ME597/PHYS57000
Fall Semester 2010
Lecture 04

The Transition from STM to AFM

Ron Reifenberger
Birck Nanotechnology Center
Purdue University

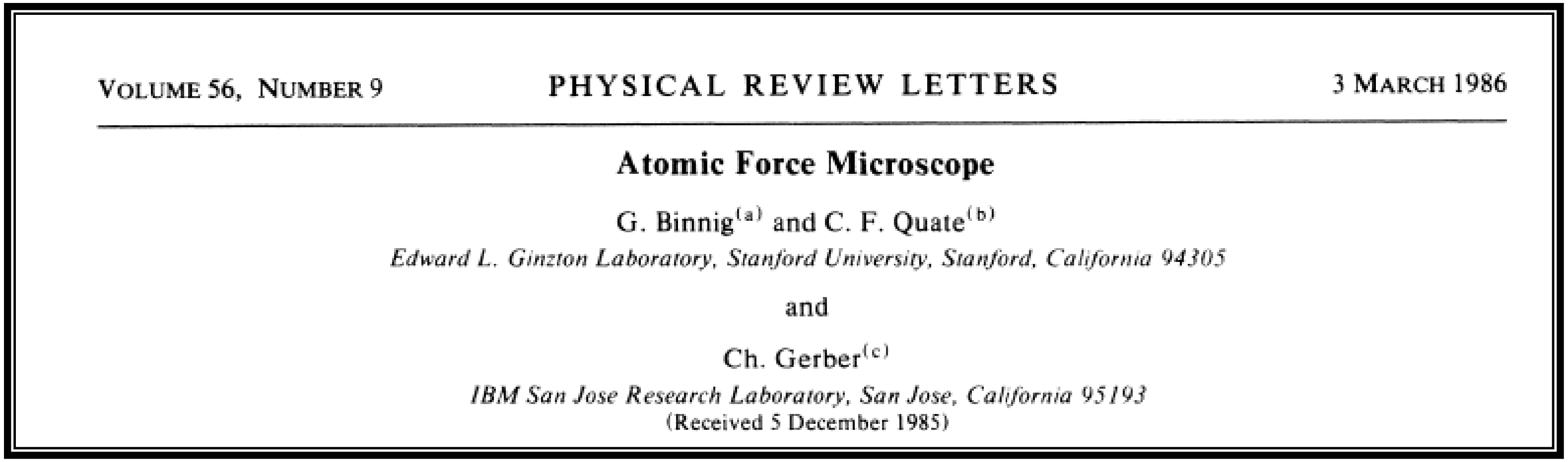
Suggested Reading: G. Binnig, C. Quate and Ch. Gerber, "Atomic Force Microscope", Phys. Rev. Lett. **56**, 930 (1986). *

***cited ~2,000 times**

Many materials of interest do not conduct electricity. Is it possible to use scanning probe to study them?

Even at the First International STM Conference in July 1986, there was discussion about how to extend STM techniques to non-conducting materials.

Overcoming Limitation of a Conducting Substrate: the Atomic Force Microscope



VOLUME 56, NUMBER 9 PHYSICAL REVIEW LETTERS 3 MARCH 1986

Atomic Force Microscope

G. Binnig[a] and C. F. Quate[b]
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

and

Ch. Gerber[c]
IBM San Jose Research Laboratory, San Jose, California 95193
(Received 5 December 1985)

Control the tip-substrate force!

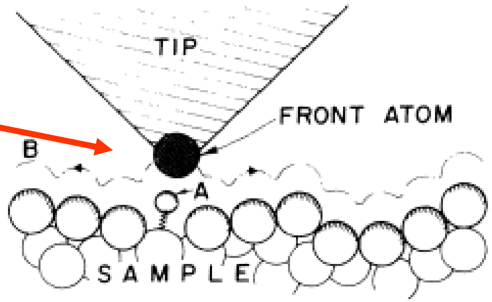


FIG. 1. Description of the principle operation of an STM as well as that of an AFM. The tip follows contour *B*, in one case to keep the tunneling current constant (STM) and in the other to maintain constant force between tip and sample (AFM, sample, and tip either insulating or conducting). The STM itself may probe forces when a periodic force on the adatom *A* varies its position in the gap and modulates the tunneling current in the STM. The force can come from an ac voltage on the tip, or from an externally applied magnetic field for adatoms with a magnetic moment.

Key Idea: use sensitivity of STM to measure the rise and fall of a tip mounted on a cantilever when rastered across an insulating substrate.

Initial Implementation:

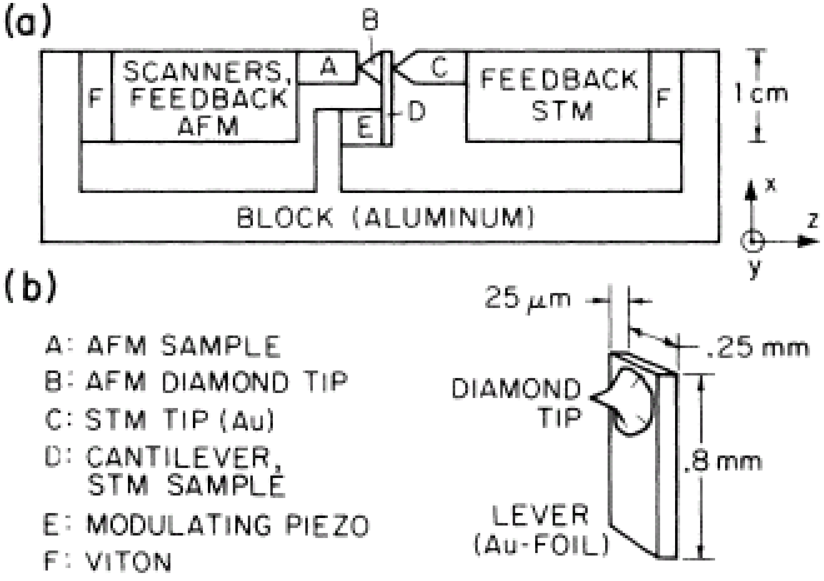


FIG. 2. Experimental setup. The lever is not to scale in (a). Its dimensions are given in (b). The STM and AFM piezoelectric drives are facing each other, sandwiching the diamond tip that is glued to the lever.

First Topographic Scans

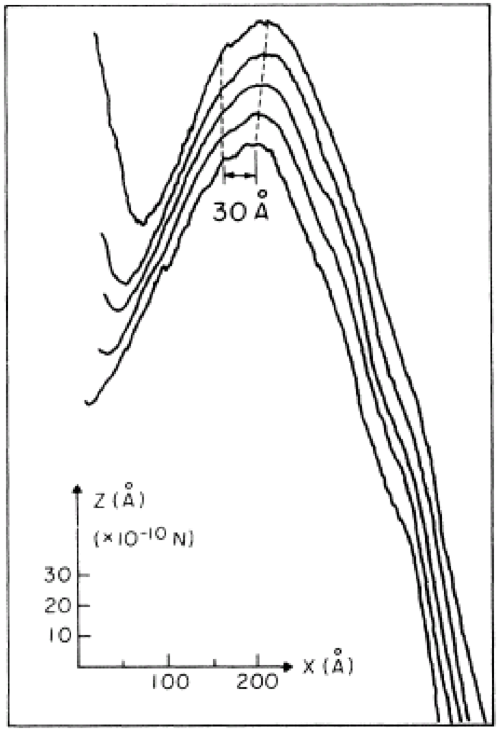
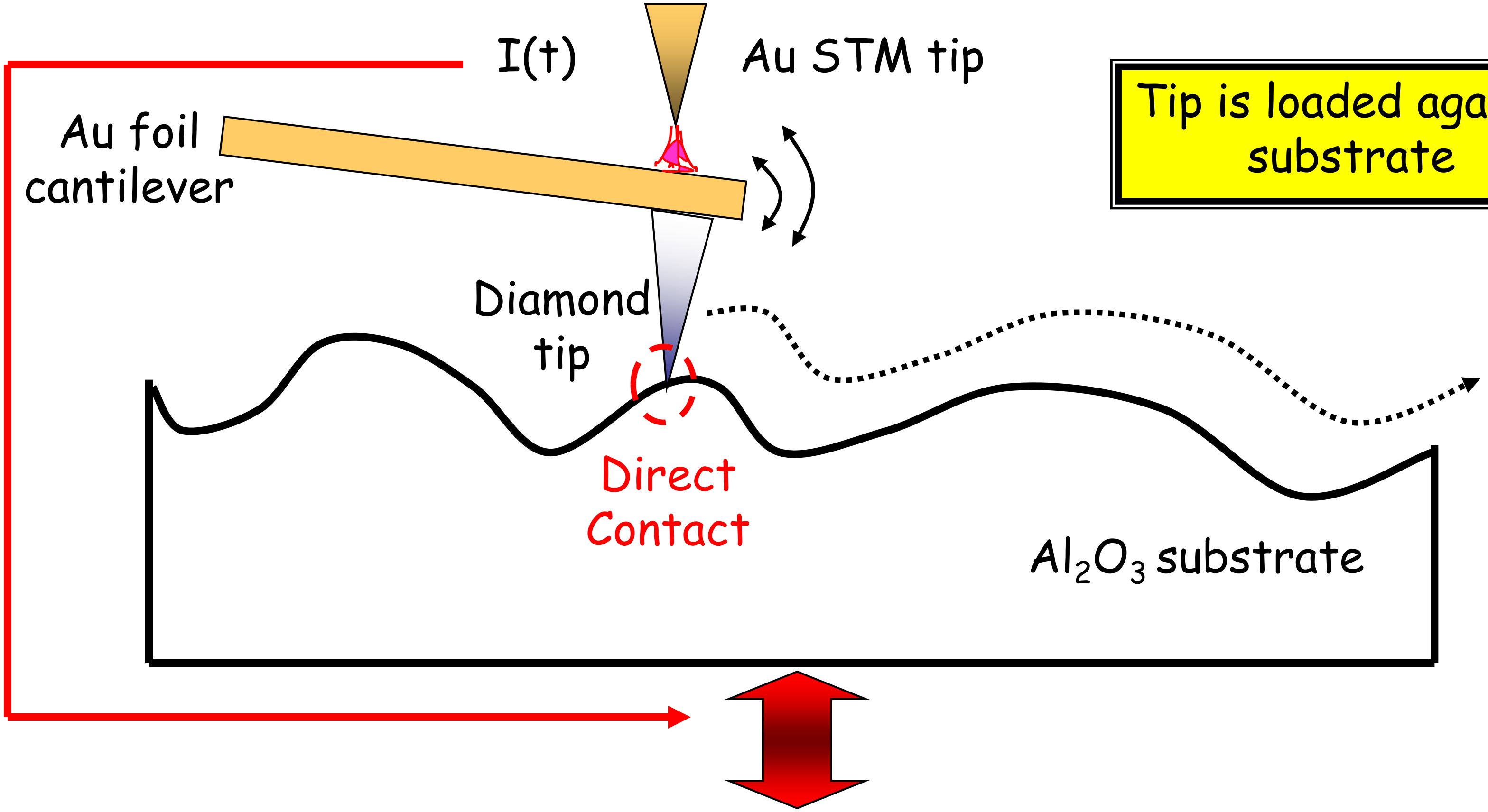


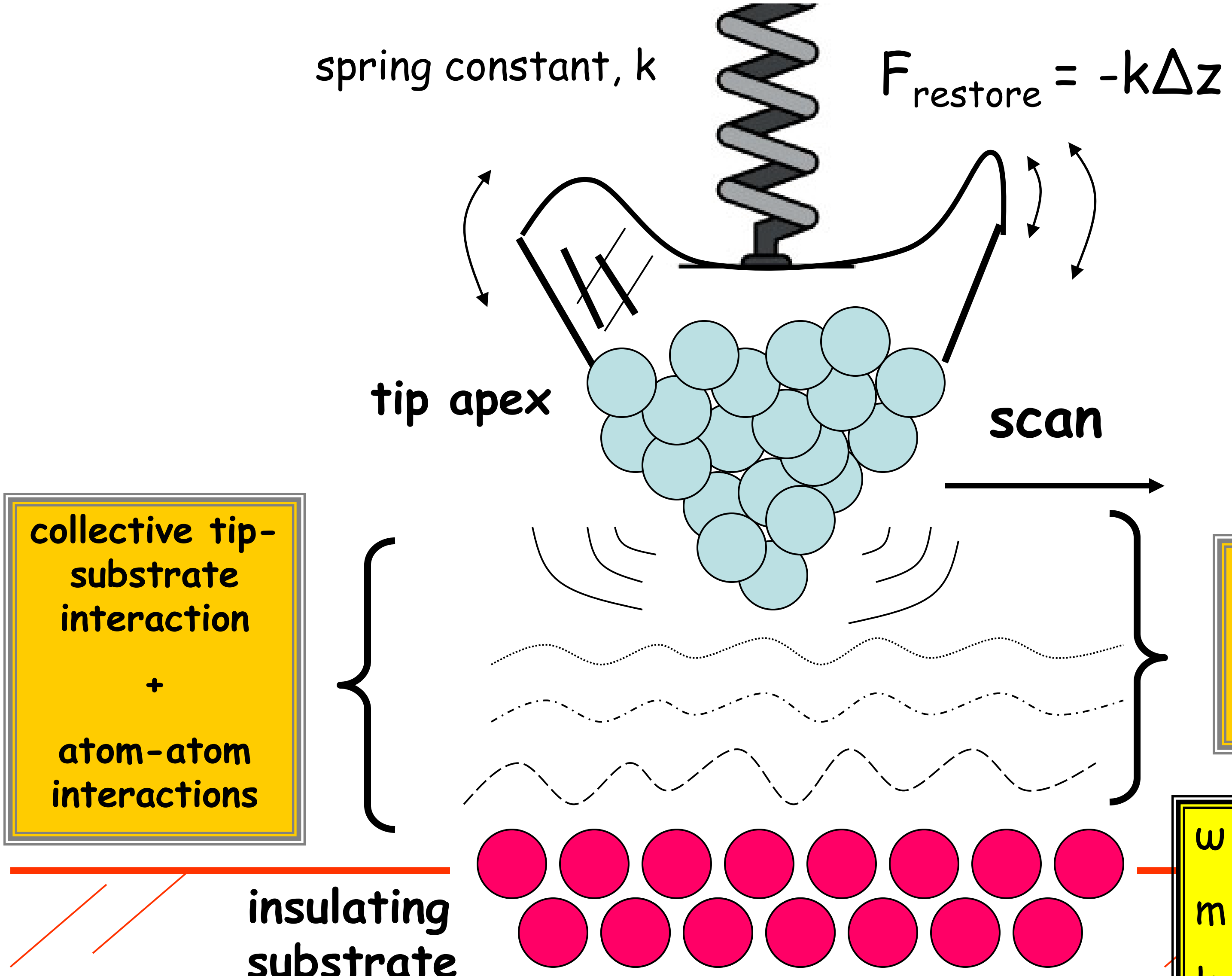
FIG. 3. The AFM traces on a ceramic (Al_2O_3) sample. The vertical scale translates to a force between sample and tip of 10^{-10} N/Å. For the lower trace the force is near 3×10^{-8} N. The stability of the regulated force is better than 10^{-10} N. The successive traces are displaced by a small drift along the *y* axis.

Scanning Mode



Tip is loaded against substrate

What controls the atomic force?



spring constant, k

$F_{restore} = -k\Delta z$

tip apex

scan

collective tip-substrate interaction

+

atom-atom interactions

Long range

+

Short range

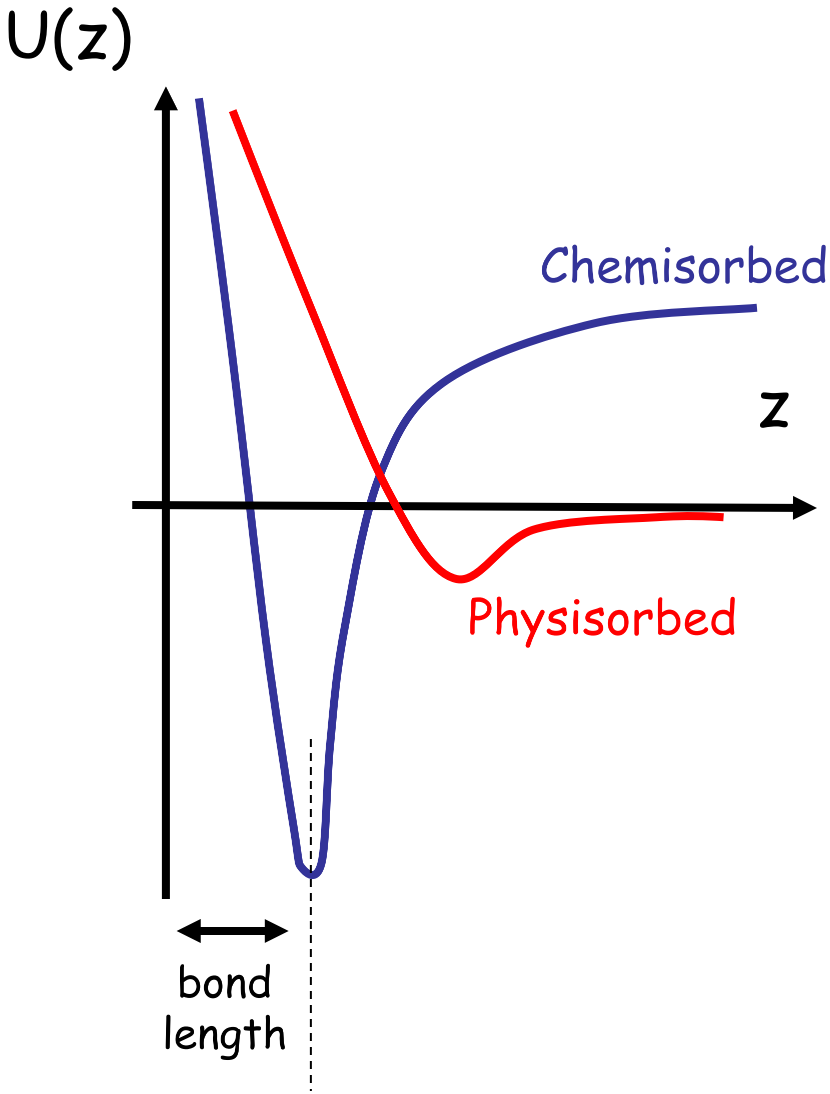
insulating substrate

$\omega \sim 10^{15}$ Hz

$m \sim 10^{-30}$ kg

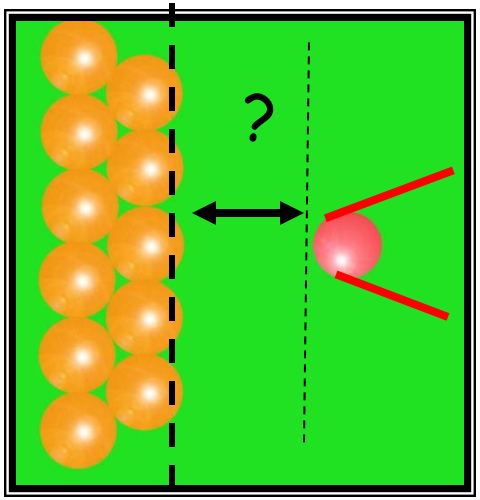
$k \sim \omega^2 m \sim 1$ N/m

Short-range atom-atom interactions?



	Physisorbed	**Chemisorbed**
Interaction	vdW bond	chemical bonds (common electronic orbitals)
Energetics	< 20 kJ/mol	>100 kJ/mol
Equilibrium Separation	0.4-0.6 nm (long range)	<0.3 nm (short range)
Adsorbed Layers	> 1	1
Specificity	Non specific	Specific
Temperatu re	depends on boiling point	activation energy

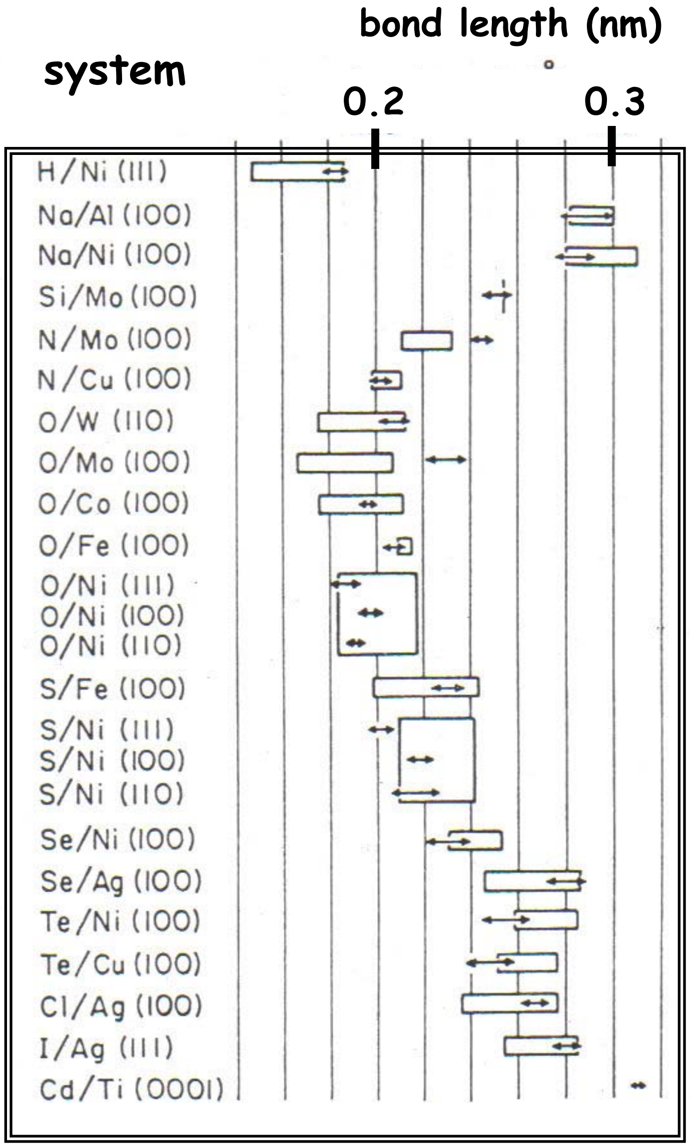
How Close is the Front Atom to the Substrate?



Legend:

↔ bond length for surface structures

▭ bond lengths in bulk and in molecules



Source: *Physics Vade Mecum*, H.L. Anderson, Editor , Am. Inst. Physics (1981).

Tip-Substrate Interactions

Electrostatic,magnetic

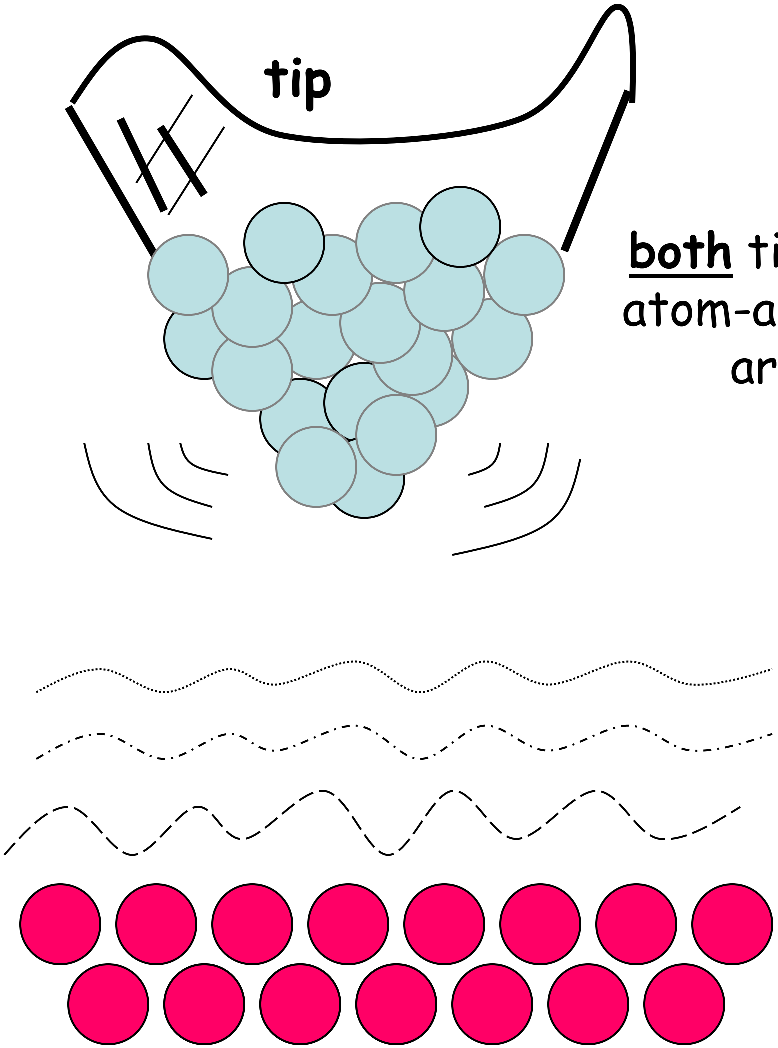
van der Waals (1873)

Capillary

Chemical:
(chemisorbed,physisorbed)

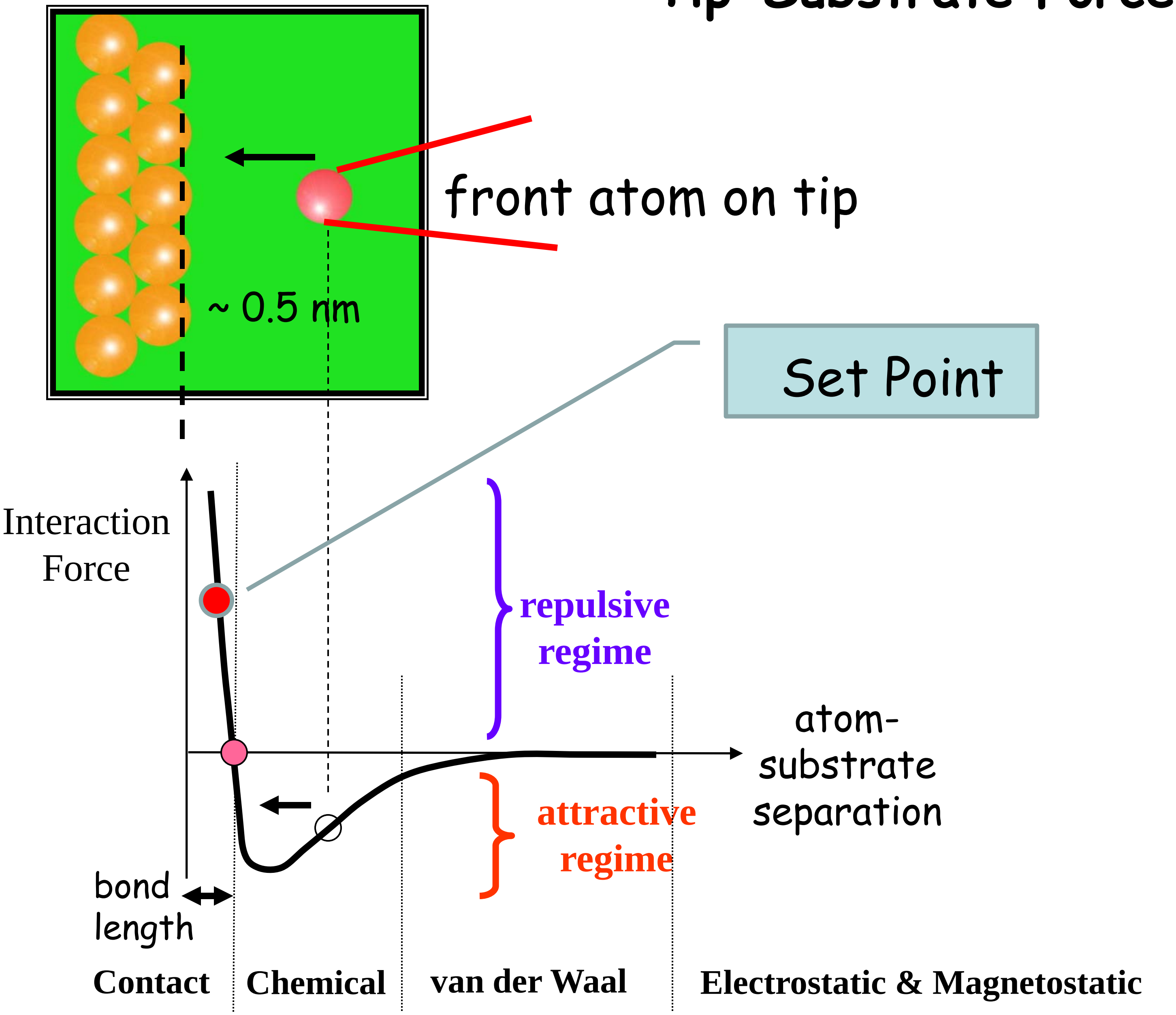
Friction

Deformation (indentation)

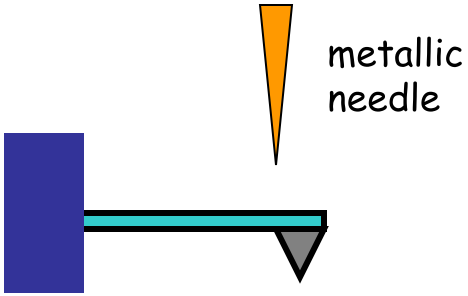


<u>both</u> tip-substrate and atom-atom interactions are important

Tip-Substrate Forces

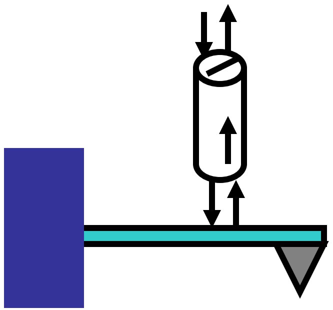


Detecting Deflection



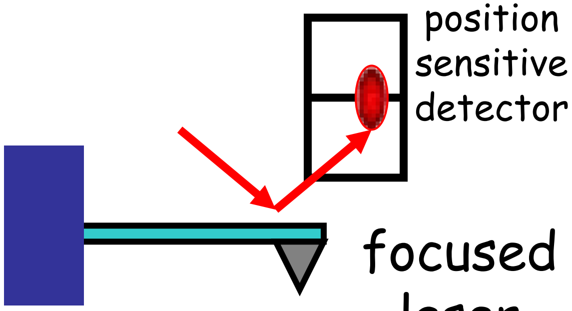
STM

Binnig *et al.*, Phys. Rev. Lett. **56** (1986)



optical fiber

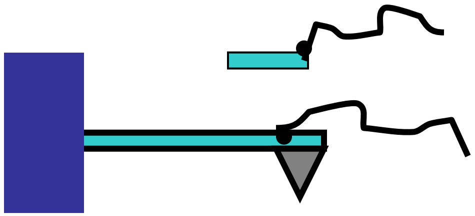
Martin *et al.*, J. App. Phys. **95** (1987)



focused
laser

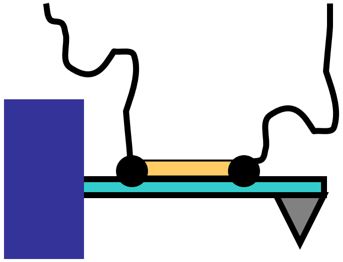
Marti *et al.*, J. Microscopy, **152** (1986)

G. Meyer and N. Amer, Appl. Phys. Lett. **53** (1988)



capacitance

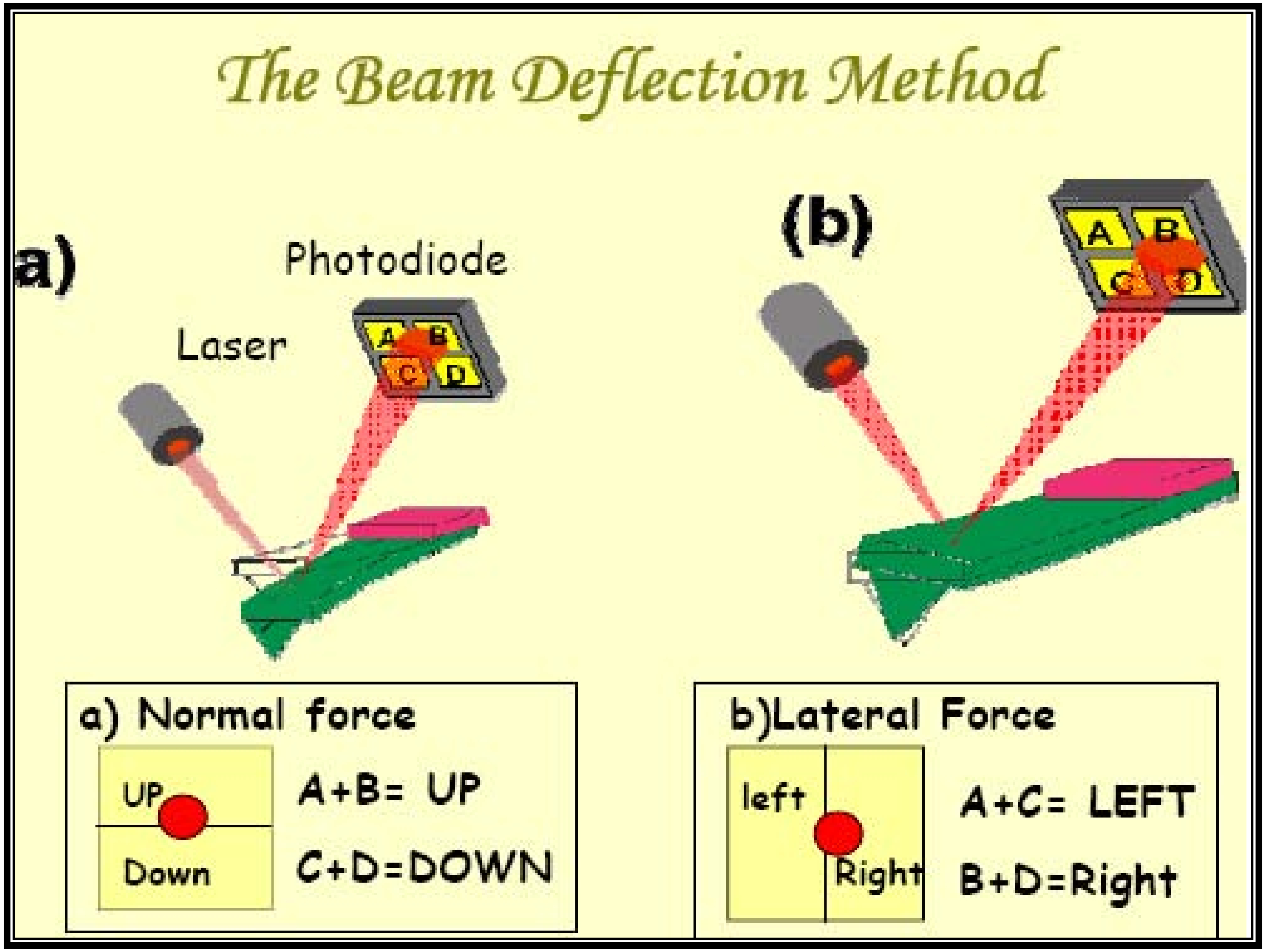
Göddenhenrich *et al.*, J. Vac. Sci. Technol. **A8** (1990)



piezoresistance

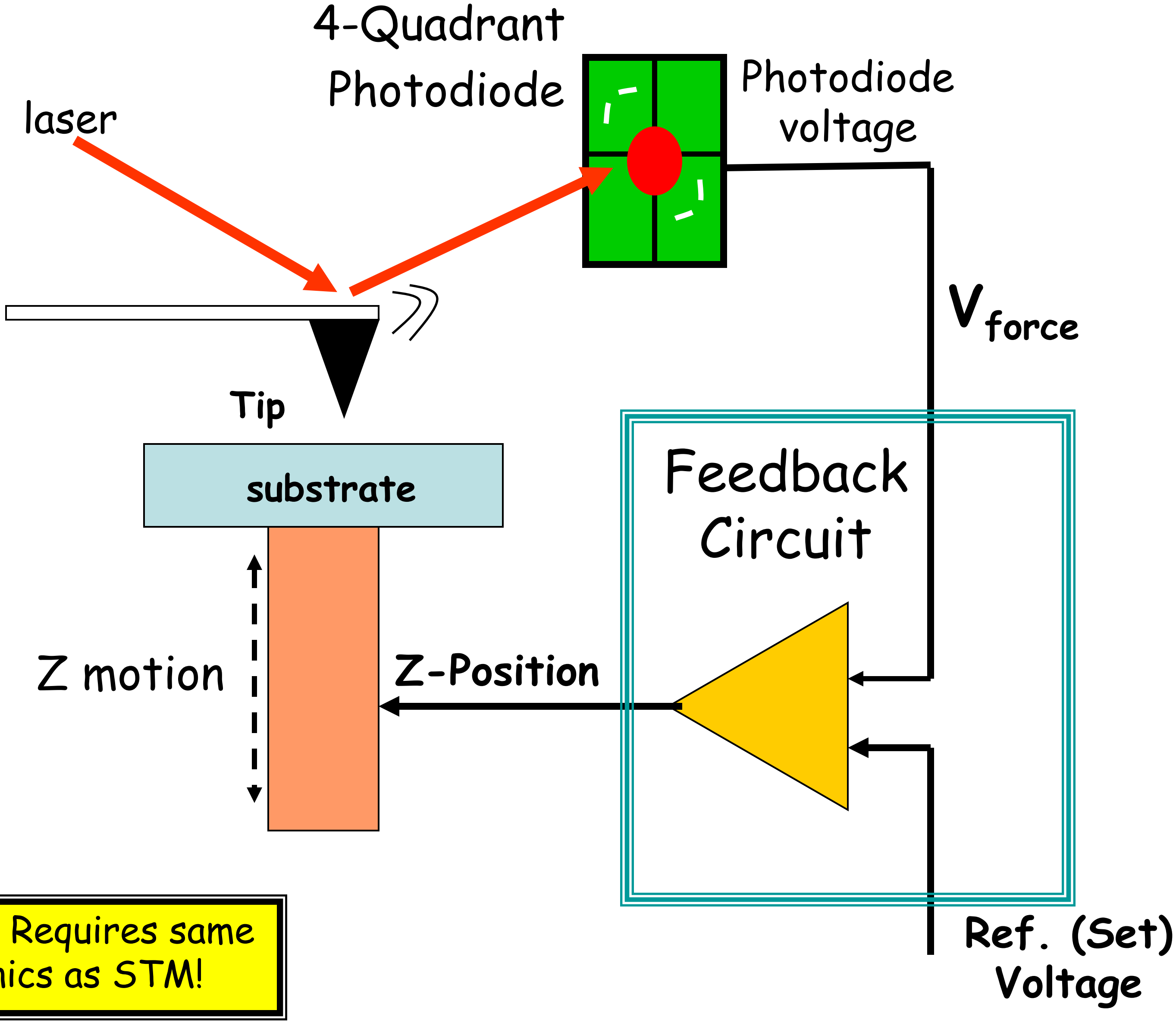
Tortonese *et al.*, App. Phys. Lett. **62** (1993)

The Method of Choice - Today



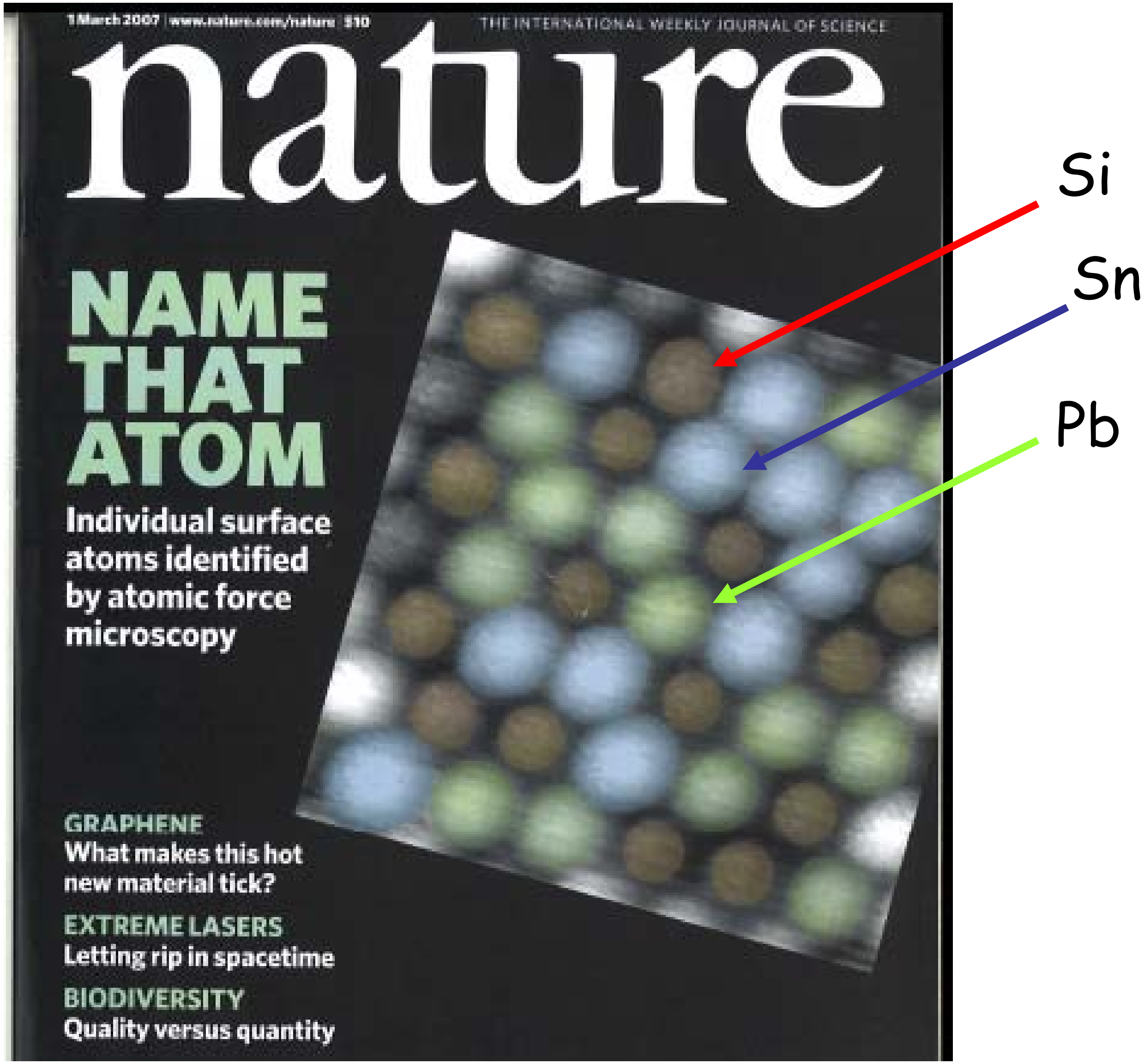
graphic by J. Gomez-Herrero

Maintaining a constant force



KEY IDEA: Requires same electronics as STM!

AFMs have come a long way



1 March 2007 | www.nature.com/nature | $10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

nature

NAME THAT ATOM

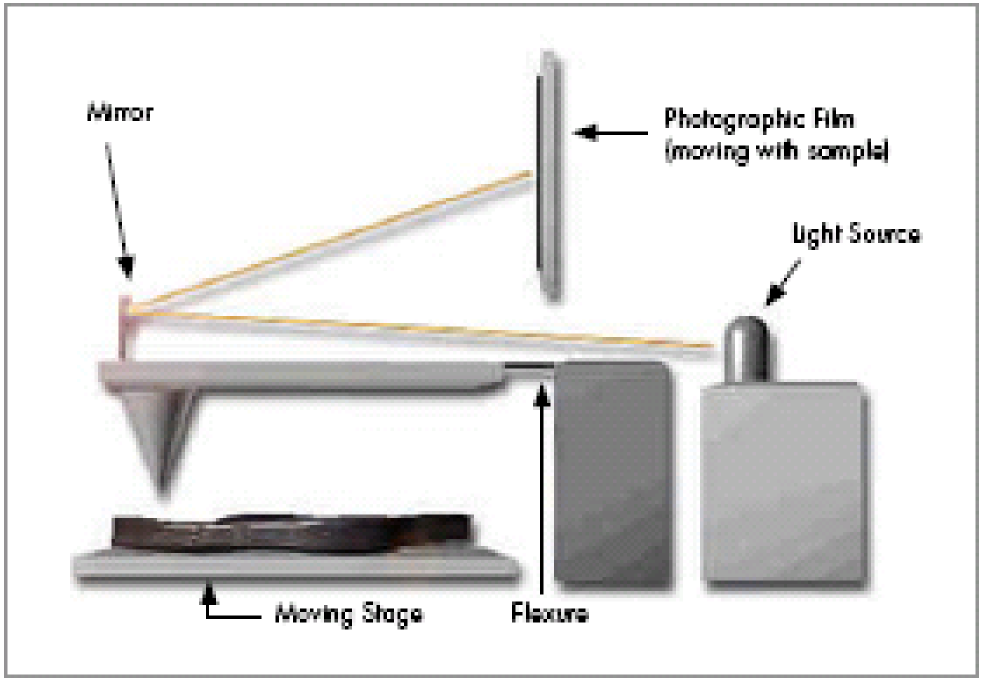
Individual surface atoms identified by atomic force microscopy

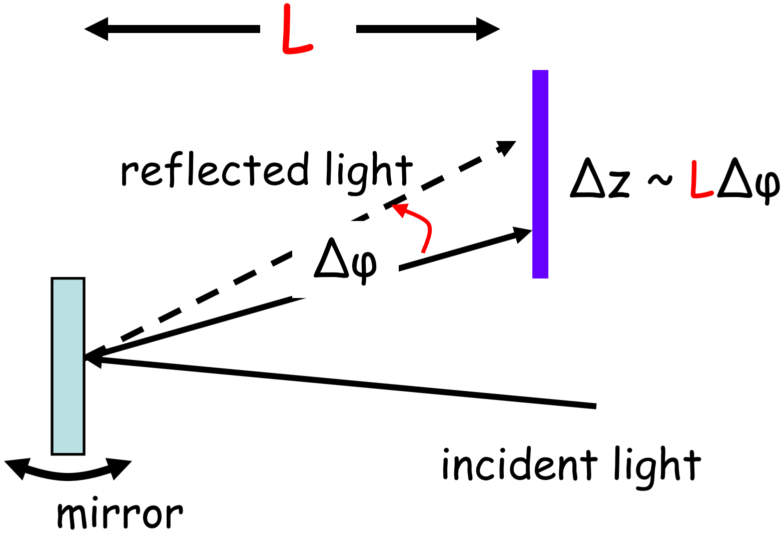
GRAPHENE
What makes this hot new material tick?

EXTREME LASERS
Letting rip in spacetime

BIODIVERSITY
Quality versus quantity

Early Stylus Profiler - Schmalz in 1929





The probe is in contact with the substrate

Stylus arm monitors up and down motion of sharp probe mounted at the end of a cantilever

Record motion of the stylus on photographic paper to obtain profile of surface

This “microscope“ can generate profile “images“ with a magnification of greater than 1000x

G. Schmalz, Verein Deutscher Ingenieure, Oct 12, 1929, pp. 1461-1467

Seeing with Proximal Probes – a Selected Timeline for Scanning Probe Microscopy

1981 – Binnig and Rohrer invent the first scanning probe microscope - the Scanning Tunneling Microscope (STM)

1986 – Binnig, Quate and Gerber invent the Atomic Force Microscope (AFM) – contact mode

1987 – non-contact scanning mode introduced

1988 – implementation of computer control

1989 – optical beam bounce introduced

1991 – microfabricated tips

1993 – intermittent contact mode introduced

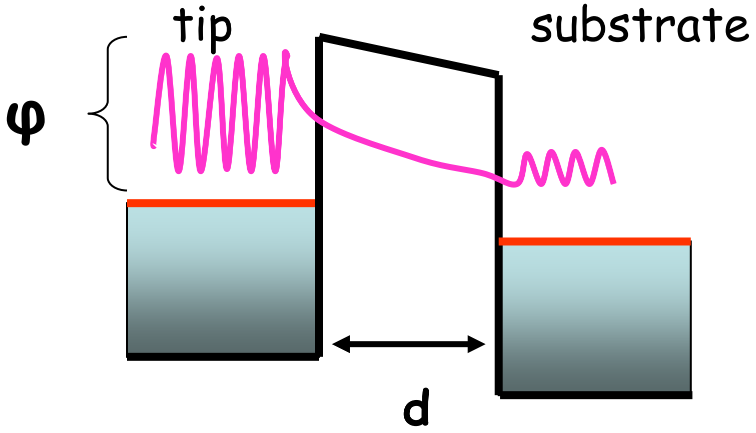
See also http://www.pacificnanotech.com/afm-history_single.html

A Checklist of Various Scanning Probe Techniques; SxM

Table adapted from *Nanotechnology: Towards a Molecular Construction Kit*, edited by A. ten Wolde (1998)

- **Scanning Tunneling Microscopy (STM)**
  - STM Techniques:
    - UHV STM - Ultra-high vacuum STM
    - STS - Scanning Tunneling Spectroscopy
    - CITS - Current Imaging Tunneling Microscopy
    - BEEM – Ballistic Electron Emission Spectroscopy
    - Tunneling Acoustic Microscopy
    - AC-STM - Alternating Current Scanning Tunneling Microscopy
- **Atomic Force Microscopy (AFM)/Scanning Force Microscopy (SFM)**
  - Contact-mode AFM Techniques:
    - FFM - Friction Force Microscopy
    - SFFM - Scanning Friction Force Microscopy
    - SHFM - Shear-Force Microscopy
    - FMM - Force Modulation Microscopy
    - AFAM - Atomic Force Acoustic Microscopy
    - SLAM - Scanning Local-Acceleration Microscopy
    - CAFM – Conductance Atomic Force Microscopy
- **Dynamic Force Microscopy (DFM)**
  - AM DFM - Amplitude Modulation DFM
  - FM DFM - Frequency Modulation DFM
  - DFM Techniques:
    - CFM - Chemical Force Microscopy
    - EFM - Electrostatic Force Microscopy
    - KFM - Kelvin Force Microscopy
    - MFM - Magnetic Force Microscopy
    - MRFM - Magnetic Resonance Force Microscopy
    - SMM - Scanning Maxwell-Stress Microscopy
    - SNAM - Scanning Near-Field Acoustic Microscopy
- **Scanning Near-Field Optical Microscopy (SNOM)/Near Field Scanning Optical Microscopy (NSOM)**
    - SNOM/NSOM Techniques:
    - PSTM - Photon Scanning Tunneling Microscopy
    - SIAM - Scanning Interferometric Apertureless Microscopy
    - SPNM - Scanning Plasmon Near-Field Microscope
- **Scanning Thermal Microscopy (SThM)**
    - SOAM - Scanning Optical Absorption Microscopy
    - SCPM - Scanning Chemical-Potential Microscopy
- **Scanning Capacitance Microscopy (SCAM)**
- **Scanning Electrochemical Microscopy (SECM)**
    - SICM - Scanning Ion Conduction Microscopy
- **Scanning Spreading Resistance Microscopy (SSRM)**

STM – essentially an electrical measurement:



AFM – essentially a mechanical measurement: