Microscopes for Science

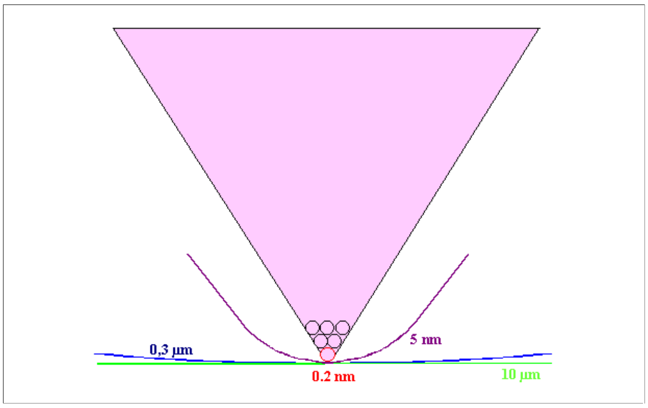
Science

4. Needle Scanning Microscopes

Principle and Scanning Tunneling Microscope

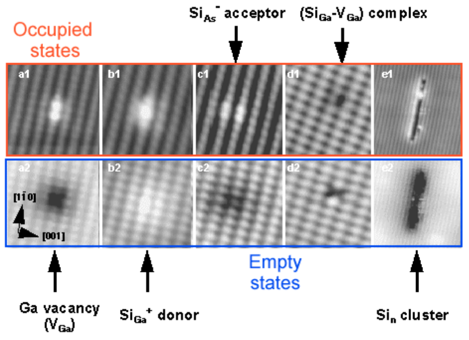
- Just about thirty years ago in 1981, **Gerd Binnig** and **Heinrich Rohrer** surprised all and sundry by introducing a new kind of microscope into science; the **scanning tunneling microscope** or ***STM***. Looking back, this might be seen as the starting point for nanoscience since the STM not only allowed to see "nano things" in a relatively simple and especially cheap way, but also to manipulate nano objects like atoms in an unprecedented way.
  - The Nobel prize was duly awarded in 1986. Since the Nobel prize committee had never honored the equally important invention of electron microscopes, they divided the prize. One half went to **Ernst Ruska**, the last survivor from early electron microscope times, and the other half to Binnig and Rohrer.
- So what is a STM? Nowadays it is just one example for what one calls "scanning probe microscopy" or, a bit vulgarly, "needle scanning microscopy", with the tacit understanding that the probe is a mechanical object, usually a "needle" with a sharp tip. If you would take an electron beam as the probe, you would have a common scanning electron microscope or SEM, which we don't count among the microscopes we discuss here.
  - Scanning a sharp tip across some object in order to get some information about its surface topography is not really new. Blind persons have been doing it for millennia when they probe some surface with their finger tips or are reading Braille. The probe is not all that sharp in this case, so let's look at an old-fashioned record player. A rather sharp sapphire or diamond needle scans across some "vinyl" disc that contains a certain pattern. The pattern is not made visible in this case but audible, and the scan does not proceed in a back-and forth kind but in a in a spiral pattern - but that are just an unimportant details.
    Moreover, long before (and after) 1981 the surface topography of silicon microchips was investigated by scanning a sharp needle across it, and so on.
    It is clear, of course, that all needle scanning microscopes operate in the basic mode "surface microscopy"
  - So what was new in Binnig's and Rohrer's Nobel-prize winning scanning tunneling microscope? Essentially three things:

    1. The needle scanned across the specimen is as sharp as it can be: the tip is just one atom. Scanning in all three space directions (*x*, *y*, *z*) is done with fraction-of nanometer precision and not impaired by vibrations or other mechanical "noise". In other words, compared to the methods mentioned above, the lengths scales are far smaller.
    2. The signal measured is an (extremely small) electrical current that flows from the sample to the needle as soon as the needle is "close enough", i.e. only fractions of nanometers off the sample surface atoms. On this scale the current is always a "**tunneling current**" that can only be understood with quantum theory. Now we know why it is called a scanning *tunneling* microscope.
    3. A closed-loop feed-back system always adjust the distance between the tip (atom) and the sample surface atoms in such a way that the tunnel current is constant. This involves moving the tip up or down by fractions of nanometers in the *z*-direction while the whole system is scanned in *x*- and *y*-direction. The picture generated is obtained by displaying the distance that the tip needs to move in *z*-direction. The picture thus gives a kind of image of the surface topology.
- Let's look at these three points a little bit closer. The figure below gives you an idea of what it means to make an atomically sharp tip. It is not all that easy but nowadays rather routine and I won't go into this.



Comparison of atomically sharp tip with other "sharp" things.

    - The red circle symbolizes an atom with a radius of curvature of about 0.2 nm. The outlines show different radii of curvature, typical (roughly) for: very sharp diamond coated surgical blades (5 nm); sharp knife (0.3 µm); tip of a diamond needle used for record players (10 µm). The latter is just a straight line on this scale.
- A much tougher requirement than making sharp needles is to keep the whole apparatus isolated from vibrations and mechanical shocks of all kinds. You know that stamping on the floor or banging the door might rattle the china in your kitchen cupboard. If similar things happen in your lab, chances are that just breathing while standing perfectly still would rattle a STM enough to wipe out its function.
    - Let's assume you solved those problems. Now you need to start scanning, and that implies to move your tip in all three space directions by defined small fractions of a nm. How are you going to do this? Certainly not by cranking some kind of spindle, or in any other mechanical way. You need to use *piezoelectric* or *electrostricitive* materials that change their dimensions ever so slightly if you expose them to an electrical field by applying some voltage. And no, I won't explain how "piezo" or "electrostrictive " works. Just take it for granted that we know what we are doing here.
- The "electrical" part, while not without challenges, is fairly simple. You need electronic components for measuring very small currents, keeping some current constant by adjusting the tip height via a feed back loop, and modules for displaying the results.
    - The tough question is: what, exactly, do I see? In other words: how does a tunneling current depend on what is going on at the surface? The answer to this rather tricky question involves a lot of quantum theory and I won't go into that. If you don't care about details, the answer is that you see more or less the surface topography - provided your specimen has a well defined surface and is an electrical conductor. The latter condition is clear: you cannot run a current, however small, through an insulator. So let's take a copper sample? Yes - but you are still not going to see the copper atoms in a nice crystalline arrangement because copper, like pretty much everything else, is always covered by some amorphous oxide - and that is not what you want to see.
    - Alright, so we put our copper (Cu) sample in an ultra-high vacuum vessel, take off the oxide (I leave open how that is done) and now scan our needle across that clean surface. That will work - but now we are no longer talking about "cheap and simple" microscopy.
- If you can cough up the cash (> 1 Mio €) to buy a state-of-the-art STM with an ultra-high vacuum environment and so on, you now can do surface microscopy with atomic resolution in all kinds of special modes. Who says that you always need to keep the the current constant? How about the voltage? With both kinds of polarity and all kinds of values?
    - You have now many options to produce pictures. The questions is, as always in high resolution microscopy, what does the picture show? Here are a few examples



Gallium arsenide (GaAs) crystal imaged with different STM modes.

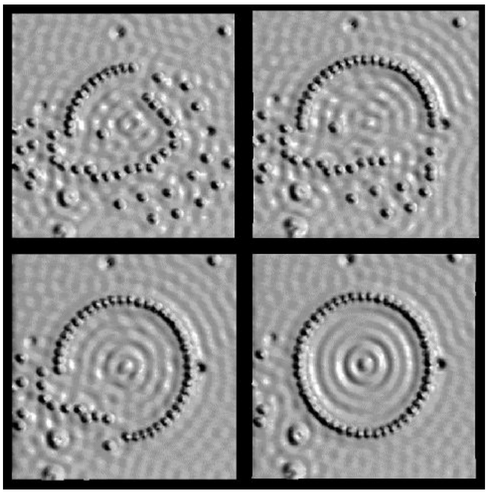
Source: KFA Jülich. Germany; Prof. Knut Urban's group. With friendly pemission from Knut (who kept me in line when I was a Ph.D studnt).

    - What one can see is the electronic behavior of silicon (Si) point defects (substitutional foreign atoms in this case) in a GaAs host crystal. In other words, you do not so much see the silicon *atom* that replaced a gallium or arsenic atom and so on, but if it lost ("empty states") or captured ("occupied states") an electron.
    - What that tells us is that STM is a powerful tool for investigating surface-related details of conducting (or semiconducting) samples, provided it is operated by experts who can interpret the images obtained.
- But we still can't look at non-conducting samples. It's time to invent the:

Atomic Force Microscope

How about letting the atom that forms the tip of your needle just touch the sample surface and register its up-and-down movements? In other words, just extending the good old "reading Braille" concept to atomic dimensions? Well - yes, it is done but there might be problems. The tip atom might simply bond to the surface atoms. Some atoms of your finger tip will also bond to atoms of the substrate you are touching, but most will not because both surfaces are quite rough. It thus takes very little effort per area increment to disengage again, in contrast to our sharp needle tip.

The bonding effect allows you to pick up some relatively loose atoms from the surface and to transport them to another place, effectively enabling "writing by atoms" as shown in the backbone figure. here is another extremely famous picture that shows how it is done:



How a "quantum corral" is made

Source: Image originally created by IBM Corporation.

First you distribute some iron atoms (the dark spheres) on an atomically flat copper (Cu) surface. Then you pick one up with the tip of your STM and place it where you want it to be. Picking up and releasing can be manipulated by changing conditions like voltage and current. Eventually you produce a circular "corral" with walls of iron atoms that contains a single electron. The wavy pattern inside the corral *is* the electron - demonstrating directly why "wave functions" are central to quantum theory.

The long and short of this is that the "contact mode" might not work in many cases. Then we do the following:

- The cantilever holding the sharp needle is made to vibrate up and down ever so slightly with a fixed frequency, just a bit above its resonance frequency.
- Some feed-back loop keeps this frequency (or the oscillation amplitude) constant while the needle is lowered and records what it takes to do that.
- The "effort" to keep the vibrations constant is recorded and displayed.

Why does this give an image of the sample surface? Because as soon as your tip gets close enough to the surface, forces between the tip atom and the sample atoms are felt and those forces always tend to change the vibration frequency. This effect is measurable long before the tip atom actually "touches" the surface atoms. As a new feature, you can do that even "under water", i.e. you can look at surfaces submerged in some liquid.

Let's stop here. There are many more kinds or variations of the "scanning probe microscopy" topic, and many more are sure to come in the near future.