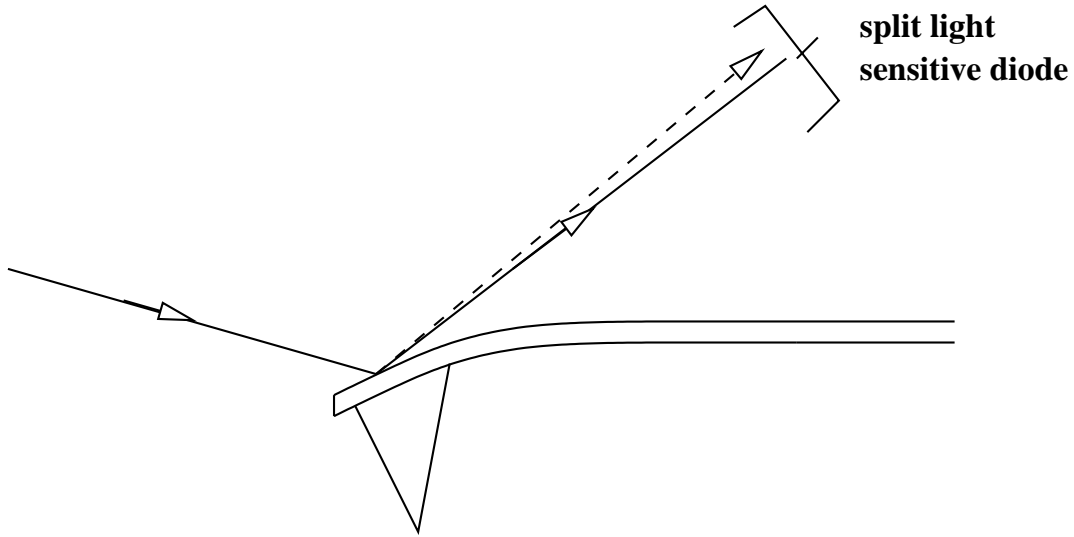


Figure 10: The deflection of the tip is measured by bouncing a laser off the cantilever arm

which gives us the contour of the surface at atomic resolution (since inter-atomic forces are related to the distance between the atoms). One possible complication is formation of bonds between the tip and the surface atoms.

The deflection of the spring is measured using the setup shown in Figure 10. A laser beam is reflected off the cantilever arm, and its deflection is measured using a split-diode.

The spring is made of extremely thin metal (Al) foil, or micro-fabricated cantilevers. It is extremely light, and susceptible to external vibrations. To avoid this, the natural frequency of vibration of the spring (ω) should be small. But

$$\omega = \sqrt{\frac{k}{m}}$$

where k is the spring's spring constant and is small, and m is the spring's mass. Therefore, for ω to be large, m has to be extremely small, i.e., the spring should be very light.

The AFM is operated in the following modes:

1. constant height
2. constant force: this maintains a constant deflection and therefore needs a feedback loop. However, the spring's small ω means that this feedback loop will be very slow.

The AFM can also be run in *contact* (where the tip can touch the sample surface) versus *non-contact* mode. The force between the tip and the surface is related as in Figure 11.

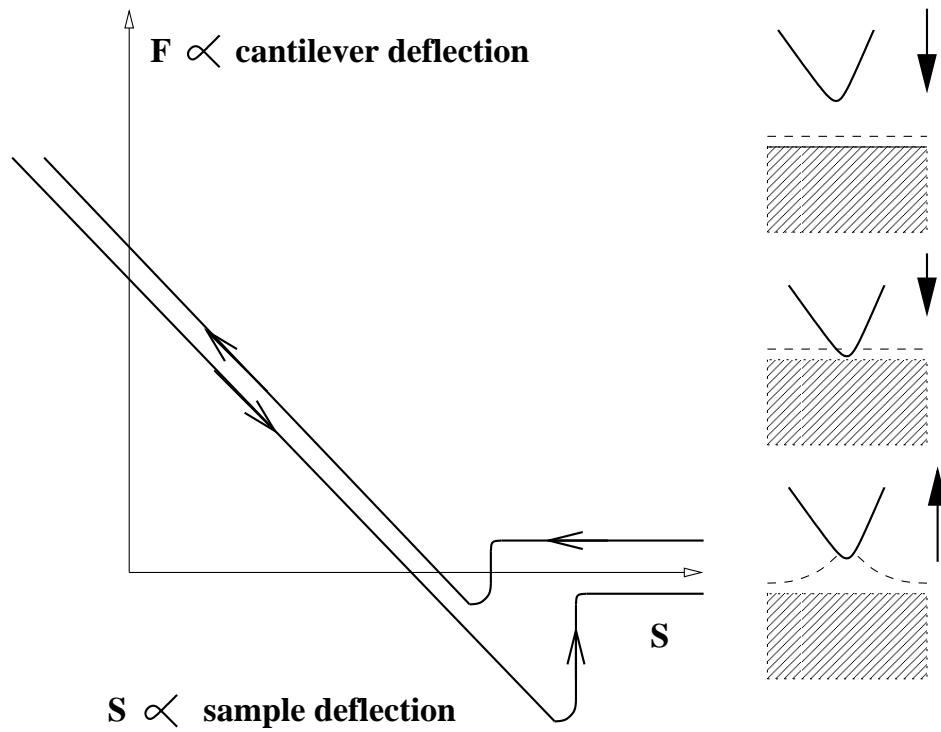


Figure 11: The force measured by an AFM

Manipulation

Manipulation of atoms is possible by using attractive forces between the probe tip and the molecule that is to be moved (see lecture slides). However, this is likely to be extremely slow.