Scanning Tunneling Microscopy

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I. INTRODUCTION

As science ventures deeper into the realm of the microscopic, probing, measuring, and even constructing at increasingly smaller scales, it must seek out a means of observing that is suitable to the desired scale and resolution. In the late 17th century, the journey into this realm began with the development of the optical microscope and the resulting observation of single cells and bacteria.[1]. However, the observation of single atoms requires far more resolution than visible light can provide, because the average wavelength of visible light is about 2,000 times greater than the diameter of a typical atom.[1] In answer to this problem, the electron microscope was developed. Utilizing the wave-like properties of the electron, an electron microscope can use electrons with wavelengths comparable to the diameter of an atom to resolve individual bulk atoms and study them in greater detail. A study of surface features at the atomic level requires a more sensitive probe still, due to the fact that high-energy electrons will penetrate into the bulk without providing surface information, and low-energy electrons are often scattered by the sample. The development of the scanning tunneling microscope (STM) by Gerd Binnig and Heinrich Rohrer in 1982[2] provided the necessary next step in imaging techniques and created a new kind of device that can be used as a tool for both observation and alteration.

II. SCIENCE OF SCANNING TUNNELING MICROSCOPY

As its name suggests, the scanning tunneling microscope takes advantage of the quantum mechanical phenomenon of tunneling. As shown in figure 1, when an electron approaches a potential barrier higher than the electron's energy, the electron is not completely reflected as one would expect classically, but rather the electron's wavefunction exponentially decays as it goes through the barrier. With a sufficiently thin barrier, there is a small but non-negligible probability that the electron can be found on the other side of the barrier. Now, for the case of scanning tunneling microscopy, consider the scenario depicted in figure 2, consisting of two conducting electrodes separated by a small insulating gap (in this case, vacuum). Due to quantum tunnelling, the wavefunctions of electrons within the two conductors can "leak out" to a small degree. In essence, the electron probability cloud of each conductor extends slightly outside the conductor itself. When the gap is small enough, the two electron clouds can overlap, and a small voltage difference applied to the electrodes can cause a current as the electrons tunnel from one electrode to the other through the overlapping electron cloud, as in figure 3.

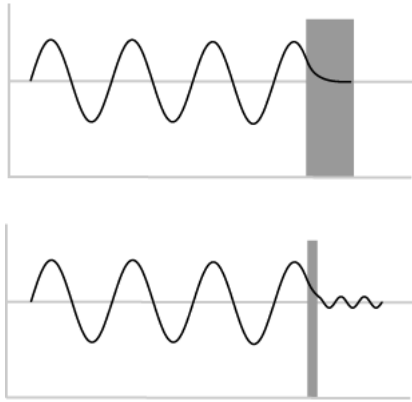

FIG. 1: An electron encounters a potential barrier higher than its energy. The electron wavefunction exponentially decays within the barrier, but for sufficiently thin barriers, there is a probability of finding the electron on the other side. [3]

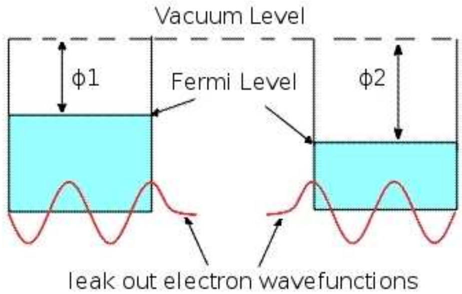

FIG. 2: Two conducting electrodes separated by an insulating vacuum gap. The electron wavefunctions from each electrode "leak out" a small distance beyond the electrodes. [4]

In practice, the two electrodes consist of the sample to be studied and the fine tip of the STM, as shown in figure 4. The tunneling current J_T in such a situation with a plannar tunnel energy barrier of average height ϕ and width s is given by

$$J_T \propto \exp(-A\phi^{1/2}s)$$

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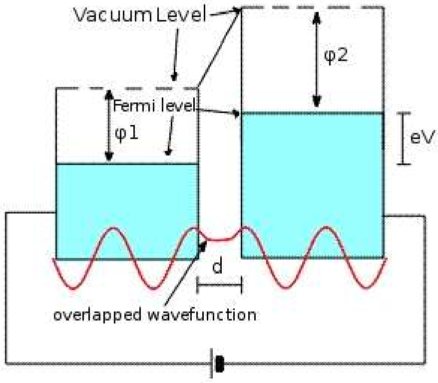

FIG. 3: With a sufficiently thin gap and an applied potential difference, a tunneling current can form between the electrodes due to the overlapping electron wavefunctions. [4]

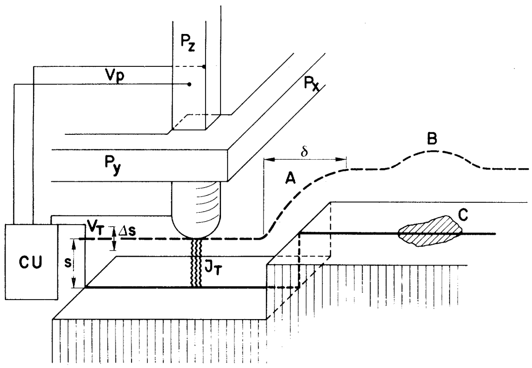

FIG. 4: Principle of operation of the scanning tunneling microscope. (Schematic: distances and sizes are not to scale.) The piezodrives P_x and P_y scan the metal tip M over the surface. The control unit (CU) applies the appropriate voltage V_p to the piezodrive P_z for constant current J_T at constant tunnel voltage V_T. For constant work function, the voltages applied to the piezodrives P_x, P_y, and P_z yield the topography of the surface directly, whereas modulatoin of the tunnel distance s by Δs gives a measure of the work function as explained in the text. The broken line indicates the z displacement in a y scan at (A) a surface step and (B) a contamination spot, C, with lower work function.[2]

where, in vacuum, $A = (4\pi/h)2m)^{1/2} = 1.025\text{Å}^{-1}$ eV$^{-1/2}$, with m the free-electron mass.[2] This tunneling current is extremely sensitive to the distance between the tip and the sample. In fact, with barrier heights (i.e. work functions) of a few eV, a change in the distance by an amount equal to the diameter of a single atom (2-5 Å) causes the tunneling current to change by up to 3 orders of magnitude[2]. As shown in figure 4, a piezoelectric drive consisting of arms Px, Py, and Pz serves to move the tip over the sample. Px and Py scan the tip over the sample while Pz controls the vertical height between the tip and sample surface. Depending on the mode of oper-

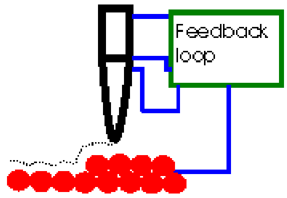

FIG. 5: STM in constant current mode. A feedback loop is applied to the tip to adjust the tip's vertical position in such a way that the tunneling current remains constant. The tunnel current is proportional to the local density of states, and therefore the tip follows a contour of a constant density of states. The vertical position of the tip is recorded during scanning to produce a kind of topograpic image.[6]

ation, a feedback current can be applied to Pz in order to maintain a constant tunneling current by keeping the tip at a constant height relative to surface. With this constant current method, a topographical map of a surface can be obtained. However, while this procedure will yield purely topographical information when used on an electronically homogeneous surface, when this STM method is applied to a electronically inhomogeneous surface, the tunneling current will depend on both surface topography and the local electronic structure.[5] For example, if the effective local tunneling barrier height increases or decreases at a scan site, then the feedback system must decrease or increase the tip-sample separation in order to maintain a constant tunneling current. Therefore the final image obtained will contain electronic structure information folded in with the topographical information.

III. MODES OF OPERATION

Fortunately, there are multiple modes in which an STM probe can operate that can help to disentangle the topographical and electronic information available in a scan. Constant current mode, in which an electrical feedback loop is applied to the tip to maintain a constant tunneling current, has already been explained and is illustrated in figure 5. Constant height mode (figure 6) is similar in purpose to constant current mode, but in this mode the tip is scanned over the surface while held at an absolute constant height above it. The changing tunneling current as a function of tip position conveys the same information as obtained in constant current mode. Constant height mode proves a faster scanning rate than constant current mode, but, as it increases the risk of crashing the tip into the sample, it is generally only used on atomically smooth, flat surfaces.

In the case of the aforementioned electronically inhomogeneous sample, barrier height imaging mode (figure 7) can be used to measure the varying work function (tunneling barrier height) over the sample. In this mode, the tip is scanned over each measurement site, and the distance between the tip and the sample is varied while

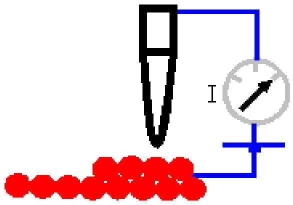

FIG. 6: STM in constant height mode. In this mode the vertical position of the tip remains constant, and the current as a function of lateral position represents the surface image. This mode is only appropriate for atomically flat surfaces as otherwise a tip crash would be inevitable. One of its advantages is that it can be used at higher scanning frequencies than constant current mode. [6]

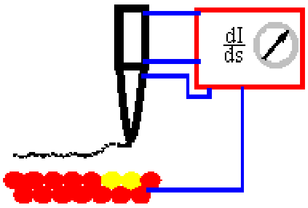

FIG. 7: STM in barrier height imaging mode. The tip-sample distance is varied at each scan site while recording the rate of tunnel current change with respect to the separation distance. [6]

recording dI/ds, the rate of tunnel current change with respect to tip-sample distance. From this information the work function at each location, and hence the sample's electronic makeup, can be determined.

IV. APPLICATIONS OF STM

The ability of STM techniques to obtain accurate topographical information at the nanoscale level makes the scanning tunneling microscope an extremely valuable tool across multiple disciplines in the physical sciences. One of the first major successes of scanning tunneling microscopy was the 7×7 reconstruction of the Si(111) surface in real space in 1982[7]. Due to the complexity of the unit cell, which contains 49 atoms, scientists had had great difficulty in unambiguously determining its surface structure, and no model had yet been able to reconcile all of the available experimental data. Using the new approach of scanning tunneling microscopy, G. Binnig et. al. produced the first images of the 7×7 unit cell, shown in figures 8 and 9 From this image, the group produced a new, more accurate model of the surface configuration, as shown in figure 10.

STM techniques have been applied to many other investigations across many disciplines, including the imaging of biological structures. In 1990, Robert J. Driscol et. al. published a paper in which a scanning tunnelling microscope was used to directly image a strand of DNA.[8] In the images from that paper, one of which is reproduced in figure 11, one can clearly see the helical turns of the DNA structure.

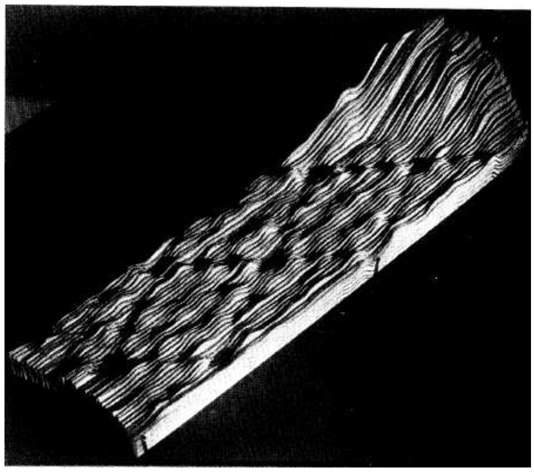

FIG. 8: Relief of two complete 7×7 unit cells, with nine minima and twelve maxima each, taken at 300 ℃. Heights are enhanced by 55%; the hill at the right grows to a maximal height of 15 Å. The $[\bar{2}11]$ direction points from the right to left, along the long diagonal. [7]

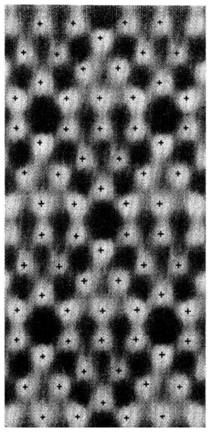

FIG. 9: Top view of the relief shown in Fig 8 (the hill at the right not included) clearly exhibiting the sixfold rotational symmetry of the maxima around the rhombohedron corners. Brightness is a measure of the altitude, but is not to scale. The crosses indicate adatom positions of the modified adatom model (see Fig 10).[6]

V. COMPARISON OF STM WITH OTHER MICROSCOPE TECHNIQUES

As the last section demonstrated, scanning tunneling microscopy has applications in a wide range of disciplines dealing with surface science. Among possible probing methods, scanning tunneling microscopy holds a number of unique advantages such as the following [9]:

1. It gives 3-D images of surfaces direct in real space

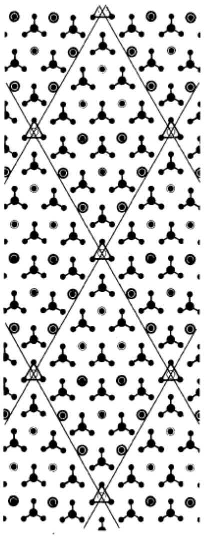

FIG. 10: Modified 7 × 7 Si(111) adatom model. The underlying top-layer atom positions are shown by dots, and the rest atoms with unsatisfied dangling bonds carry circles, whose thickness indicates the depth measured as discussed in the text. The adatoms are represented by large dots with corresponding bonding arms. The empty potential adatom position is indicated by an empty circle in the triangle of adjacent rest atoms. The grid indicates the 7 × 7 unit cells [7]

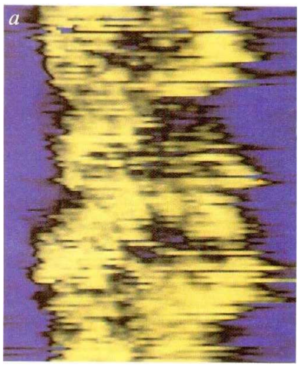

FIG. 11: Unsmoothed, unfiltered plane-subtracted DNA image from Driscol et. al. The image scale is 35 Å× 55 Å. Yellow indicates topographical maxima. [8]

and on an atomic scale in *all three* dimensions.

2. It employs only bound particles and no lenses (the only other real-space, lens-less method is field ion microscopy, FIM).
3. It is nondestructive. Electron energies and electric fields on the surface lie in the mV and 10^4 V/cm range, respectively (typical values, but, in principle, there are no difficulties in going to considerably lower eneries and fields and, if desired, also to higher ones).
4. It is a structural *and* chemical method, applicable to both periodic and nonperiodic surface features.
5. It can also be operated.at ambient pressure (with some loss in resolution) and in liquids.

In addition, compared to other methods of imaging, STM can acheive a wide range of both lateral and vertical scale as shown in figure 12. However, the requirement that the STM tip must always follow the surface within the tunneling distance sets a limit on the speed of this imaging technique. STM remains one of the best tools available to image surface phenomena and structure, and, as figure 12 shows, provides an excellent and versatle alternative and complement to other imaging techniqes.

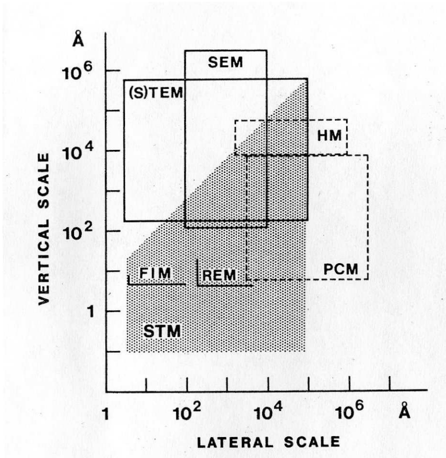

FIG. 12: Comparison of resolutions of different microscopes. STM: shaded area. HM: high-resolution optical microscope, PCM: phase-contrast microscope, (S)TEM: (scanning) transmission electron microscope, SEM: scanning electron, REM: reflection electron microscope, and FIM: field ion microscope.[10]

VI. ATOMIC MANIPULATION USING STM

In addition to the benefits that scanning tunneling microscopy offers for high resolution imaging, a scanning tunneling microscope can also be used for atomic or molecular manipulation. During imaging, tip-sample interactions can potentially alter the sample in undesirable ways, but those same interactions can be controlled to move atoms on the surface in order to fabricate nanostructures. Specifically, the three parameters that can be used to acheive this manipulation are the electric field between the tip and the substrate, the tunneling current, and the forces between the tip and the surface.[11]. Additionally, a distinction is made between the two modes of manipulation: lateral mode, in which the stm tip pushes, pulls, or slides a particle along the surface while maintaining particle-surface contact (see figure 13, and vertical mode, in which the tip picks the particle up from the surface and places back at a different location (see figure 14.

The first example of lateral mode manipulation was demonstrated by D. M. Eigler and E. K. Scheizer in 1990

FIG. 13: STM performing lateral mode manipulation [12]

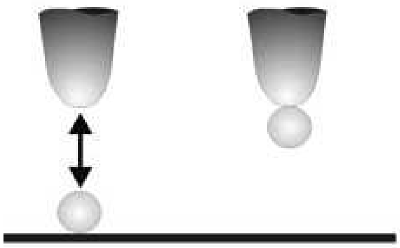

FIG. 14: STM performing vertical mode manipulation [12]

by writing the "IBM" company logo with Xe atoms on a Ni(110) surface (see figure 15)[14], and the first example of vertical mode manipulation was demonstrated by D. M. Eigler, C. P. Lutz, and W. E. Rudge in 1991 with the realization of an atomic switch using a xenon atom moved between an STM tip and a nickel surface.[13]

The ability to manipulate as well as measure on the atomic level marks the scanning tunneling microscope as a tool of great versatility and importance in the growing field of nanoscience.

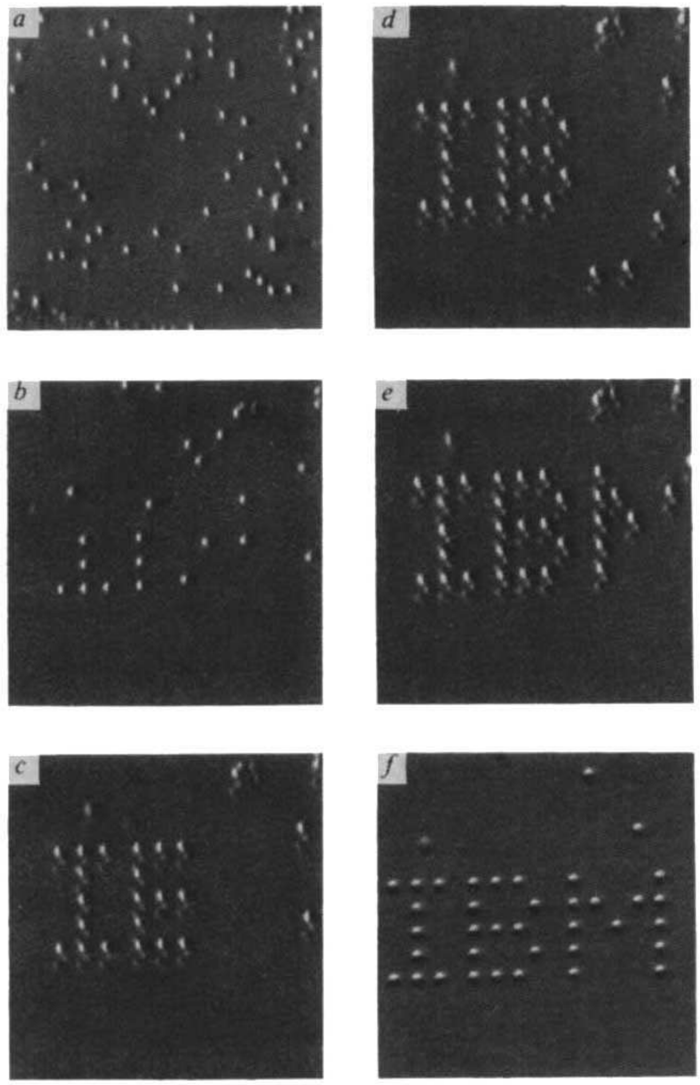

FIG. 15: A sequence of STM images taken during the construction of a patterned array of xenon atoms on a nickel (110) surface. Grey scale is assigned according to he slope of the surface. The atomic structure of the nickel surface is not resolved. The $(1\bar{1}0)$ direction runs vertically. a) The surface after xenon dosing. b-f) Various stages during the construction. Each letter is 50 Åfrom top to bottom. [14]

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