4.2: Scanning Tunneling Microscopy (STM)

Introduction

The scanning tunneling microscope (STM) is widely used in both industrial and fundamental research to obtain atomic scale images of metal surfaces. For an STM, good resolution is considered to be 0.1 nm lateral resolution and 0.01 nm depth resolution. With this resolution, individual atoms within materials are routinely imaged and manipulated. It provides a three dimensional profile of the surface which is very useful for characterizing surface roughness, observing surface defects, and determining the size and conformation of molecules and aggregates on the surface.

The STM can be used not only in ultrahigh vacuum but also in air, water, and various other liquid or gas ambients, and at temperatures ranging from near zero kelvin to a few hundred degrees Celsius. Its development in 1981 earned its inventors, Gerd Binnig and Heinrich Rohrer (at IBM Zürich), the Nobel Prize in Physics in 1986.

STM can be a challenging technique, as it requires extremely clean and stable surfaces, sharp tips, excellent vibration control, and sophisticated electronics.

Construction & Working

The components of an STM include scanning tip, piezoelectric controlled height and x, y scanner, coarse sample to tip control, vibration isolation system, and computer. First, a voltage bias is applied and the tip is brought close to the sample by coarse sample to tip control, which is turned off when the tip and sample are sufficiently close. At close range, fine control of the tip in all three X, Y & Z dimensions when near the sample is typically done by piezoelectric scanner, maintaining tip sample separation W typically in the 47 Å (4.7 nm) range, which is the equilibrium position between attractive ($3<W<10$Å) and repulsive ($W<3$Å) interactions. In this situation, the voltage bias will cause electrons to tunnel between the tip and sample, creating a current that can be measured.

The electron cloud associated with metal atoms at a surface extends a very small distance above the surface. When a very sharp tip in practice, a needle which has been treated so that a single atom projects from its end is brought sufficiently close to such a surface, there is a strong interaction between the electron cloud on the surface and that of the tip atom, and an electric tunneling current flows when a small voltage is applied. The resulting tunneling current is a function of tip position, applied voltage, and the local density of states (LDOS) of the sample . At a separation of a few atomic diameters, the tunneling current rapidly increases as the distance between the tip and the surface decreases. The information is acquired by monitoring the current as the tip's position scanning across the surface, and is usually displayed in an image form showing surface topography or roughness of sample under observation in the form of colour contrast. All images produced by STM are black & white, with color optionally added in post processing in order to visually emphasize important features.

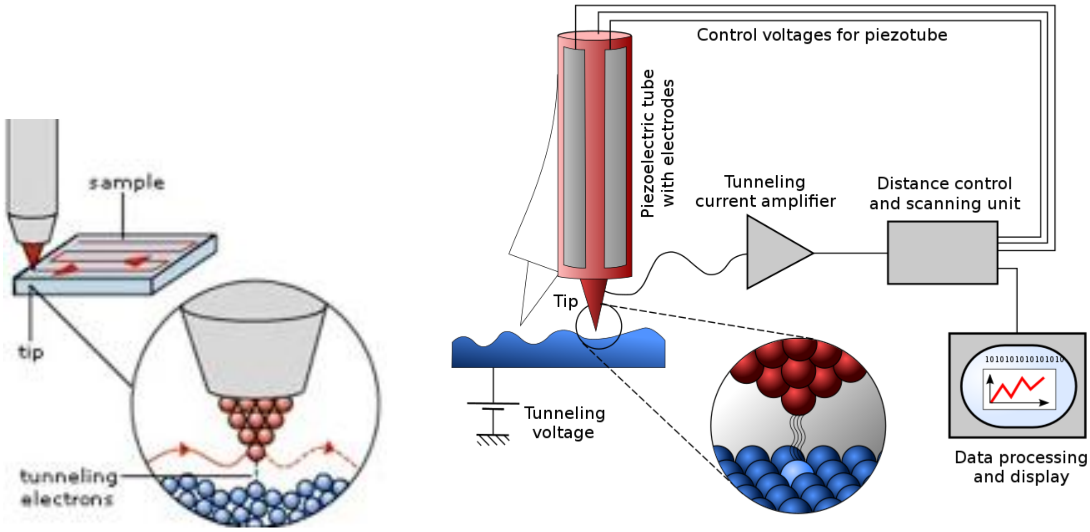

Fig. 4 (a) Schematic view Scanning Tunneling Microscope setup [By Michael Schmid and Grzegorz Pietrzak-Raster tunnel mikroskop-schema.svg]

Modes of operation of STM

Once tunneling is established, the tip's bias voltage and position with respect to the sample can be varied and data are obtained from the resulting changes in current. STM can be operated in two different modes called constant height mode and constant current mode as described below. Each of these modes has its own advantages and disadvantages.

I. Constant height (or variable current) mode of operation

If the tip is moved across the sample in the xy plane at a constant height Z, the changes in sample surface Z distance from tip due to roughness and hence density of states cause changes in tunneling current. These changes in tunneling current due to rough surface are mapped in images as a function of tip position in the form of colour contrast e.g in case of black & white images, bright white colour corresponds to bump (or something high on surface giving more tunneling current due to less distance from tip) and dark black colour shows trench (or something deep on the surface giving very less tunneling current due to large distance from tip). Other colours dark gray or light gray corresponds to intermediate cases for medium or low depth of rough surface respectively.

All images produced by STM are gray scale, with color optionally added in post processing in order to visually emphasize important features.

II. Constant current (or variable height) mode of operation

In constant current mode, feedback electronics adjust the height of tip from sample surface keeping tunneling current constant by applying a voltage to the piezoelectric height control mechanism. This means that when tip scans rough sample surface containing bumps or trenches, when tip reach above trench, the tunneling current decreases due to increase in tip sample distance, then feedback electronics systems automatically moves the tip down so close to trench bottom surface that tunneling current remains constant as we obtained at bump surface. This leads to a height variation of tip which can be directly measured from piezoelectric scanner Z movement as a function of tip position, giving us direct measure of surface roughness or topography.

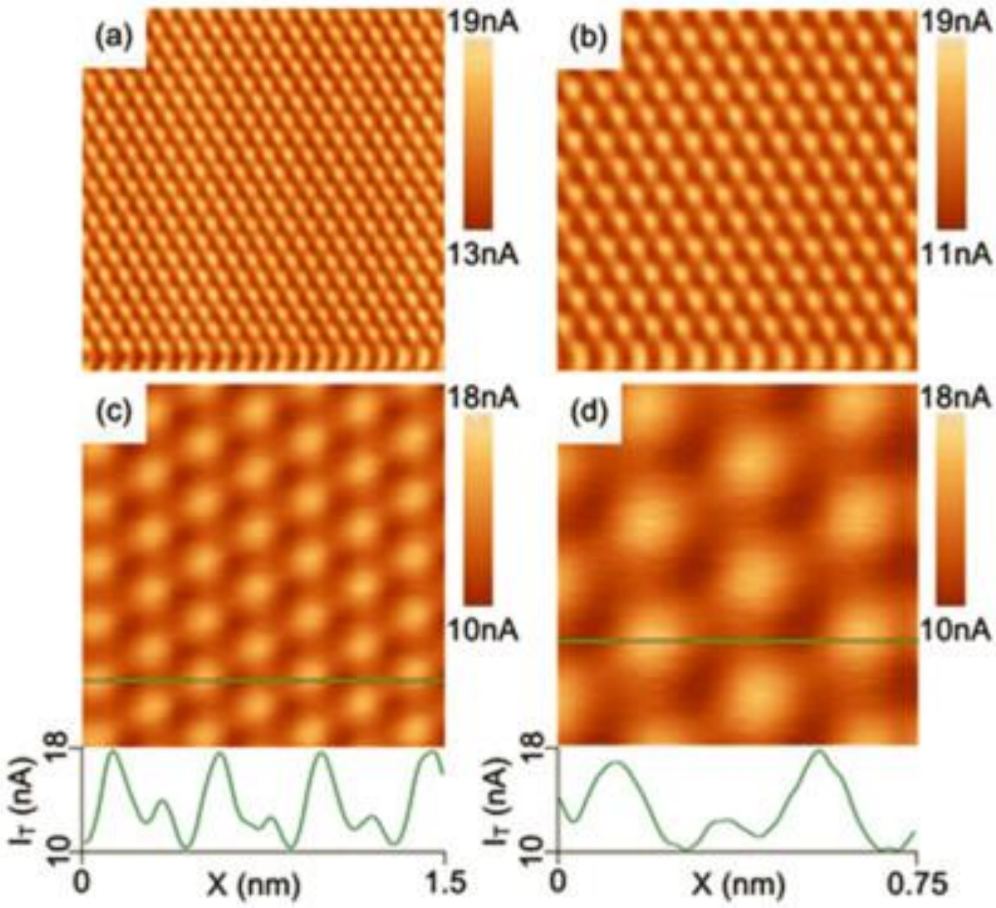

Fig. 4.2 (b) Atomic-resolution STM images (raw data) of graphite taken in ambient conditions. The scan range are: (a) 4.5 nm (b) 3 nm (c) 1.5 nm (d) 0.75 nm. [Ref: Chinese Journal of Chemical Physics, 2018, 31(5): 731-734]

Advantages & disadvantages of constant height mode over constant current mode

- ❖ One of main advantages of using a constant height mode is that it is faster, as the piezoelectric movements require more time to register the height change in constant current mode than, the current change in constant height mode.

- ❖ Another advantage is that, no feedback electronics sydtem is required to adjust the height of tip from sample, because height is fixed.

- The main drawback of constant height mode is that, it can’t image very rough surfaces, because tunneling current can be measured at just few nanometer height above sample surface, while in variable height mode, tip can be move down from few to few ten of nanometers to measure deep trenches or holes on surface.

Resolution

The resolution of an image is limited by the radius of curvature of the scanning tip of the STM. With ultra sharp tips containing single atoms at its end atomic resolution (< 1 nm) can be obtained. Additionally, image artifacts can occur if the tip is damaged at its end, and have more atoms rather than a single atom at its end. This leads to “double tip imaging,” a situation in which both tips contribute to the tunneling.

Therefore it has been essential to develop processes for consistently obtaining sharp, usable tips. Recently, carbon nanotubes have been used in this instance. The tip is often made of tungsten or platinum iridium, though gold is also used. Tungsten tips are usually made by electrochemical etching, and platinum iridium tips by mechanical shearing.

Vibration isolation

Due to the extreme sensitivity of tunnel current to height, proper vibration isolation or an extremely rigid STM body is imperative for obtaining usable results. In the first STM by Binnig and Rohrer, magnetic levitation was used to keep the STM free from vibrations; now mechanical spring or gas spring systems are often used.