672 Advanced Solid State Physics

Scanning Tunneling Microscopy

Biao Hu

Outline:

1. Introduction to STM
2. STM principle & working modes
3. STM application & extension
4. STM in our group

1. Introduction to STM

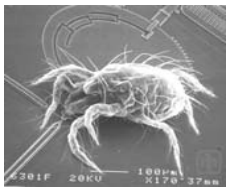
I. Invented by G.Binnig & H.Rohrer in 1982

II. Richard Feynman’s address: “There’s Plenty of Room at the Bottom” at Caltech in 1959

The Scale of Things

Office of Basic Energy Sciences

Things Natural

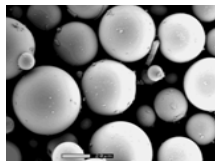


Dust mite

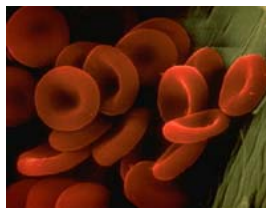
200 μm

Ant
~ 5 mm

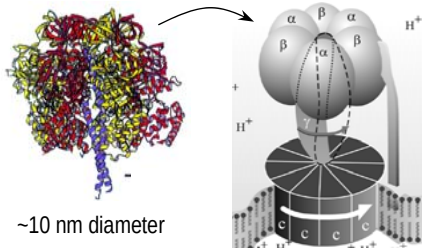
Human hair
~ 60-120 μm wide



Fly ash
~ 10-20 μm



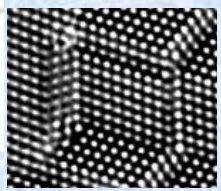
Red blood cells
(~7-8 μm)



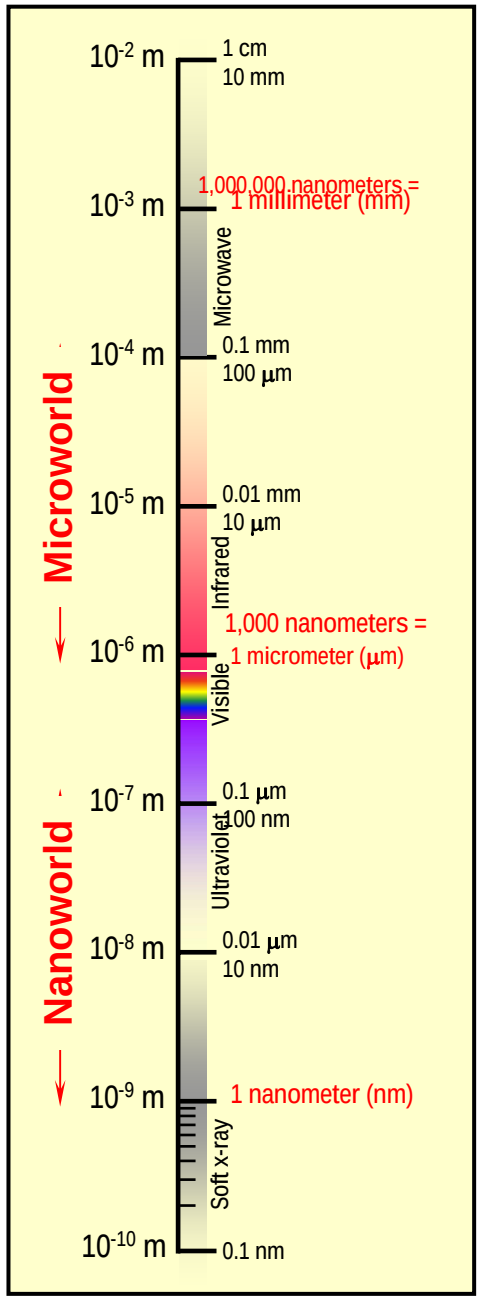
~10 nm diameter

ATP synthase

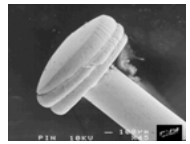
DNA
~2-1/2 nm diameter



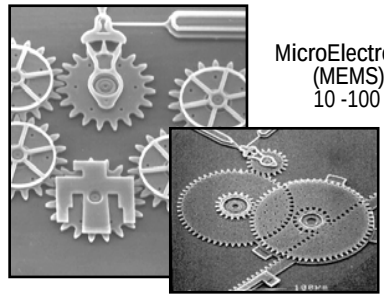
Atoms of silicon
spacing ~tenths of nm



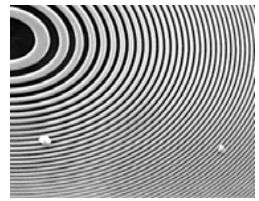
Things Manmade



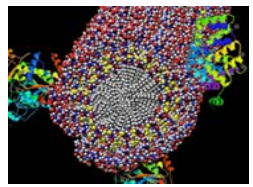
Head of a pin
1-2 mm



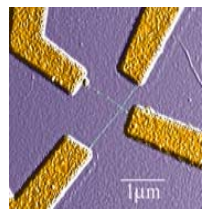
MicroElectroMechanical
(MEMS) devices
10 -100 μm wide



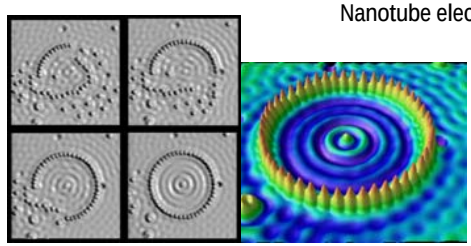
Zone plate x-ray "lens"
Outer ring spacing ~35 nm



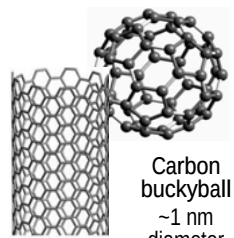
Self-assembled,
Nature-inspired structure
Many 10s of nm



Nanotube electrode



Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm

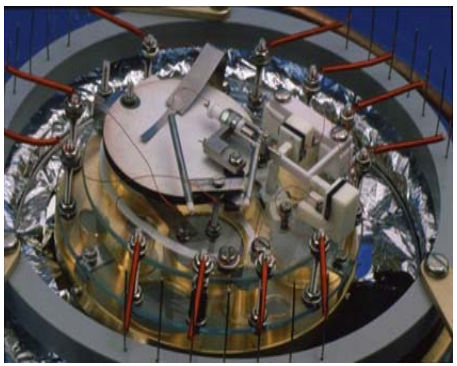


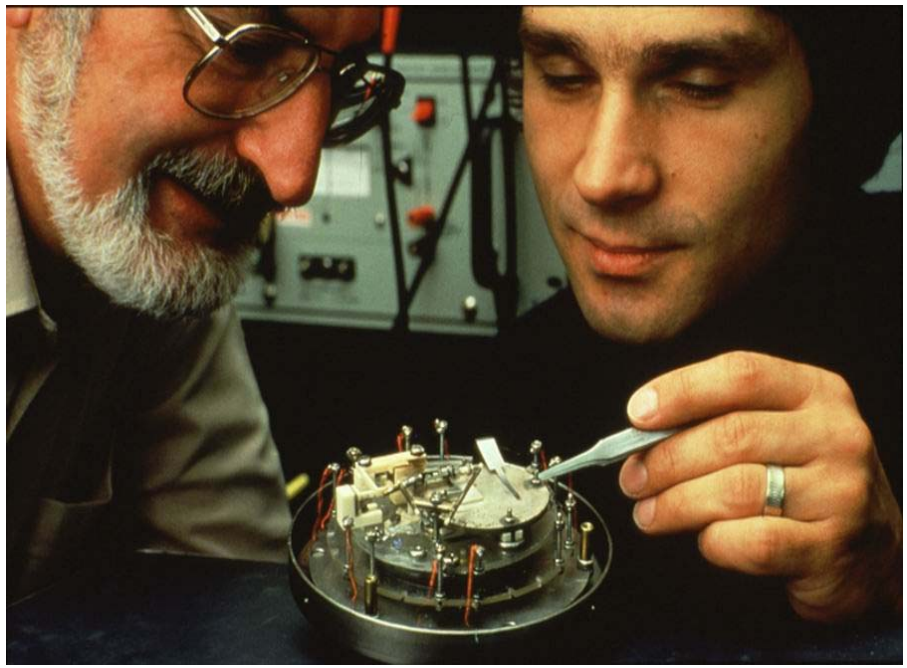
Carbon
buckyball
~1 nm
diameter

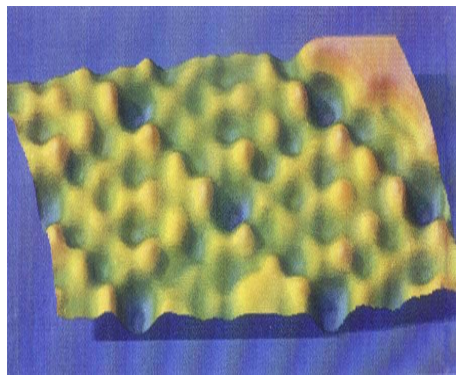
Carbon nanotube
~1.3 nm diameter

Scanning Tunneling Microscopy

"See,feel, hear and touch" Atoms







Nobel Prize

Open "door" for nanoscience

2. STM principle & working modes

i: Principle:

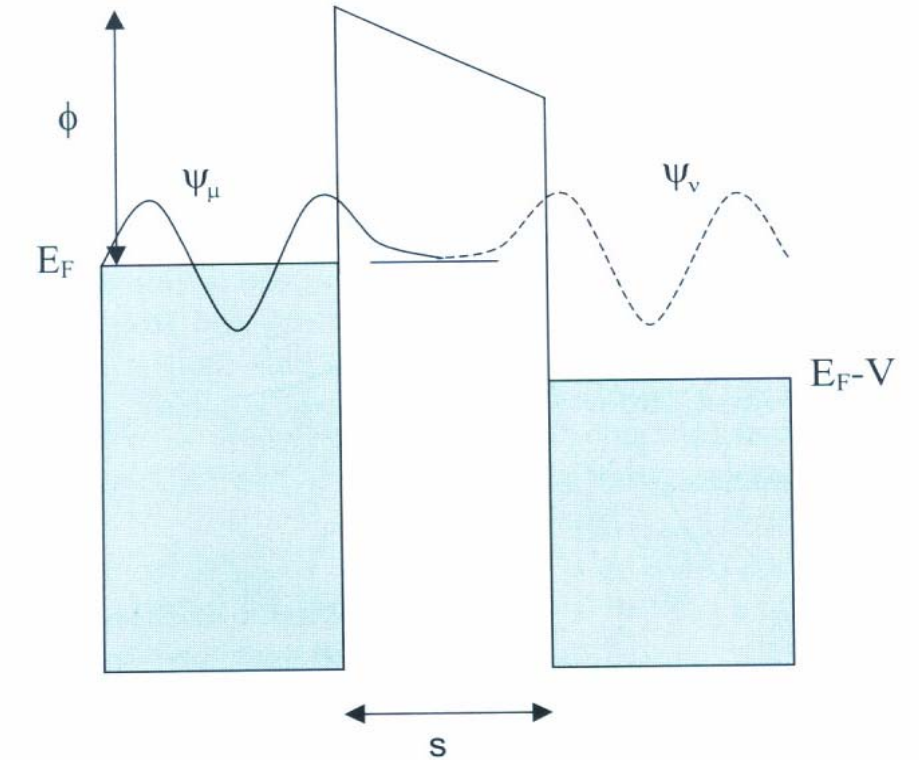


Fig.1

The wave function of tip and sample overlap.

In the classically forbidden region:

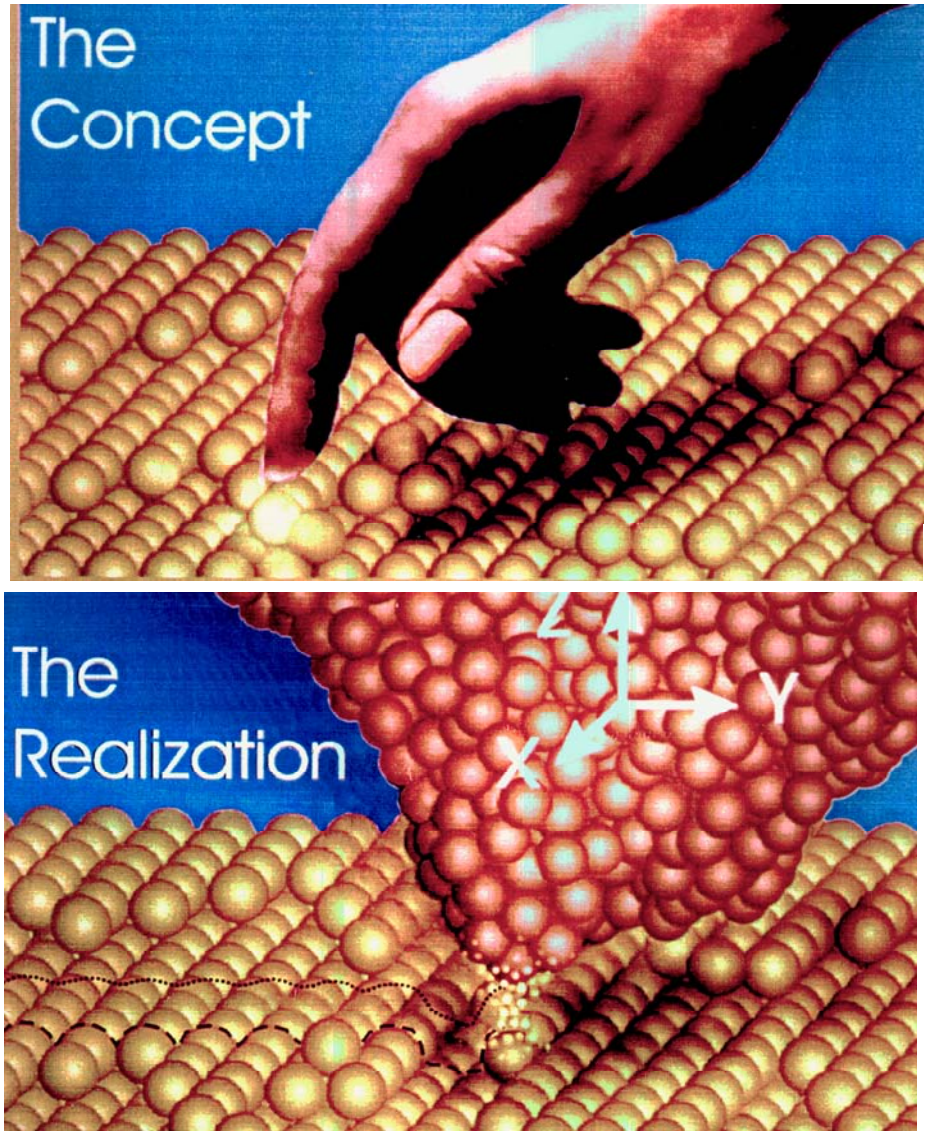
$$\psi(z) = \psi(0)\exp\left[-\frac{\sqrt{2m(\phi - E)}z}{\hbar}\right] \qquad (1)$$

The tunneling current:

$$I_t \propto V\rho_s(E_F)\exp\left[-2\frac{\sqrt{2m(\phi - E)}z}{\hbar}\right] \propto V\rho_s(E_F)e^{-1.025\sqrt{\phi}z} \qquad (2)$$

In gold, $\phi = 5eV$, current drops an order of magnitude, gap is changed by one Å

ii: Working modes:



- ***idea for STM, like "finger", to "touch" the atoms***

(a) Constant current mode

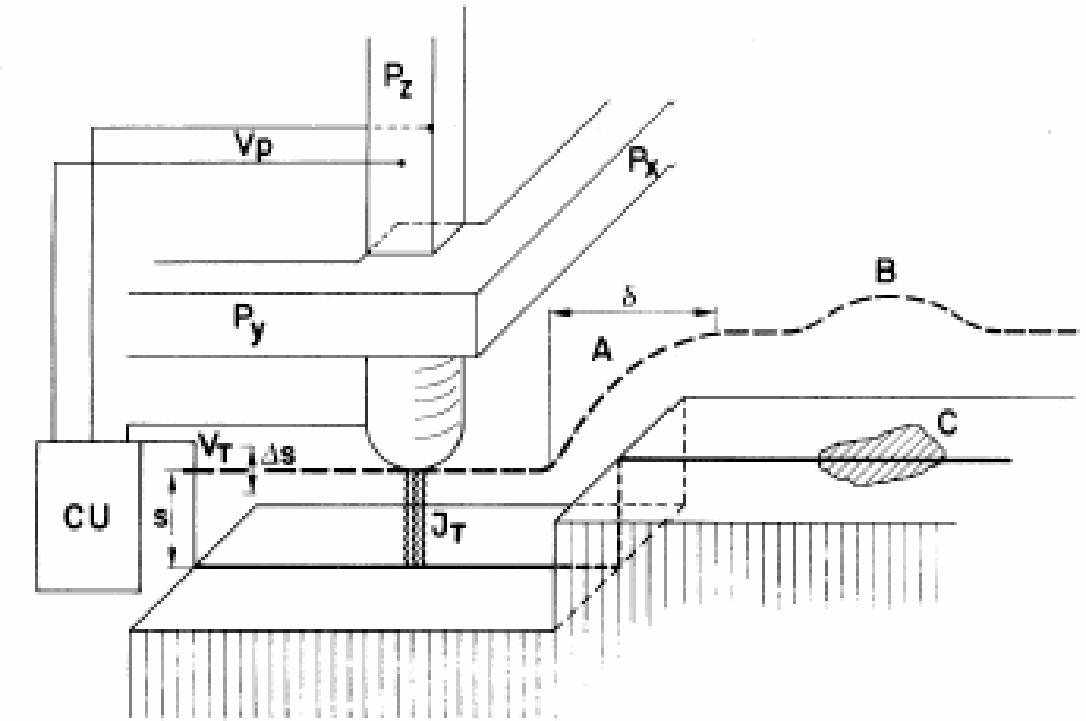


Fig. 2

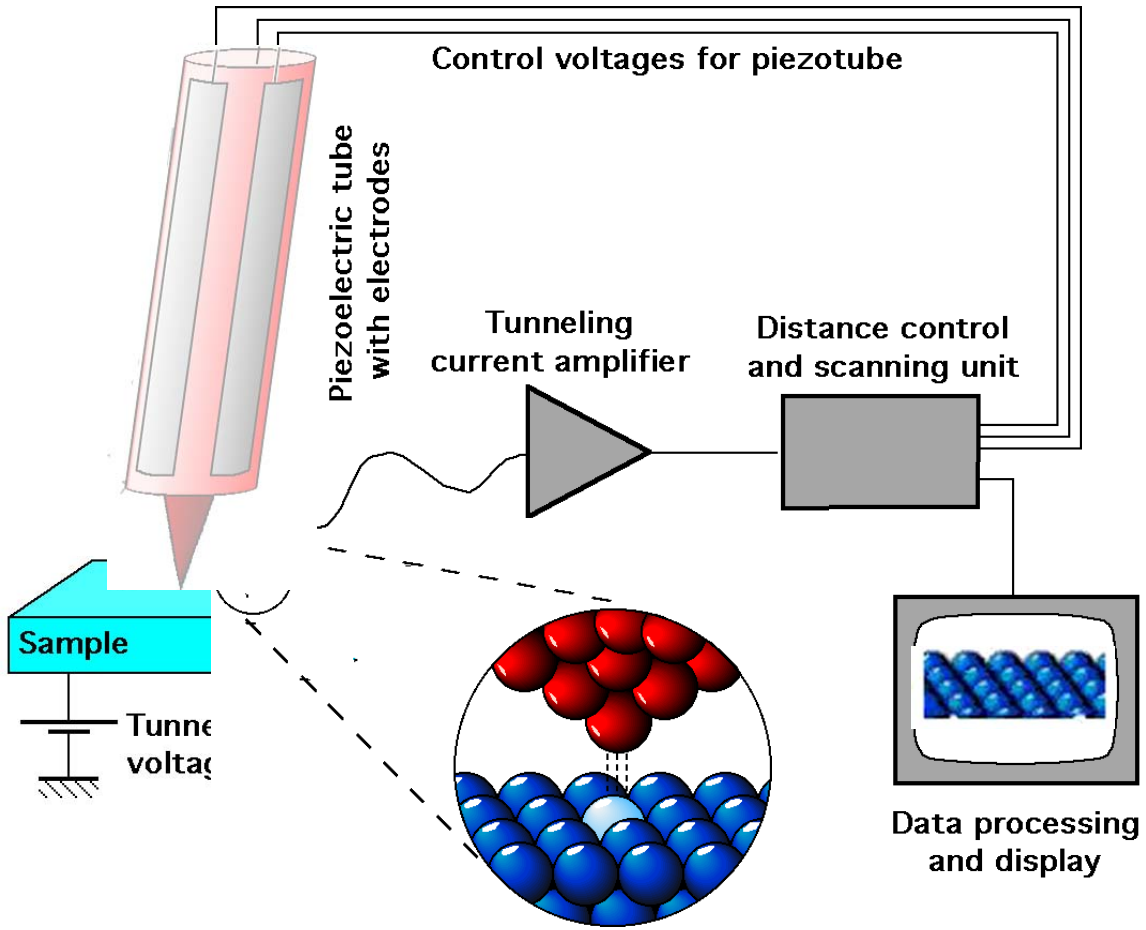
Suited tip; Actuator; Controller.

Vibrational isolation;

Atomic sharp tip

electron tunneling

piezoelectrics: move with voltage



STM can image individual atoms!

(b) Constant height mode

Measure the tunneling current while scanning on a given, smooth x-y-z contour.

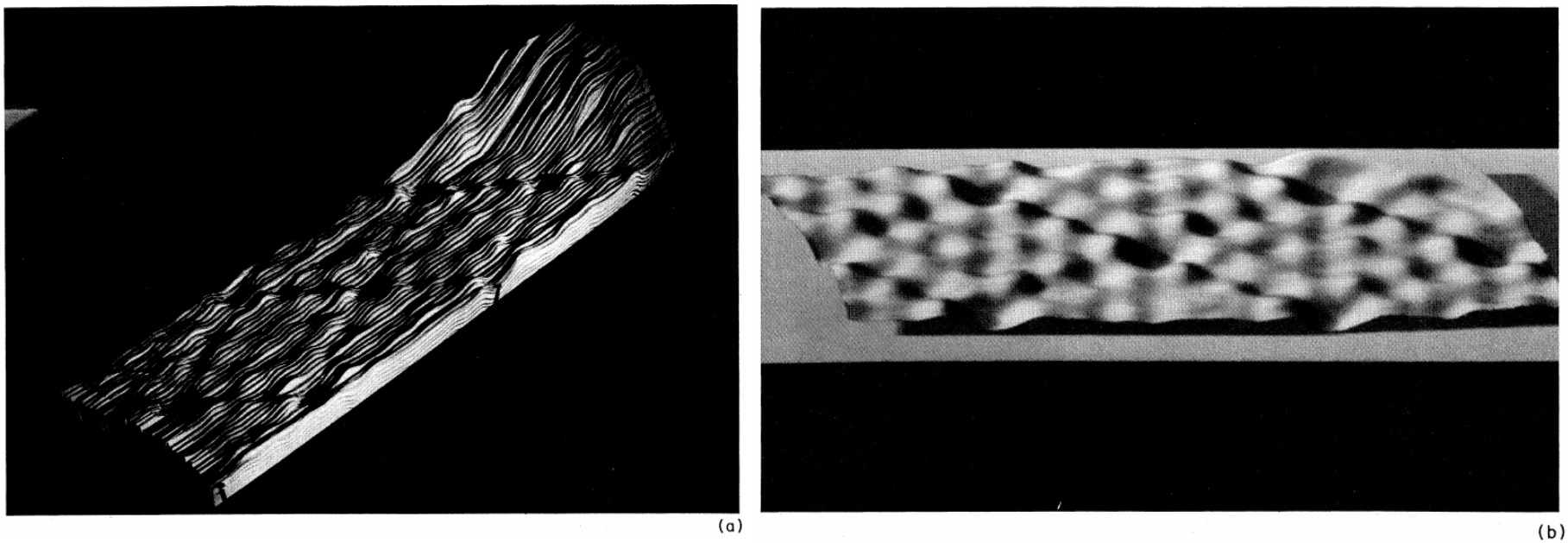
The z-position (output of feedback loop) is measured at discrete (x, y)-positions.

line-scan image, grey-scale image or color encoded image.

Observe dynamical processes, but increase the risk of crashing the tip

3. STM application & extension

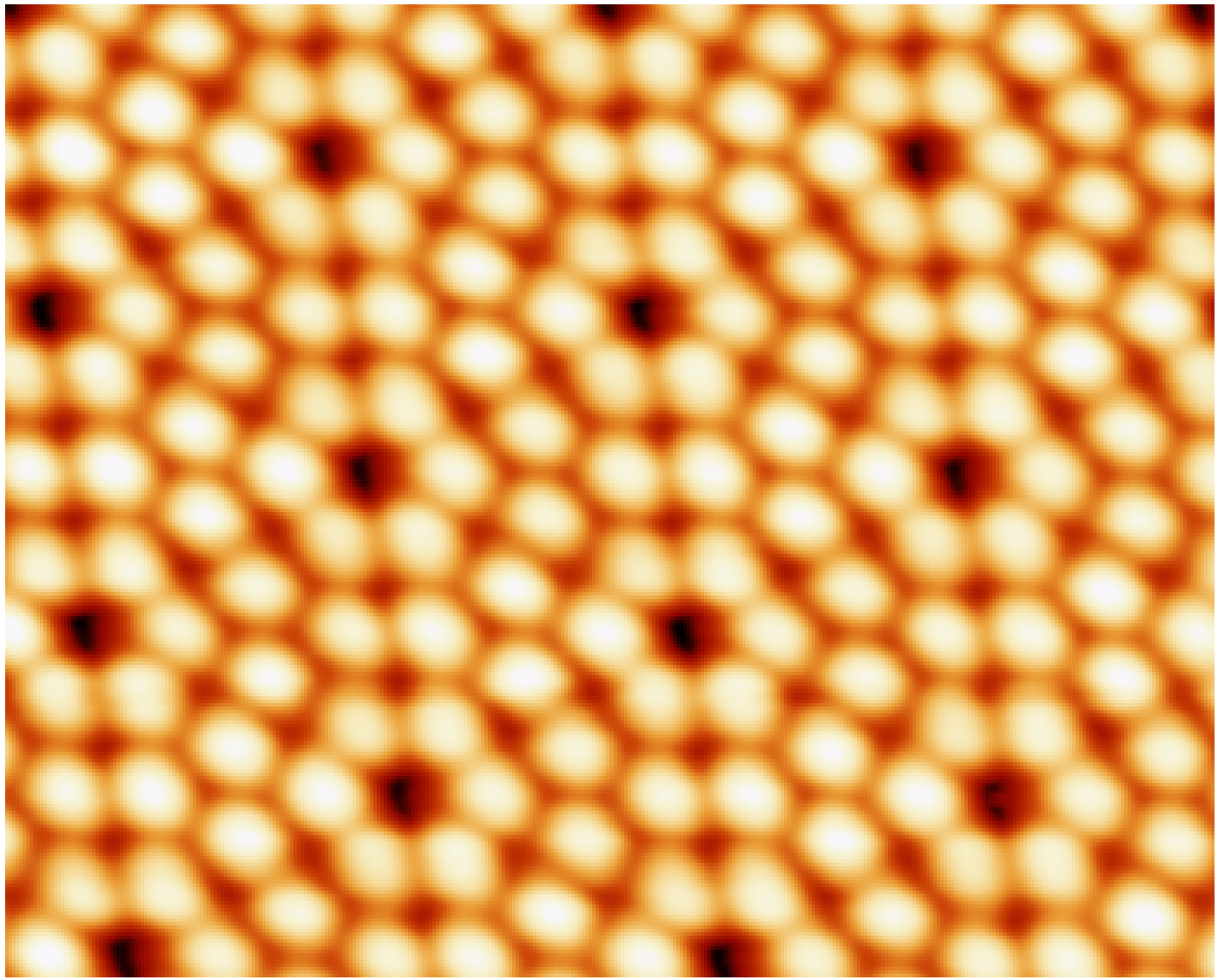
(a) Reconstruction in Si(111)



The rhombohedral surface unit cell are the corner hole and the 12 maxima, the adatoms.

G. Binnig, H. Rohrer, Ch. Gerber, and E. Weibel, Phys. Rev. Lett. **50**, 120 (1983)

Si(111) surface-7x7 reconstruction



(b) DNA

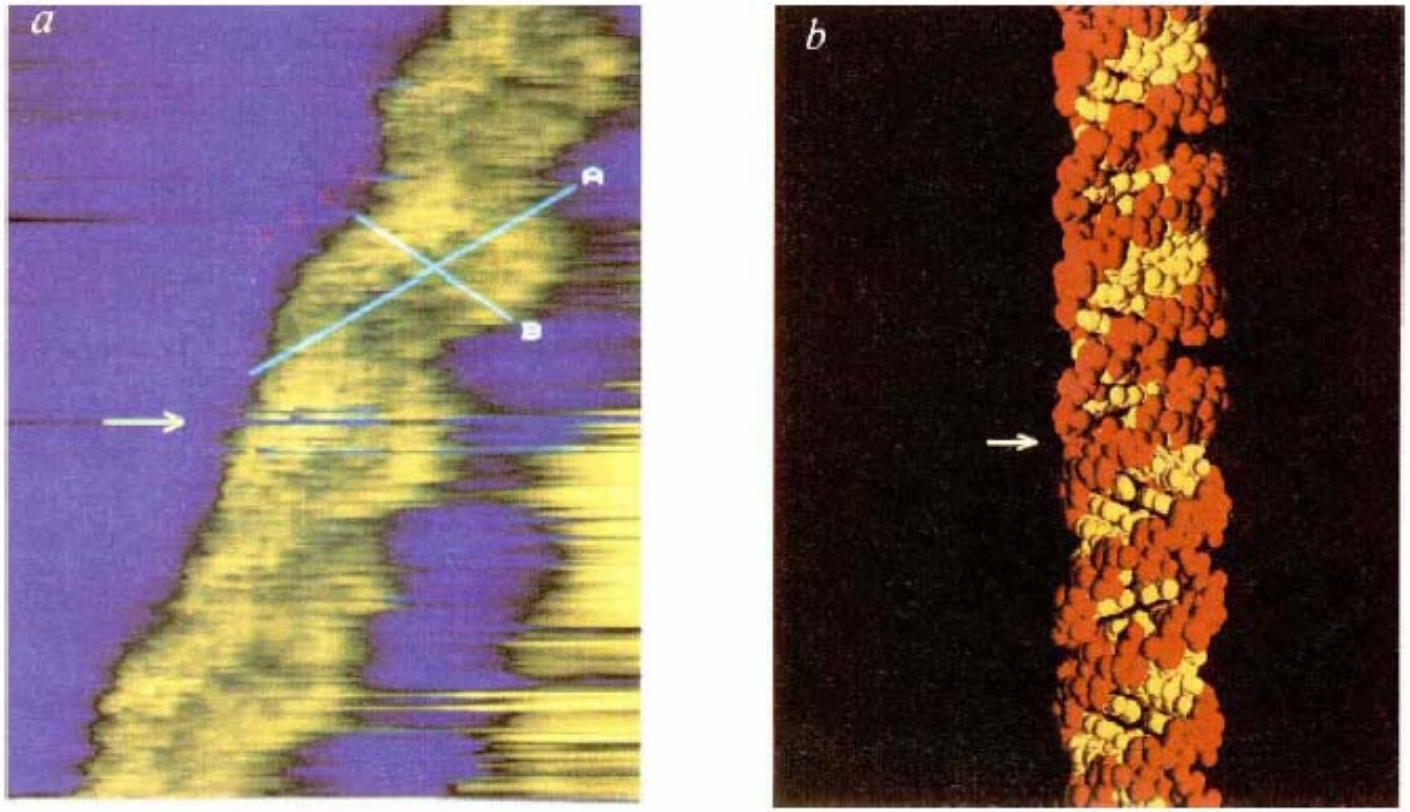
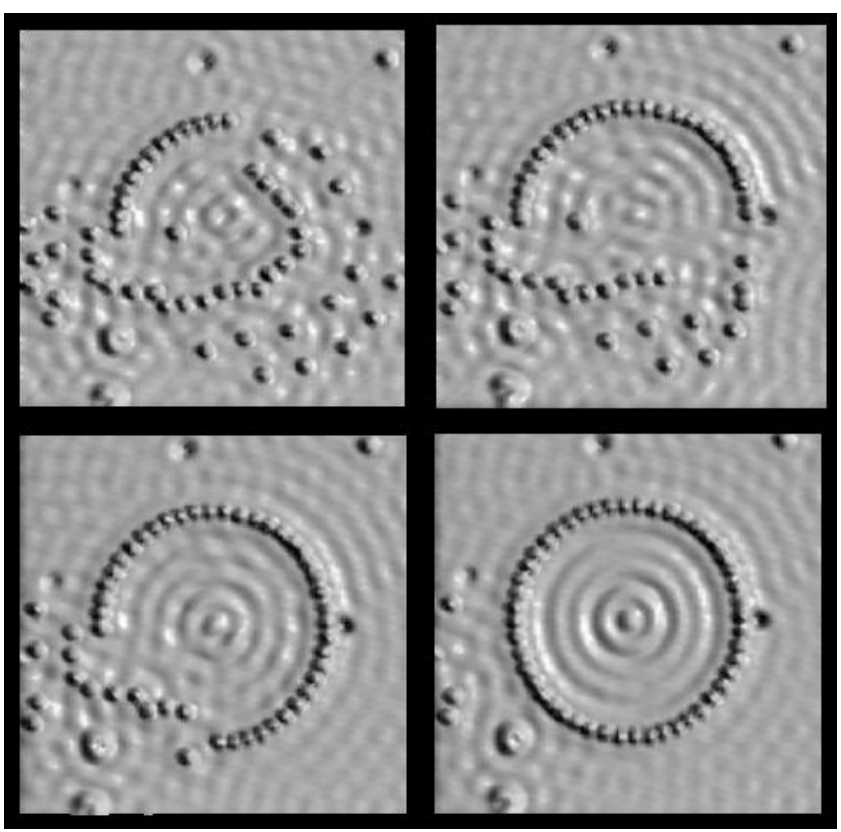


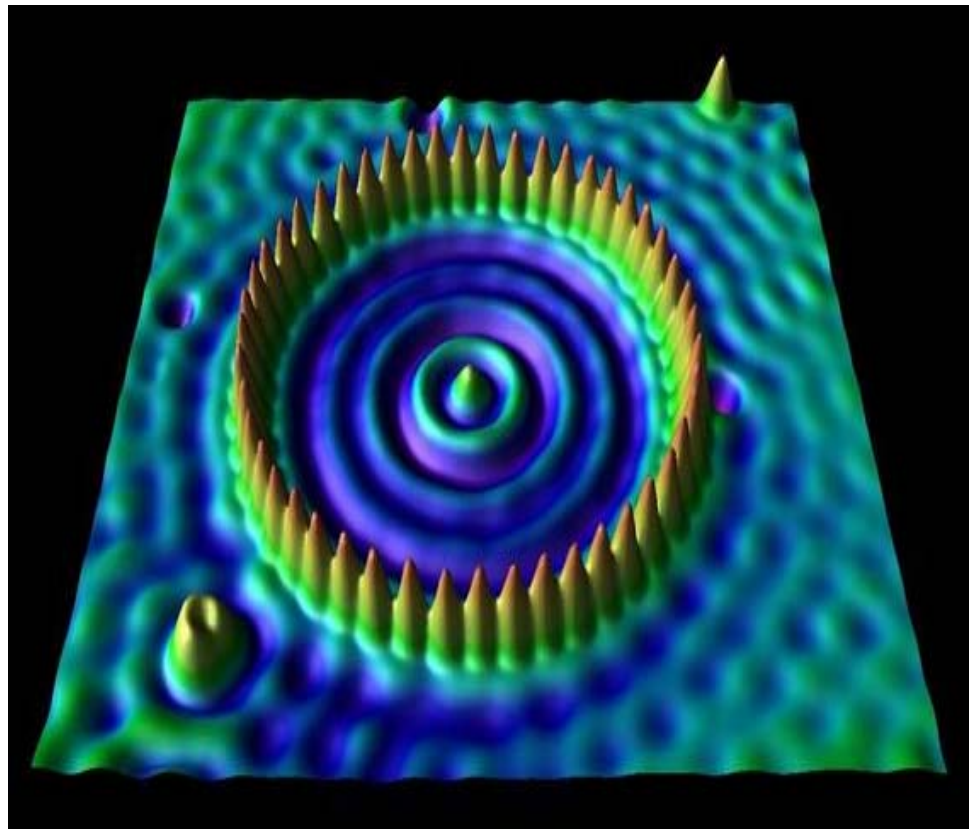
Fig. a, Unsmoothed, unfiltered plane-subtracted STM image of DNA ~80x120 Å

b. Model of the Van der Waals surface of A-DNA derived from X-ray crystallographic data, scaled to a.

Robert J. Driscoll, Michael G. Youngquist & John D. Baldeschwieler Nature **346** 294-296 (1990)

(c) Atom Manipulation and Surface Standing Wave





Quantum Corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip (corral diameter 14 nm)

G. Binnig, H. Rohrer Rev. Mod. Phys. 71, 324 (1999)

(d) STM extension

scanning near-field optical microscope (SNOM),

atomic force microscope (AFM),

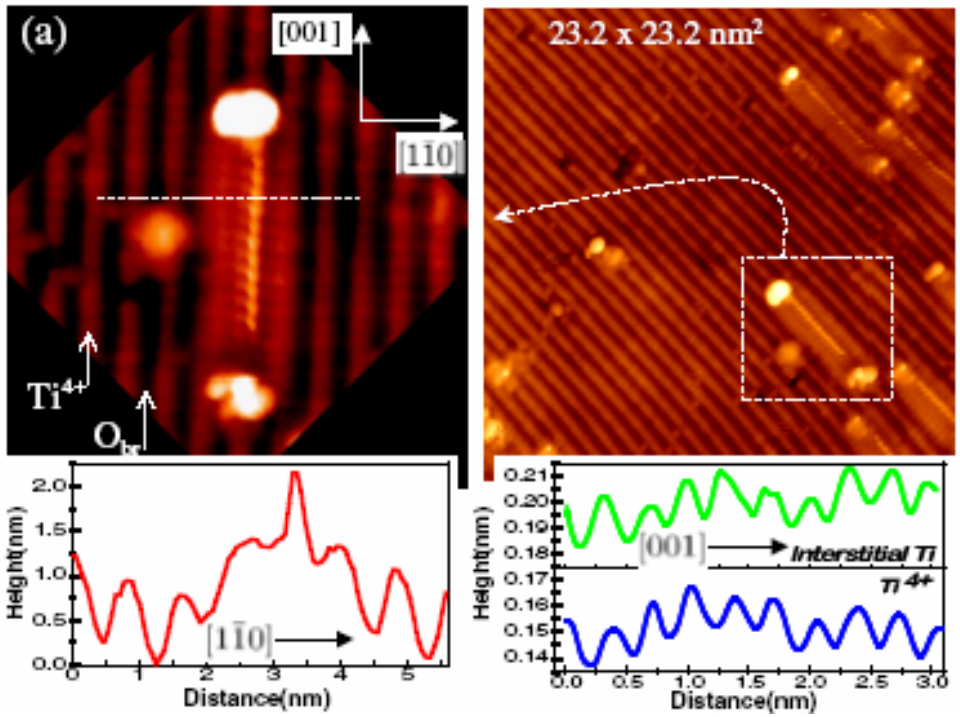
Maxwell stress microscopy,

scanning electrochemical microscopy *et. al.*

4.STM in our group

Recent work:

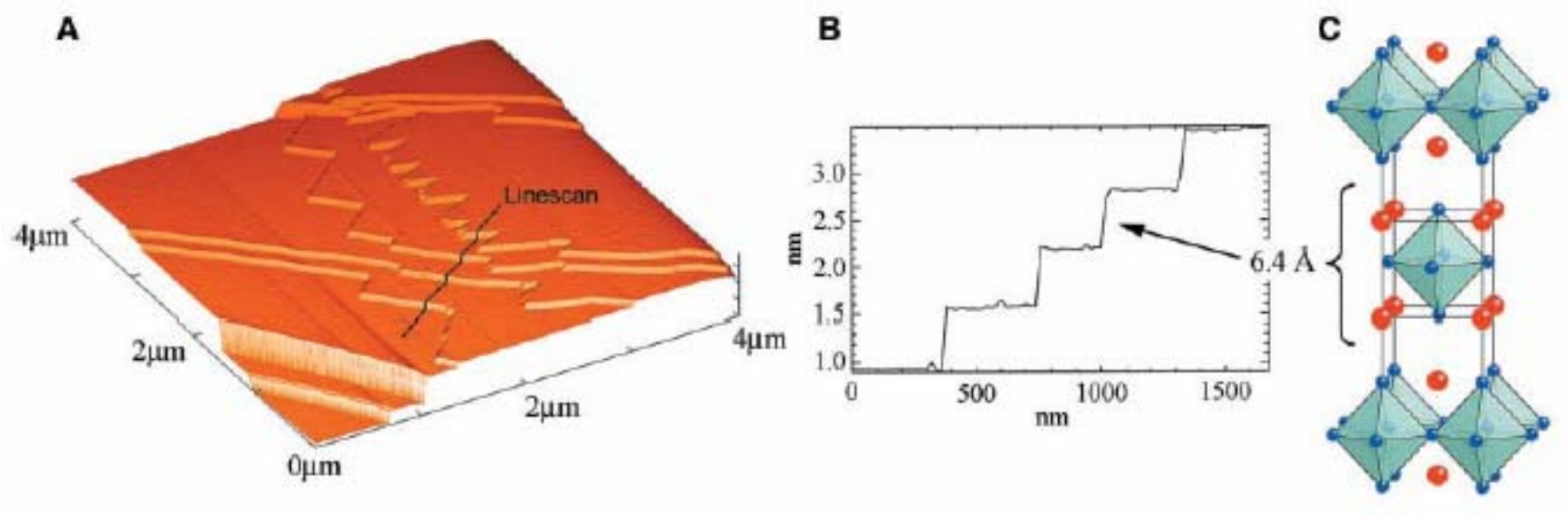
Surface reconstruction of TiO2 (110) by Ti interstitials



STM image of a strand (1.2V; 0.5nA) with the height profiles across (left, dotted line) and along (right) the line defect.

K. T. Park, M. H. Pan, V. Meunier, and E. W. Plummer, Phys. Rev. Lett. **96**, 226105 (2006)

- Sr2RuO4: layered perovskite without copper that exhibits superconductivity



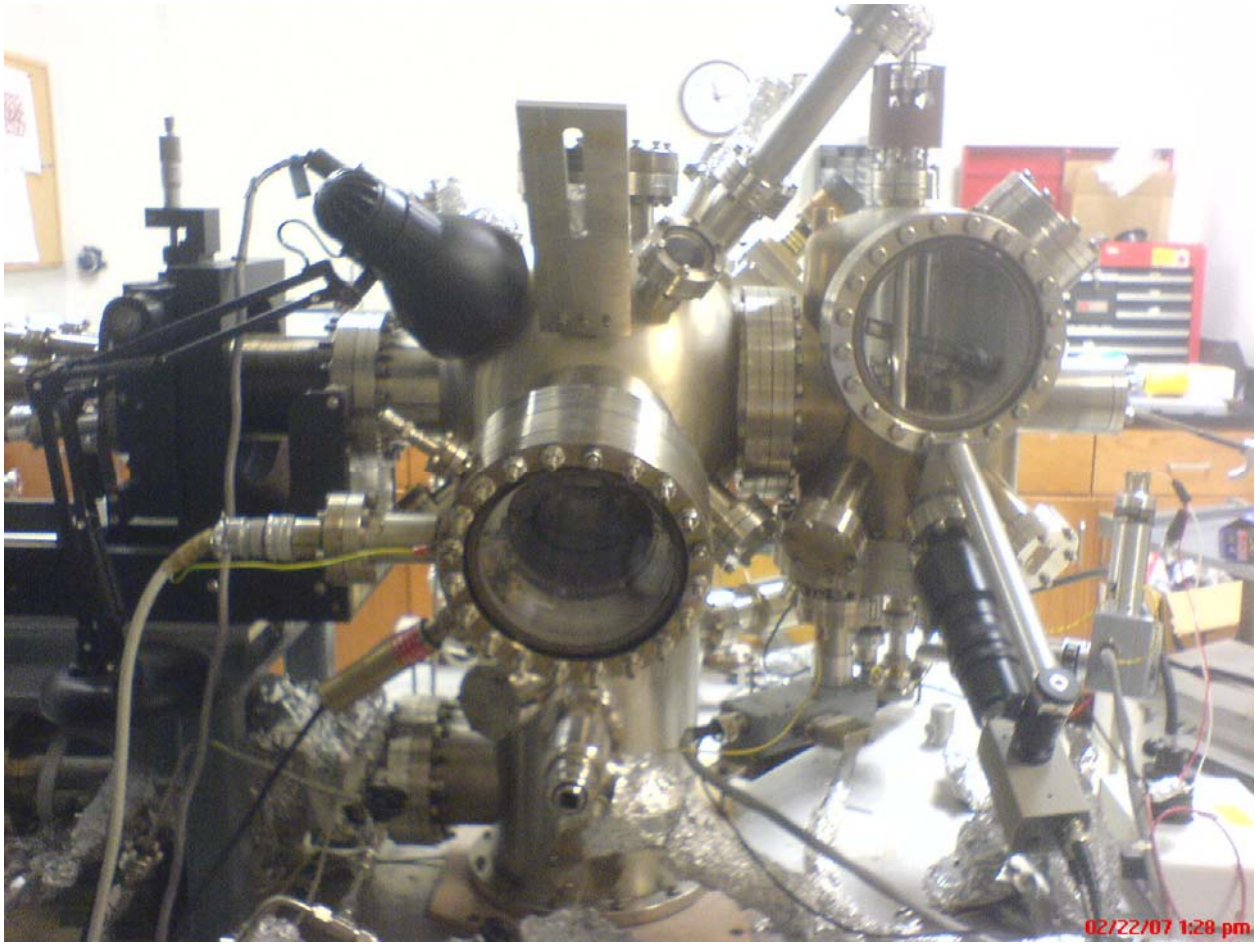
(A)STM image of a 4 by 4 surface area showing extremely large terraces and steps.

(B)Height along the line scan shown in the STM image.

(C)Ball model of the bulk unit cell of Sr2RuO4. Red, strontium; blue, oxygen; and green, ruthenium (in the center of the octahedron).

R. Matzdorf, Z. Fang, Ismail, Jiandi Zhang, T. Kimura, Y. Tokura, K. Terakura, and E. W. Plummer, Science **289**, 746 (2000)

UT STM (SERF 101-E)



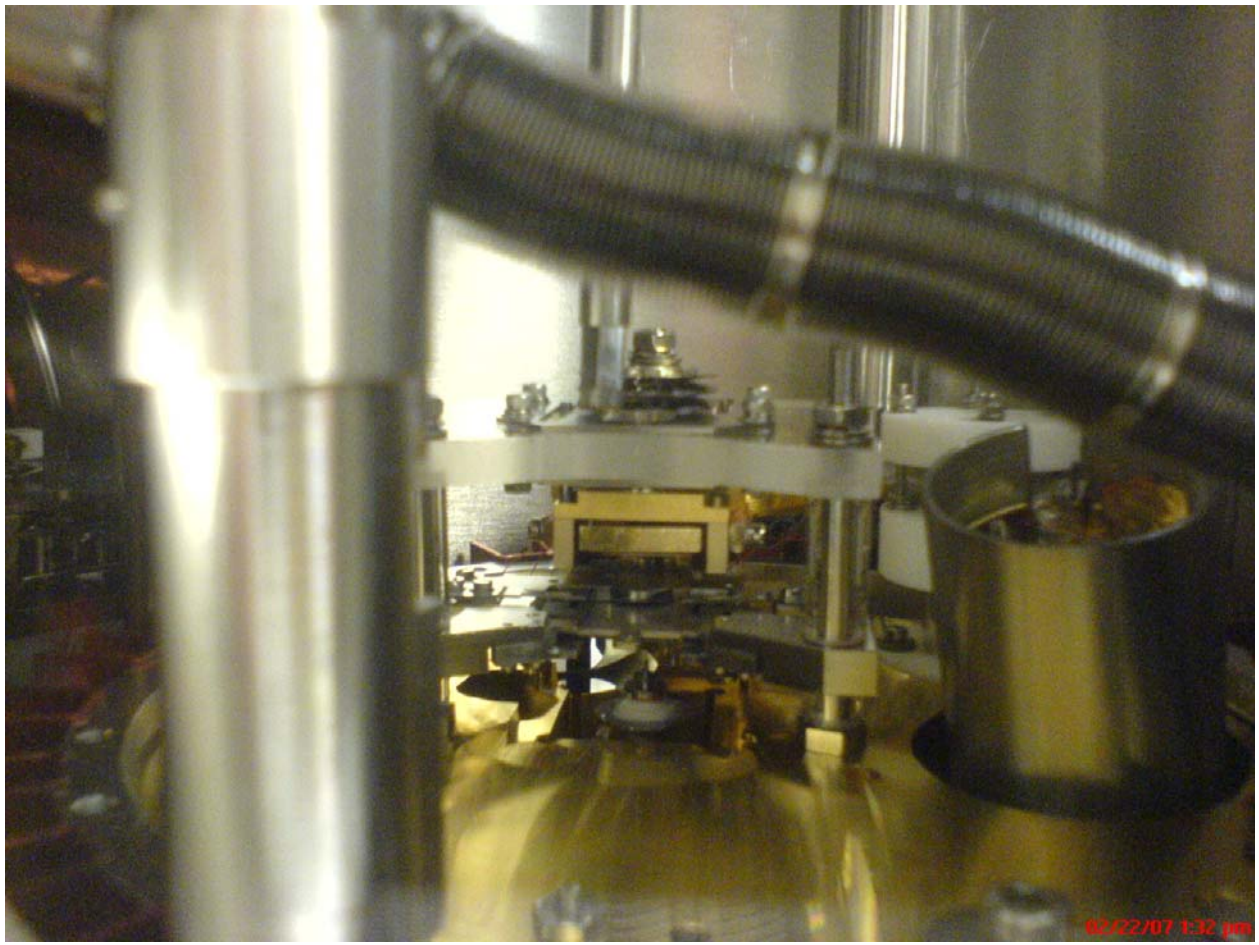
Frontview

Scan range:
xy :12 μm x12 μm

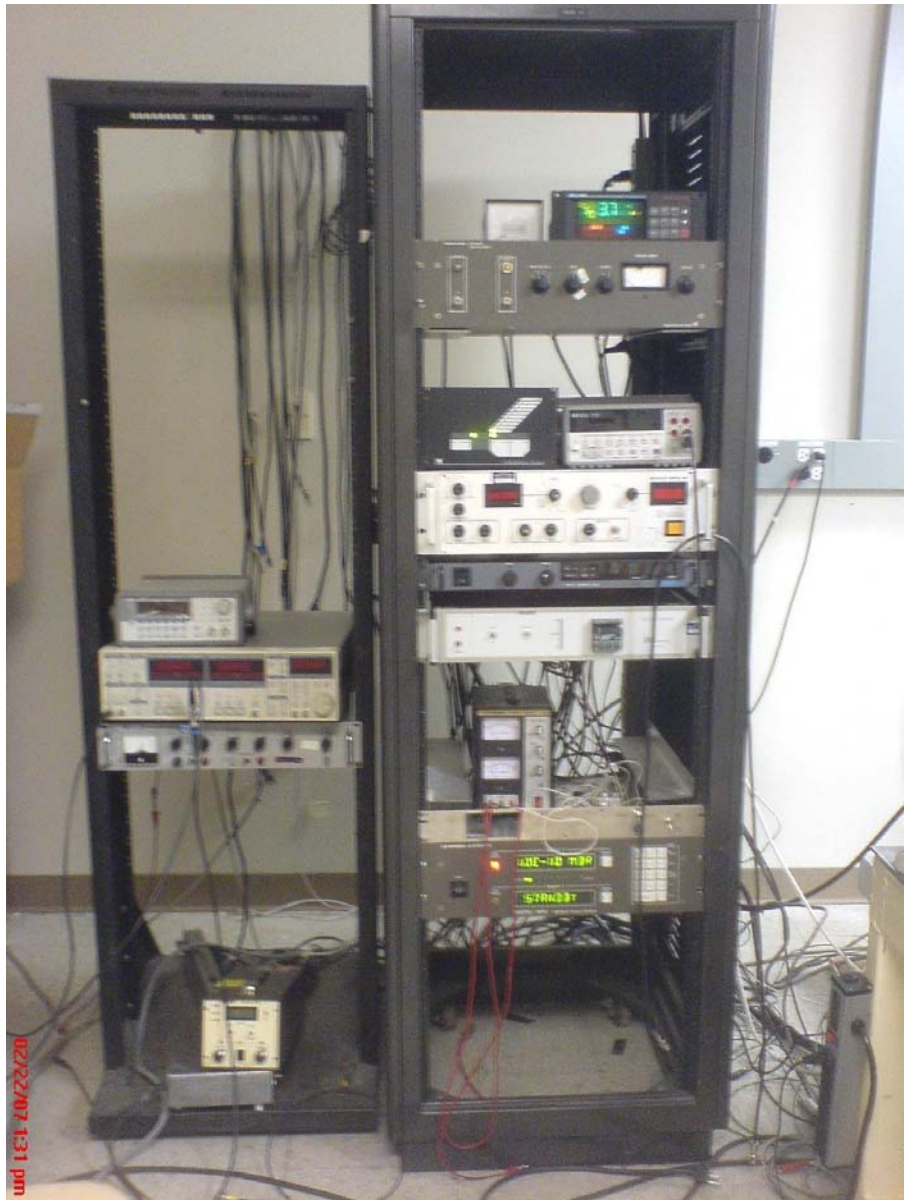
z: 1.5 μm

Resolution:
xy: 0.1nm
z: 0.01nm

Sample stage



Electronics



Low Temperature, High Field STM

Scanning Tunneling Microscope with extreme stability under extreme conditions

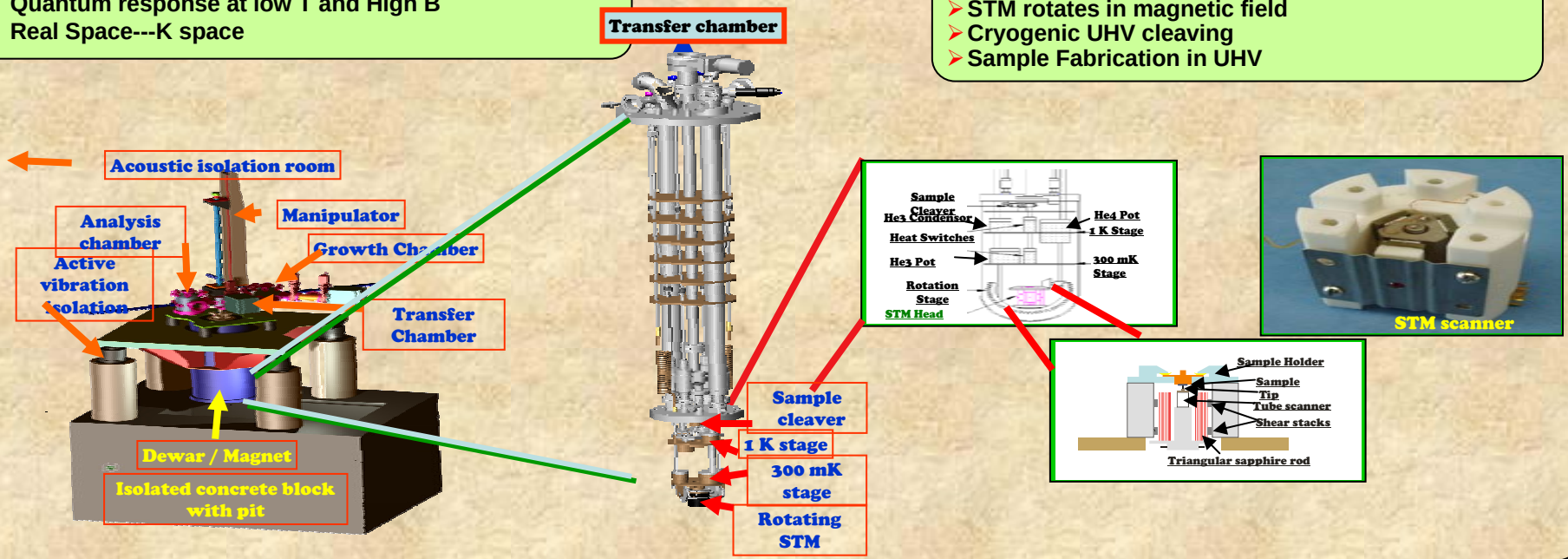
A CNMS partner instrument built by ORNL, The University of Tennessee, and The University of Houston

Scientific Drivers

- Atomically-resolved topography and spectroscopy maps
- Quantum response at low T and High B
- Real Space---K space

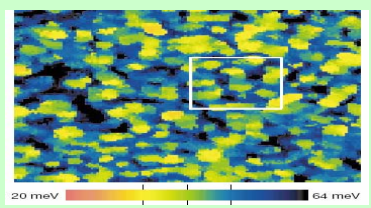
Capabilities

- Low T - 300 mK
- High B - 9 Tesla
- STM rotates in magnetic field
- Cryogenic UHV cleaving
- Sample Fabrication in UHV



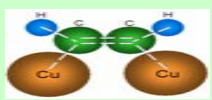
Applications

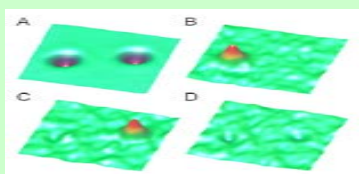
- Single atom or molecule spectroscopy.
- Atomic resolved spectroscopy maps.
- The temperature and magnetic field range to study the quantum response of nano-objects.
- Optical access to the sample in the magnetic field for probing and exciting atoms or molecules.

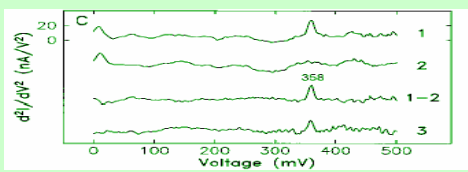


Single molecule vibrational spectroscopy: C_2H_2, C_2D_2

Science **280**, 1732 (1998)---Stipe and Ho







Nature **415**, 412 (2002)– Lang and Davis

Electronic inhomogeneity: $Bi_2Sr_2CaCu_2O_{8+\delta}$

Thanks!