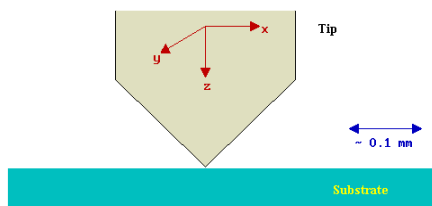


7.6: Scanning Probe Microscopy - STM and AFM

In the early 1980's two IBM scientists, Binnig & Rohrer, developed a new technique for studying surface structure - Scanning Tunneling Microscopy (STM). This invention was quickly followed by the development of a whole family of related techniques which, together with STM, may be classified in the general category of Scanning Probe Microscopy (SPM) techniques. Of these later techniques, the most important is Atomic Force Microscopy (AFM). The development of these techniques has without doubt been the most important event in the surface science field in recent times, and opened up many new areas of science and engineering at the atomic and molecular level.

Basic Principles of SPM Techniques

All of the techniques are based upon scanning a probe (typically called the *tip* in STM, since it literally is a sharp metallic tip) just above a surface whilst monitoring some interaction between the probe and the surface.



The interaction that is monitored in:

- **STM** - is the *tunnelling current* between a metallic tip and a conducting substrate which are in very close proximity but **not** actually in physical contact.
- **AFM** - is the van der Waals force between the tip and the surface; this may be either the short range repulsive force (in contact-mode) or the longer range attractive force (in non-contact mode).

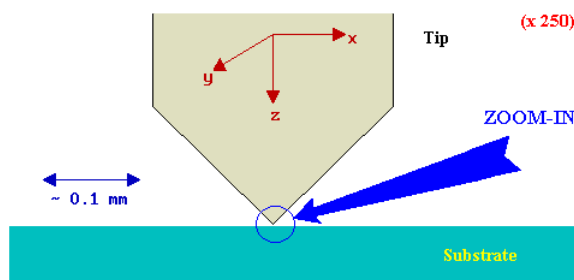
For the techniques to provide information on the surface structure at the atomic level (which is what they are capable of doing):

1. the position of the tip with respect to the surface must be very accurately controlled (to within about 0.1 \AA) by moving either the surface or the tip.
2. the tip must be very sharp - ideally terminating in just a single atom at its closest point of approach to the surface.

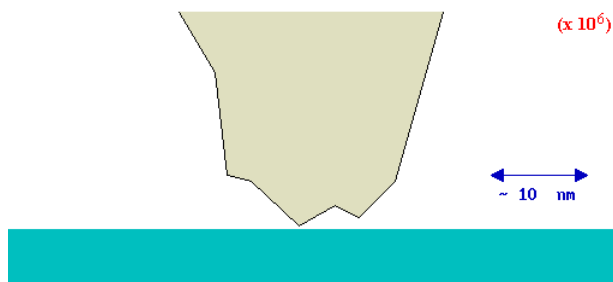
The attention paid to the first problem and the engineering solution to it is the difference between a good microscope and a not so good microscope - it need not worry us here, sufficient to say that it is possible to accurately control the relative positions of tip and surface by ensuring good vibrational isolation of the microscope and using sensitive piezoelectric positioning devices.

Tip preparation is a science in itself - having said that, it is largely serendipity which ensures that one atom on the tip is closer to the surface than all others.

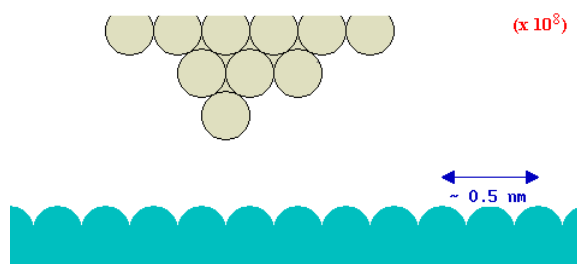
Let us look at the region where the tip approaches the surface in greater detail



... the end of the tip will almost invariably show a certain amount of structure, with a variety of crystal facets exposed ...



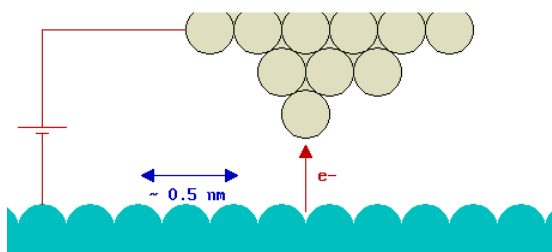
... and if we now go down to the atomic scale



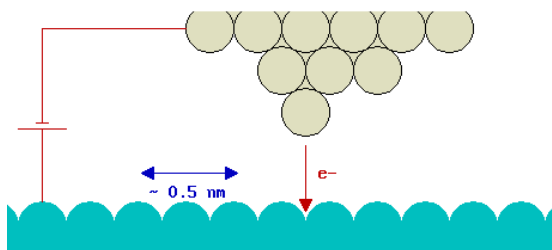
... there is a reasonable probability of ending up with a truly atomic tip.

If the tip is biased with respect to the surface by the application of a voltage between them then electrons can tunnel between the two, provided the separation of the tip and surface is sufficiently small - this gives rise to a *tunnelling current*.

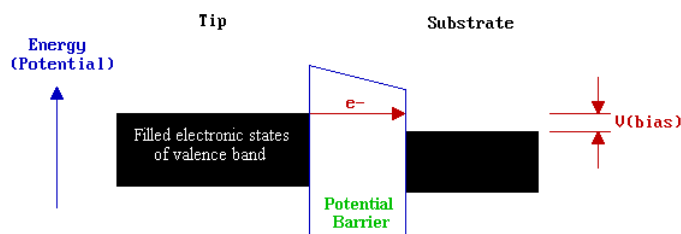
The direction of current flow is determined by the polarity of the bias.



If the sample is biased -ve with respect to the tip, then electrons will flow from the surface to the tip as shown above, whilst if the sample is biased +ve with respect to the tip, then electrons will flow from the tip to the surface as shown below.



The name of the technique arises from the quantum mechanical *tunnelling*-type mechanism by which the electrons can move between the tip and substrate. Quantum mechanical tunnelling permits particles to tunnel through a potential barrier which they could not surmount according to the classical laws of physics - in this case electrons are able to traverse the classically-forbidden region between the two solids as illustrated schematically on the energy diagram below.

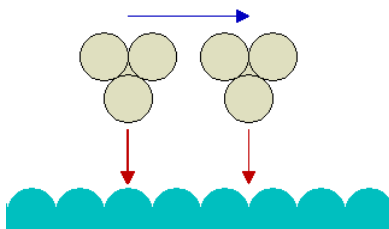


This is an over-simplistic model of the tunnelling that occurs in STM but it is a useful starting point for understanding how the technique works. In this model, the probability of tunnelling is exponentially-dependent upon the distance of separation between the tip and surface; the tunnelling current is therefore a very sensitive probe of this separation.

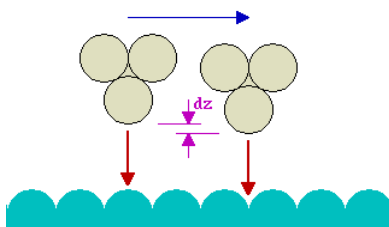
Imaging of the surface topology may then be carried out in one of two ways:

1. in constant height mode (in which the tunnelling current is monitored as the tip is scanned parallel to the surface)
2. in constant current mode (in which the tunnelling current is maintained constant as the tip is scanned across the surface)

If the tip is scanned at what is nominally a constant height above the surface, then there is actually a periodic variation in the separation distance between the tip and surface atoms. At one point the tip will be directly above a surface atom and the tunnelling current will be large whilst at other points the tip will be above hollow sites on the surface and the tunnelling current will be much smaller.



A plot of the tunnelling current i 's tip position therefore shows a periodic variation which matches that of the surface structure - hence it provides a direct "image" of the surface (and by the time the data has been processed it may even look like a real picture of the surface !).



In practice, however, **the normal way of imaging the surface is to maintain the tunnelling current constant whilst the tip is scanned across the surface**. This is achieved by adjusting the tip's height above the surface so that the tunnelling current does not vary with the lateral tip position. In this mode the tip will move slightly upwards as it passes over a surface atom, and conversely, slightly in towards the surface as it passes over a hollow.

The image is then formed by plotting the tip height (strictly, the voltage applied to the z-piezo) v 's the lateral tip position.

Summary

In summary, the development of the various scanning probe microscopy techniques has revolutionized the study of surface structure - atomic resolution images have been obtained not only on single crystal substrates in UHV but also on samples at atmospheric pressure and even under solution. Many problems still remain, however, and the interpretation of SPM data is not always as straightforward as it might at first seem. There is still very much a place for the more traditional surface structural techniques such as LEED.

This introduction to STM has concentrated on the non-invasive imaging applications of the technique, yet there is increasing interest in using such techniques as a tool for the actual modification of surfaces. At the moment this is still at the "gimmicky" stage, but the longer term implications of being able to manipulate surface structure and molecules at the atomic level have yet to be fully appreciated: we can but await the future with interest !

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