Scanning Tunneling Microscopy

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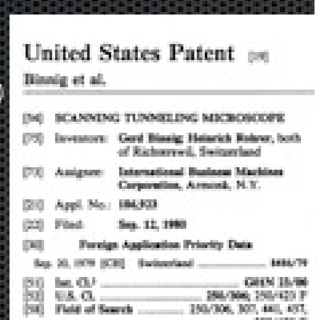
Condensed Matter II, Spring, 2010, Lecturer: Elbio Dagotto

History of the STM

Developed by Gerd Binnig and Heinrich Rohrer at IBM in Zurich

- STM patent filed in 1980
- Vacuum Tunneling demonstrated in 1981
- STM demonstrated in 1982
- Surface Reconstruction of Si published in 1983



United States Patent

Binnig et al.

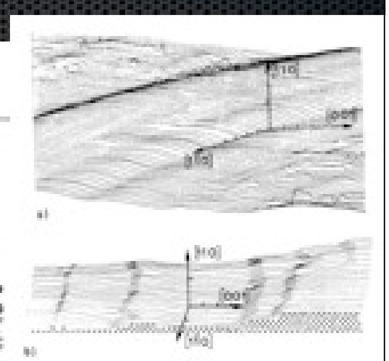
SCANNING TUNNELING MICROSCOPE

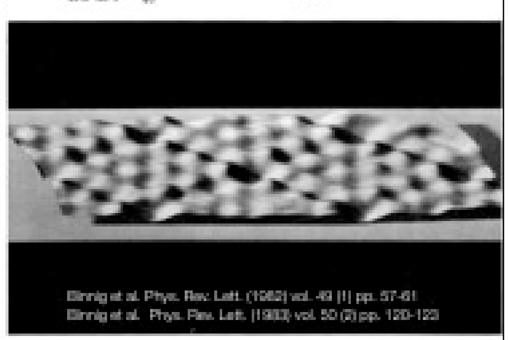
Inventors: Gerd Binnig; Heinrich Rohrer, both of Richterswil, Switzerland

Assignee: International Business Machines Corporation, Armonk, N.Y.

Filed: Sep. 12, 1980

Foreign Application Priority Data





Nobel Prize awarded to Binnig and Rohrer in 1986

New class of instrument

- Development of STM opened door to development of "local probe" class of instruments, in a field collectively known as "Scanning Probe Microscopy".
- Probes that are small enough to interact with material directly.
- STM was the first in a large development effort that brought about AFM, MFM, SPSM, and many others...

Physics of the STM

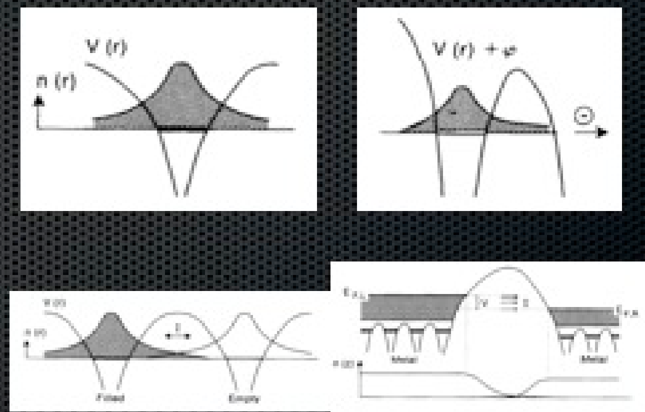
- The probe size, distance from object under study, and the decay rate of interaction between probe and material determine the resolution of a local probe.
  - At short (~1.5Å) sample-probe distances, the interaction is strongly repulsive.
  - At long (~10Å) sample-probe distances, the interaction is attractive.
  - At some equilibrium position, the net force between the sample and tip is zero.
  - At this equilibrium position the resolution of the probe interacting with the sample in an exponentially decaying manner is found:

$$resolution \propto \sqrt{(size\ of\ probe + dist\ from\ surface)(decay\ length)}$$

- For atomic scale resolution, all of these quantities are of atomic size.

Physics of the STM

- In STM, the interaction is the wave function overlap of empty and filled electronic states between sample and tip.
- Wave function overlap probabilistically allows electrons to move from one state to the other.
- A potential difference can create the tunneling current as electrons move toward acceptor states in the material with the lower fermi energy.

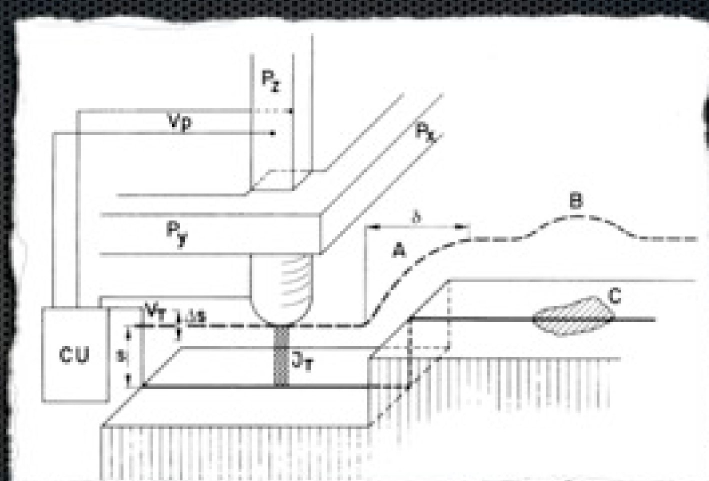


Binnig and Rohrer, Rev. Mod. Phys. vol. 71 (2) pp. S324-S330 (1999)

Operation of the STM

Binnig et al. Phys. Rev. Lett. (1982) vol. 49 (1) pp. 57-61

- A scanning tip is fabricated, down to a size of as single atom across at the very end.
- The tip is mounted on a series of piezoelectric drives in the x, y, z directions.
- As the tip is brought close the sample, the electron wave functions of the tip and sample overlap.
- Applying a bias voltage between the tip and the sample generates the tunneling current.



$$J_T \approx g(V)\exp(-A\psi^{1/2}s);\ A = \sqrt{\frac{8m\pi}{h}}$$

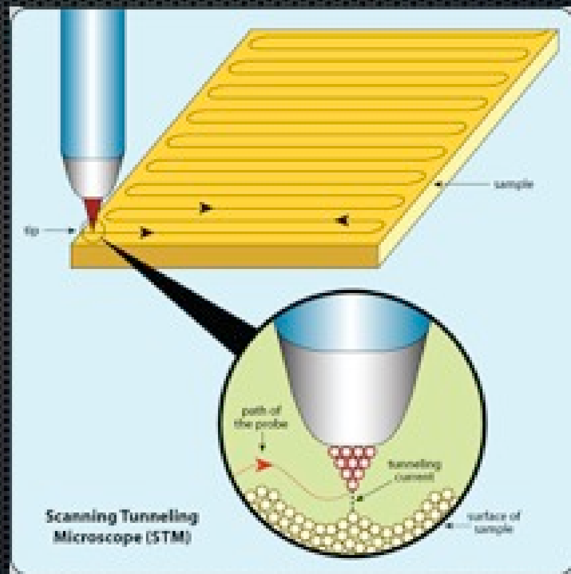
ψ = *height of potential barrier* (eV)

s = *width of potential barrier* (nm)

$g(V)$ = *density of states*

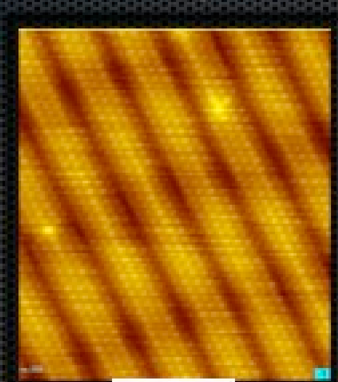
Operation of the STM

- Sawtooth voltage is applied along the x direction, and a voltage ramp along the y direction, to generate a scan of the xy plane.
- Piezo drive in the z direction responds to voltage feedback to reposition the tip as the scan goes on, automatically adjusting the height of the tip above the sample.
- The feedback from this z piezo is the recorded information of the experiment.



Output of STM Experiment

- Experiment feedback is associated with material properties, often the local density of states, or surface topography.
- With properly tuned equipment, both plots are gathered at the same time.
- Time resolved studies can capture changes in surface over time.
- STM is blind to material that has no electronic density of states at the Fermi level - *blind to insulators.*



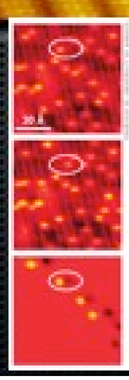


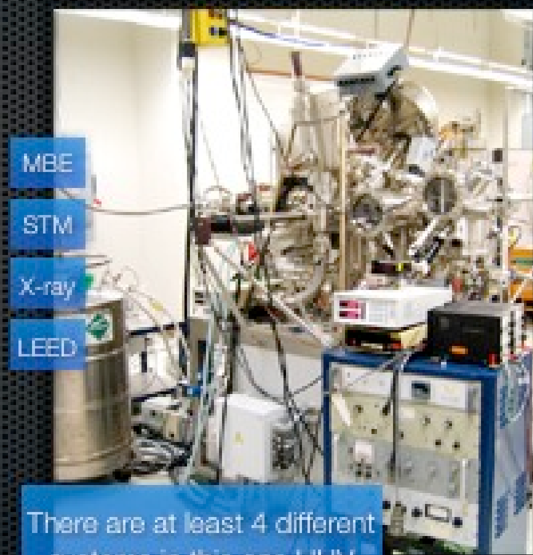
Image credits:
Binnig and Rohrer. Rev. Mod. Phys. vol. 71 (2) pp. S324-S330 (1999)

Prof. Dr. Richard Berndt , AG Raster-Tunnelmikroskopie , Institut für Exp. und Ang. Physik der Universität Kiel

Schaub et al. Science (2003) vol. 299 (5605) pp. 377-379

Laboratory Construction

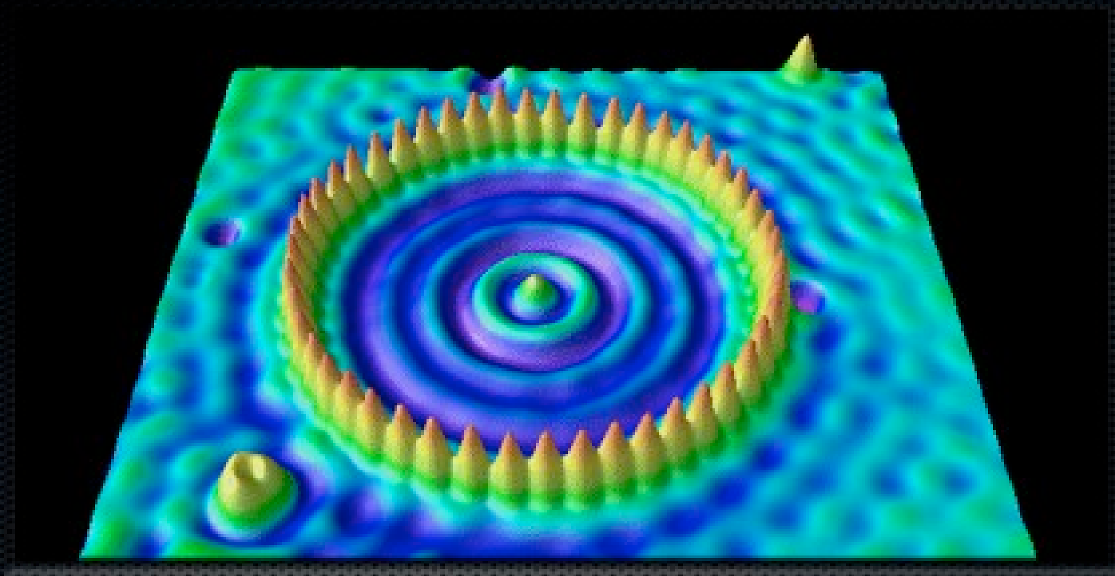
- Because of the importance of the high vacuum environment, complementary devices requiring UHV are commonly found together.
- Can find MBE, LEED, Xray, ARPES equipment along with STM setup.



There are at least 4 different systems in this one UHV unit in the Weitering Lab.

Experimental Considerations

- Surface and vacuum environment must be as clean as possible
  - Avoid contamination of images.
  - Avoid surface impurities.
- The high vacuum environment is crucial (of order 10^{-11} torr)
- Vibrational isolation essential.
- Scan times depend on resolution of desired image.
  - Rough scans can be completed in a few minutes
  - Detailed scans take many hours, and are done from many perspectives.
- Low temperatures available, but provide unique concerns for vacuum systems.
- STM tip must be only a few atoms wide for best resolution (ideally only a single atom across!), and long narrow tips are easily excited thermally.

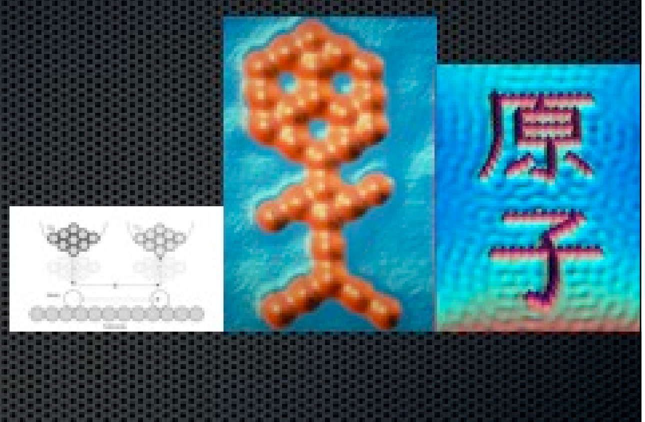


Applications of STM

The Corral Reef: [illegible] STM Image Gallery (2010)

Nanofabrication

- The tip of the STM exerts a finite force on an atom on a surface.
  - Force recently measured with AFM and STM as dependent on the surface and atom, but in the range of 10's to 100's of picoNewtons.
- By tweaking this force, it is possible to move (pushing or pulling) an atom along a surface to a different location with atomic scale precision.
- Opens huge avenues into nanofabrication and device miniaturization.



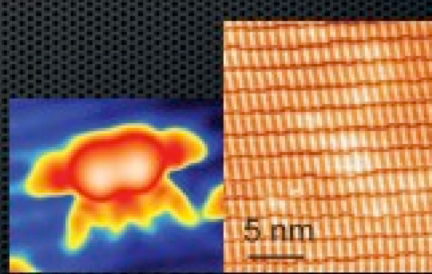
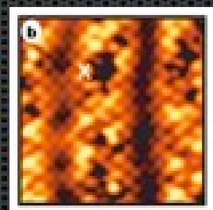
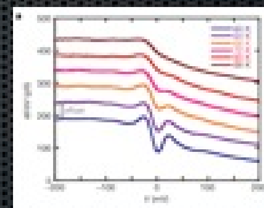


Image credits:
- [illegible] STM Image Gallery (2010)
- Kitchen et al. Nature (2006) vol. 442 (7101) pp. 436
- Snijders et al. Phys. Rev. Lett. (2007) vol. 99 (11) pp. 116102

Modern Experiments -
Pairing Pockets in Superconductors

- Modified STM equipment
  - **In addition to STM capabilities, beam is capable of breaking apart electron pairs if it is energetic enough.**
  - **By varying the energy of the electron beam, able to determine whether Cooper pairs had formed in a given spot within the material.**





Visualizing pair formation on the atomic scale in the high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$

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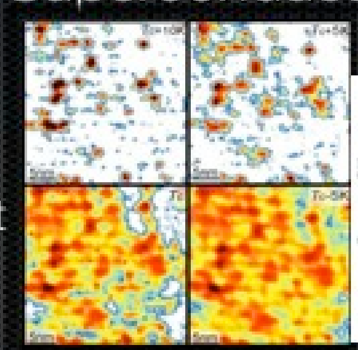
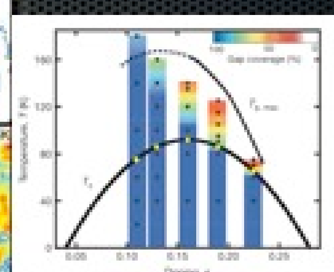
Modern Experiments -
Pairing Pockets in Superconductors





- Found that pockets of superconductivity exist well above the superconducting critical temperature.
- Potential avenue to improve High-Tc materials.

Visualizing pair formation on the atomic scale in the high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$

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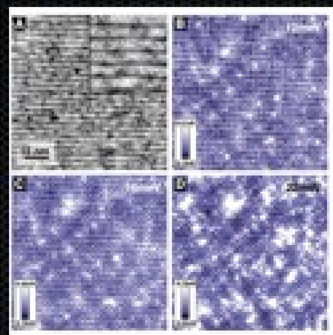
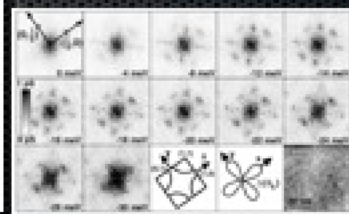
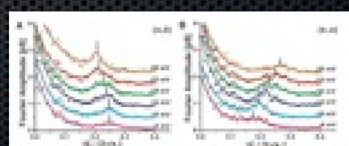
Modern Experiments -

Quasiparticles in Superconductors

- Local Density of States measurements Fourier transformed to produce dispersion maps.
- Shows evolution of scattering vectors as a function of energy, and that dispersion of quasiparticles is faster along one direction in k-space than the other.







Imaging Quasiparticle Interference in $Bi_2Sr_2CaCu_2O_{8+\delta}$

16 AUGUST 2002 VOL 297 SCIENCE www.sciencemag.org

STM availablity near UTK

- Laboratory of Dr. Weitering has STM setup as seen before.
- Also has AFM, MBE, LEED, X-ray, and ARPES (in collaboration with Dr. Mannella).

Hard superconductivity of a soft metal in the quantum regime. Nature Physics, **2**(3), 173 (2006)

STM availablity near UTK

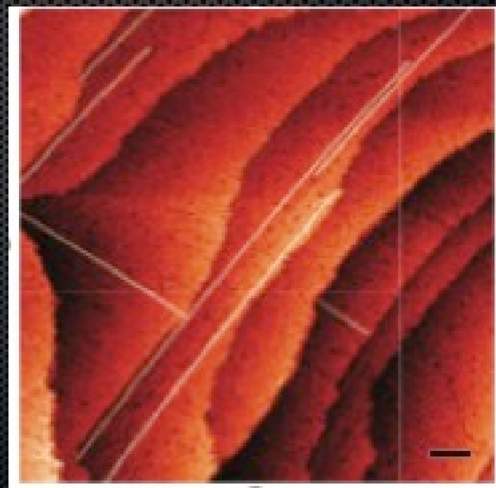
Center for Nanophase Materials Sciences

A Highly Collaborative and Multidisciplinary

U.S. DOE Nanoscale Science Research Center

OAK RIDGE National Laboratory

- CNMS at Oak Ridge National Laboratory
- Full Suite of SPS instruments, including STM, AFM, STS, MBE, and more.
- Most equipment operates at variable conditions.
- Operates on peer-reviewed proposal system.



Charge-order fluctuations in one-dimensional silicides. Nature Materials, **7**, 539 (2008)

References

- Binnig et al. Phys. Rev. Lett. (1982) vol. 49 (1) pp. 57-61
- Binnig et al. Phys. Rev. Lett. (1983) vol. 50 (2) pp. 120-123
- Binnig et al. Appl. Phys. Lett. (1981) vol. 40 pp. 178
- Binnig and Rohrer. (1999) vol. 71 (2) pp. S324-S330
- Chen. Introduction to Scanning Tunneling Microscopy. (2008) pp. 1-26
- Eigler and al. STM Image Gallery - Atomilism. http://www.almaden.ibm.com/vis/stm/gallery.html STM Image Gallery (2010)
- Eigler and Schweizer. Nature (1990) vol. 344 (6266) pp. 524
- Gomes et al. Nature (2007) vol. 447
- Hoffman et al. Science (2002) vol. 297 pp. 1148-1151
- Jenkins et al. Phys. Rev. Lett. (2009) vol. 103 pp. 227001
- Kitchen et al. Nature (2006) vol. 442 (7101) pp. 436
- Ozer et al. Nature Physics (2006) vol. 2 (3) pp. 173
- Schaub et al. Science (2003) vol. 299 (5605) pp. 377-379
- Snijders et al. Phys. Rev. Lett. (2007) vol. 99 (11) pp. 116102
- Yazdani, et. al. J. Phys.: Condens. Matter (2009) vol. 21 (16) pp. 164214
- Zeng et al. Nat Mater (2008) vol. 7 (7) pp. 539
- http://www.uni-muenster.de/Physik.PI/Zach/deutsch/dfg/dfg_en.htm

Local Resources

- Weitering Lab: http://www.phys.utk.edu/weitering/
- CNMS: http://www.cnms.ornl.gov/
  - Deadline for proposals is March 3!
  - CNMS user group: http://www.cnms.ornl.gov/uec/about_cnmsug.shtm