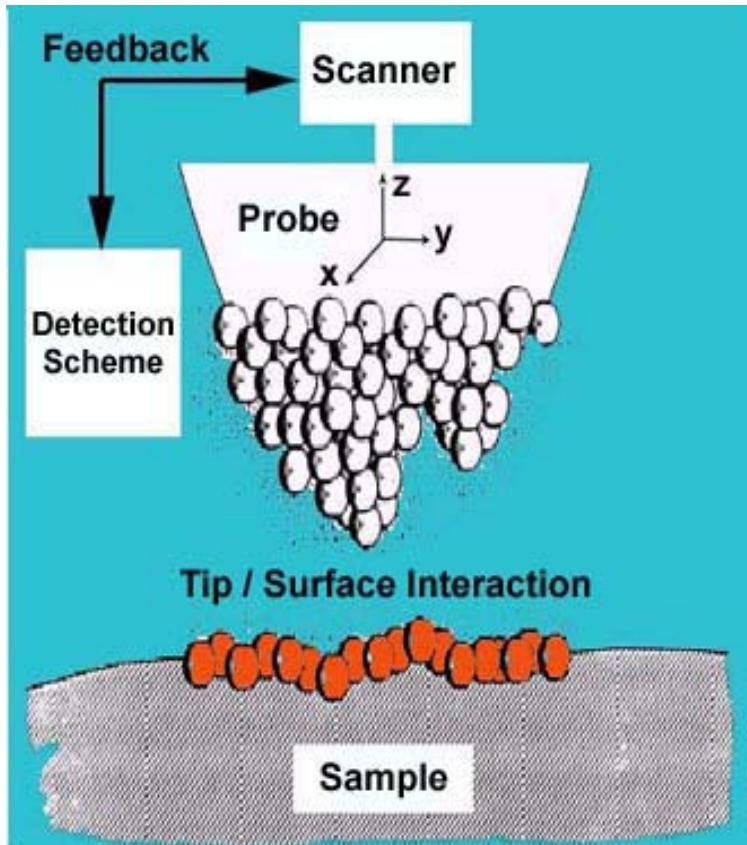


Scanning Probe Microscopy (SPM)



Scanning Tunneling Microscopy (STM)

--- G. Binnig, H. Rohrer et al, (1982)

Near-Field Scanning Optical Microscopy (NSOM)

--- D. W. Pohl (1982)

Atomic Force Microscopy (AFM)

--- G. Binnig, C. F. Quate, C. Gerber (1986)

Scanning Thermal Microscopy (SThM)

--- C. C. Williams, H. Wickramasinghe (1986)

Magnetic Force Microscopy (MFM)

--- Y. Martin, H. K. Wickramasinghe (1987)

Friction Force Microscopy (FFM or LFM)

--- C. M. Mate et al (1987)

Electrostatic Force Microscopy (EFM)

--- Y. Martin, D. W. Abraham et al (1988)

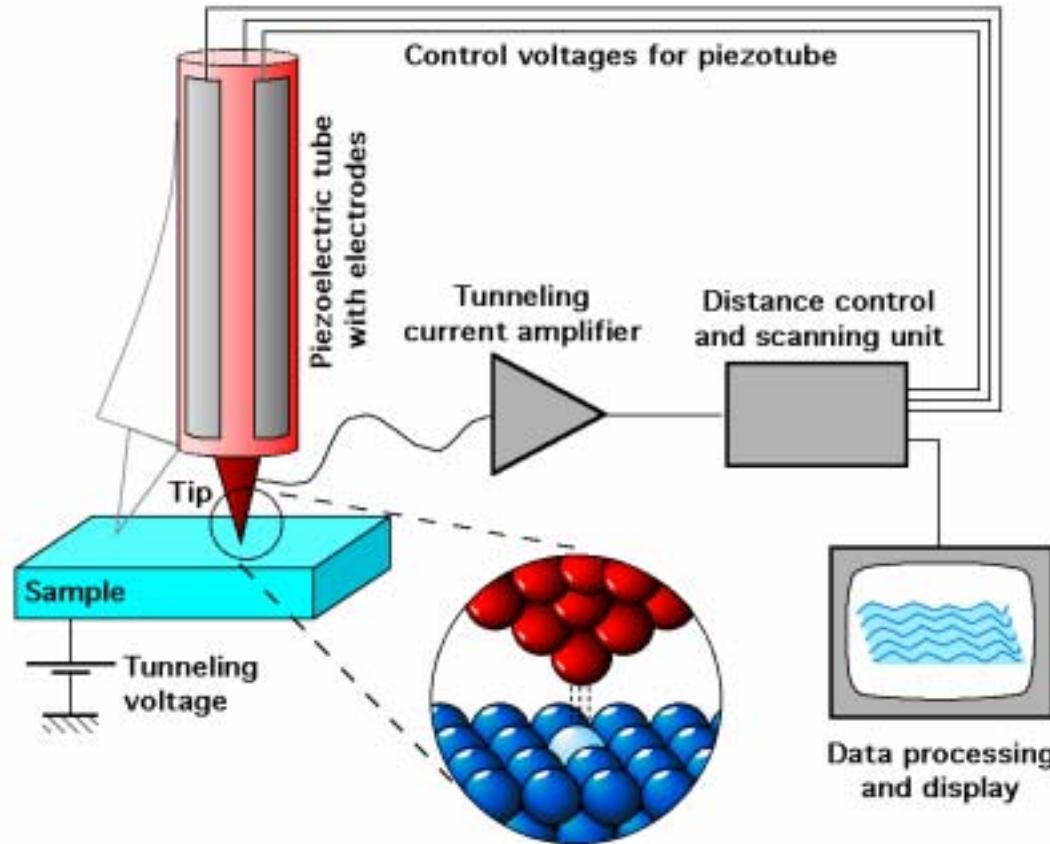
Scanning Capacitance Microscopy (SCM)

--- C. C. Williams, J. Slinkman et al (1989)

Force Modulation Microscopy (FMM)

--- P. Maivald et al (1991)

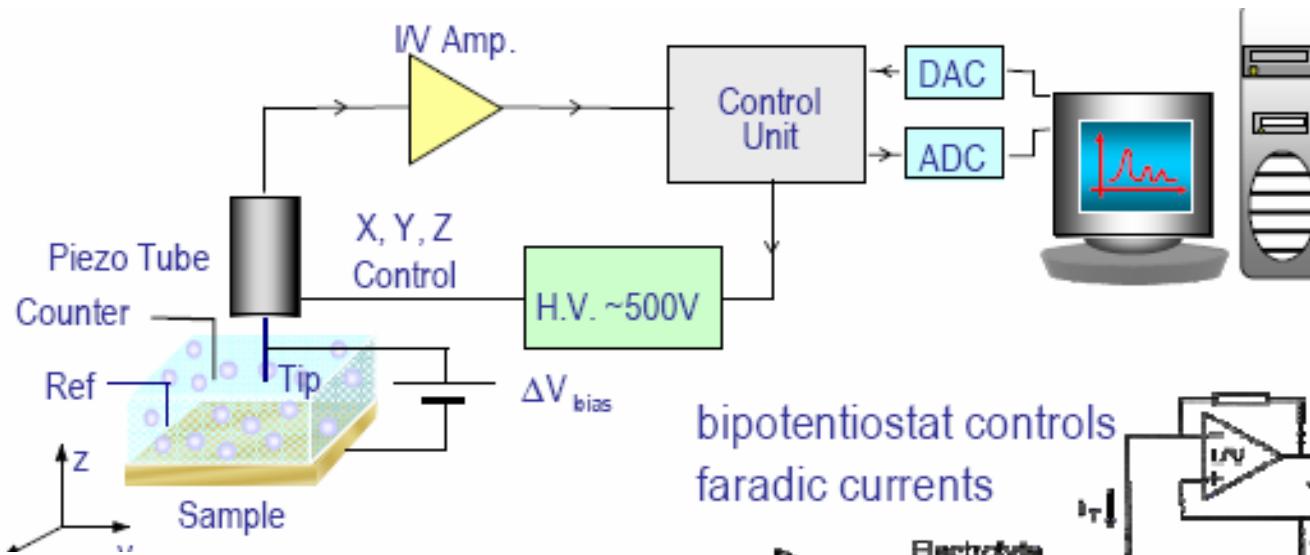
Scanning Tunneling Microscopy



Re

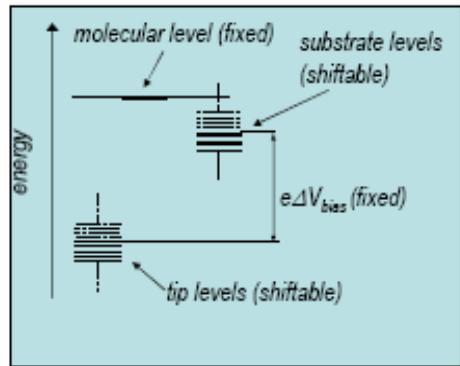
1. G. Binnig, H. Rohrer, C. Gerber, and Weibel, Phys. Rev. Lett. **49**, 57 (1982); and *ibid* **50**, 120 (1983).
2. J. Chen, *Introduction to Scanning Tunneling Microscopy*, New York, Oxford Univ. Press (1993).

Electrochemical STM

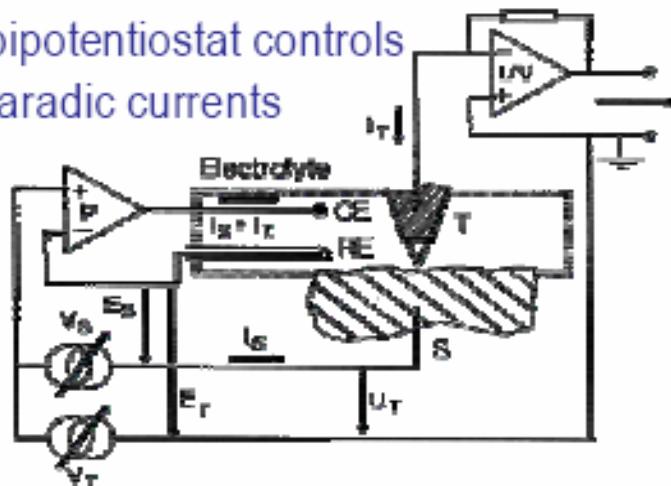


key feature:
electronic spectroscopy
of redox molecules

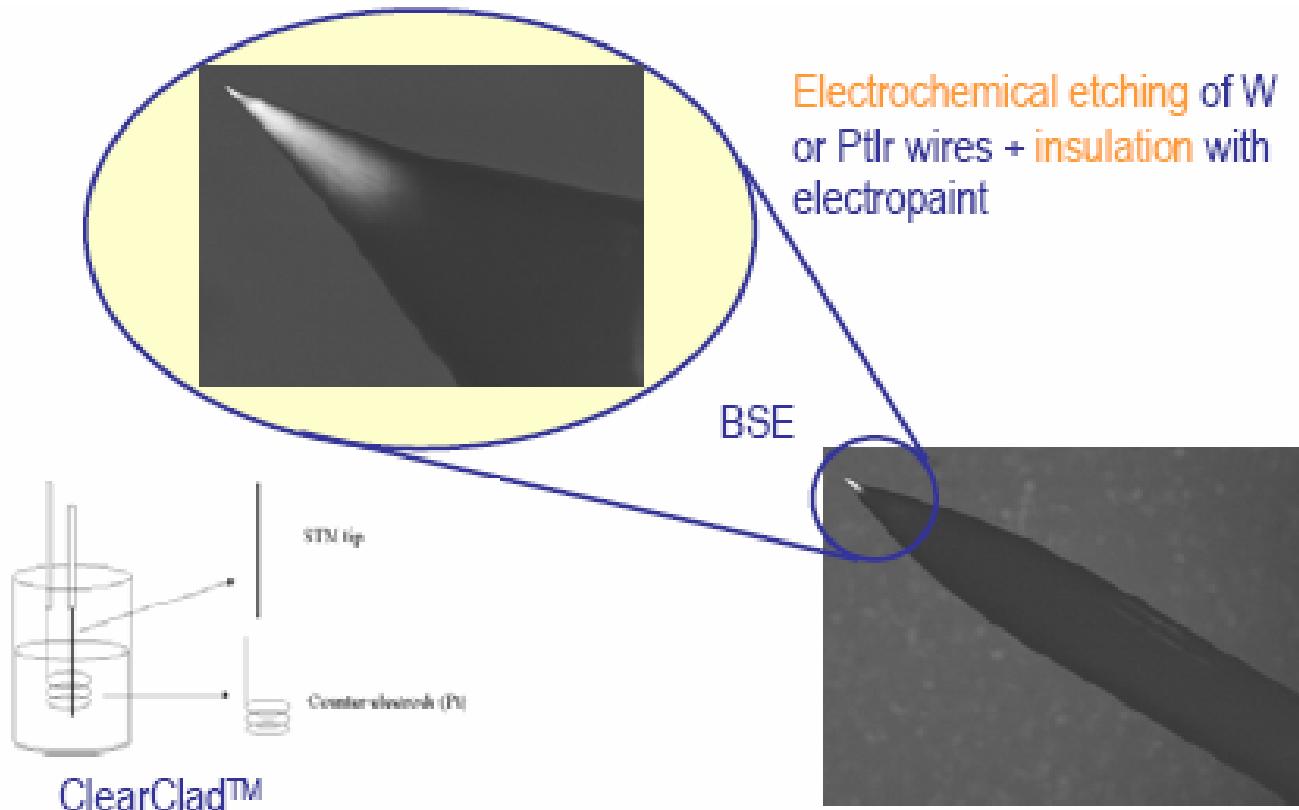
$$V_t = V_s + \Delta V_{bias}$$



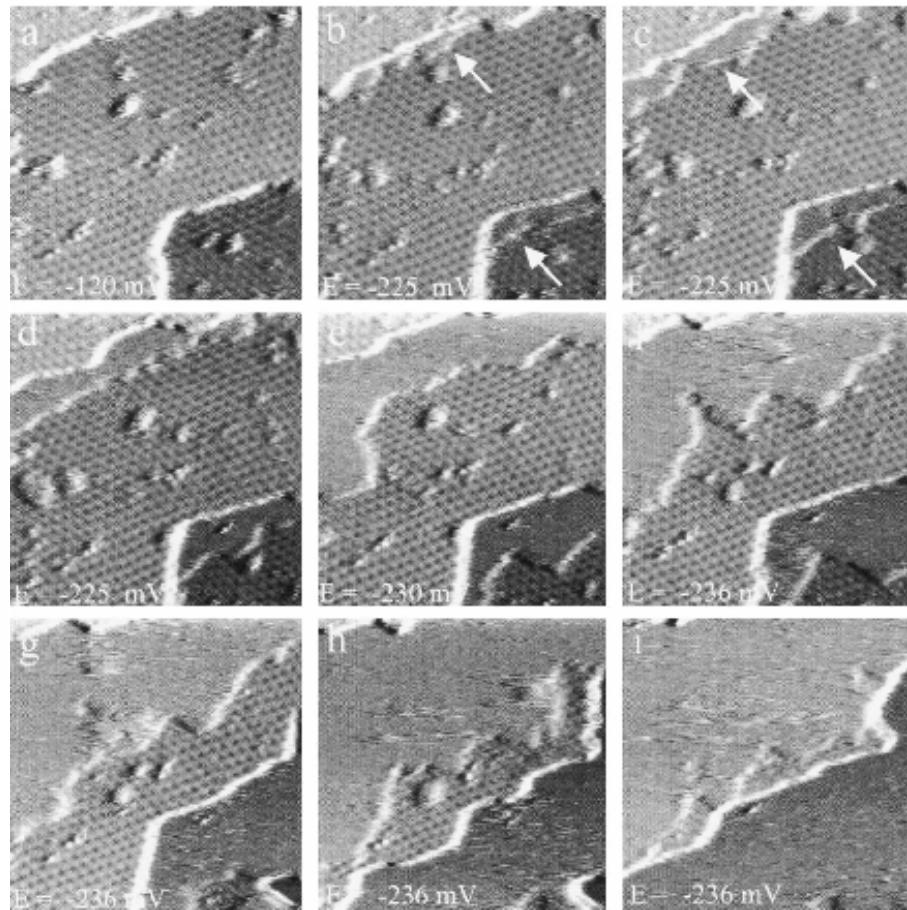
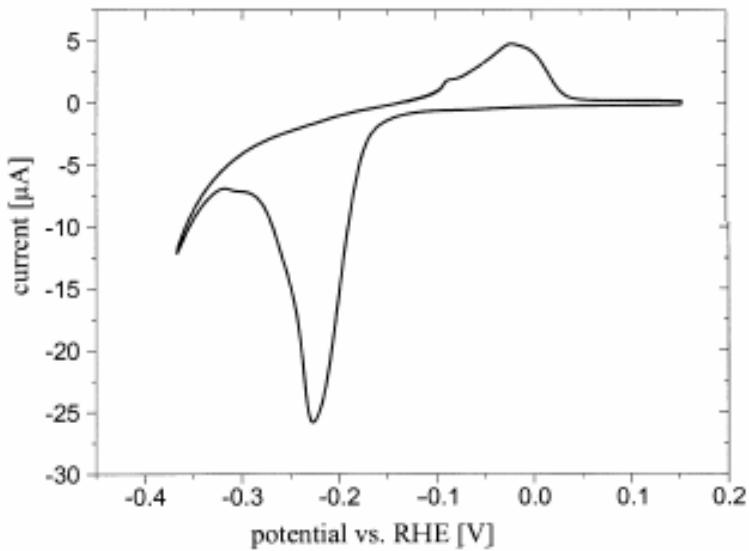
bipotentiostat controls
faradic currents



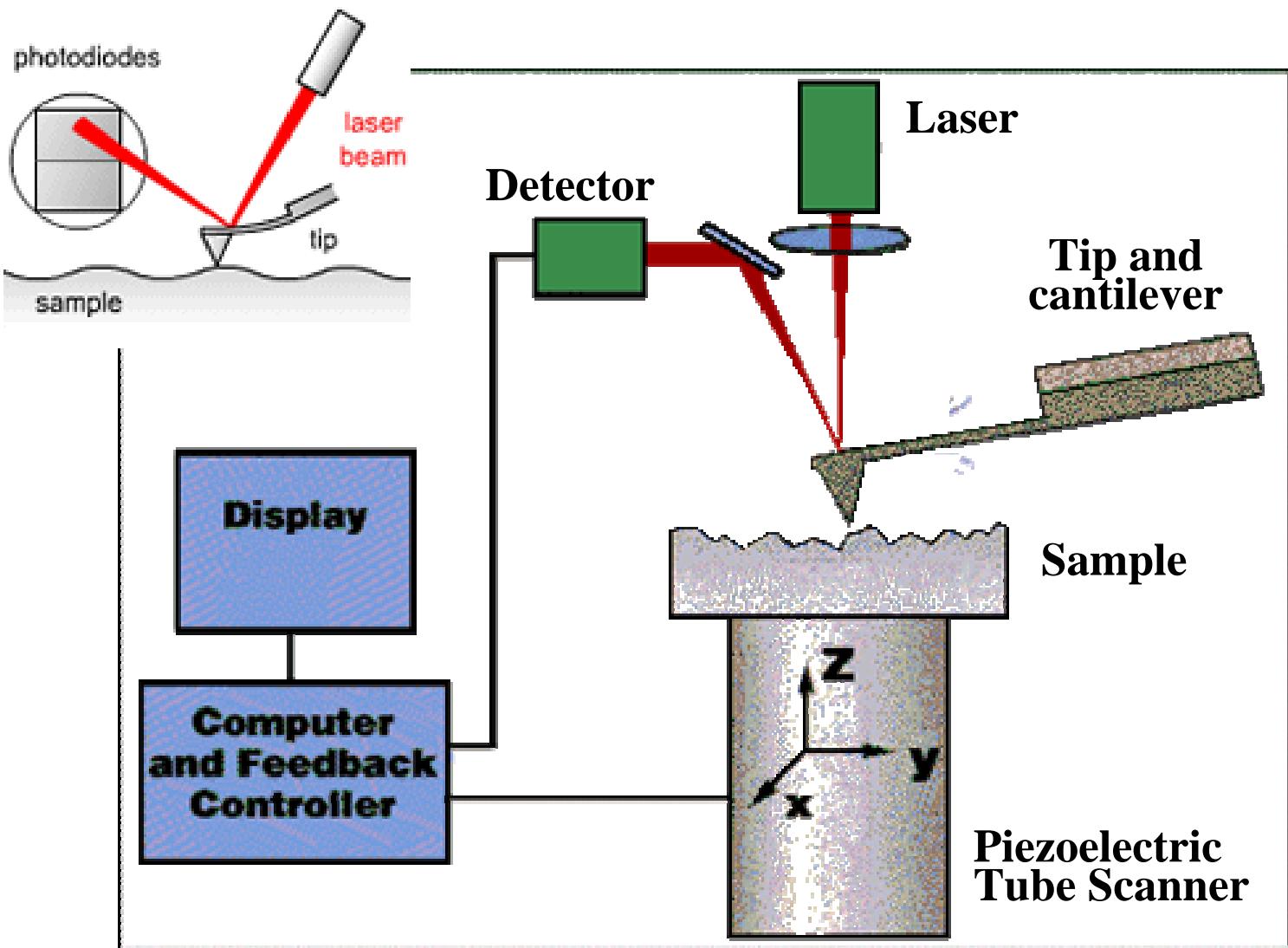
Fabrication of Tip for EC-STM



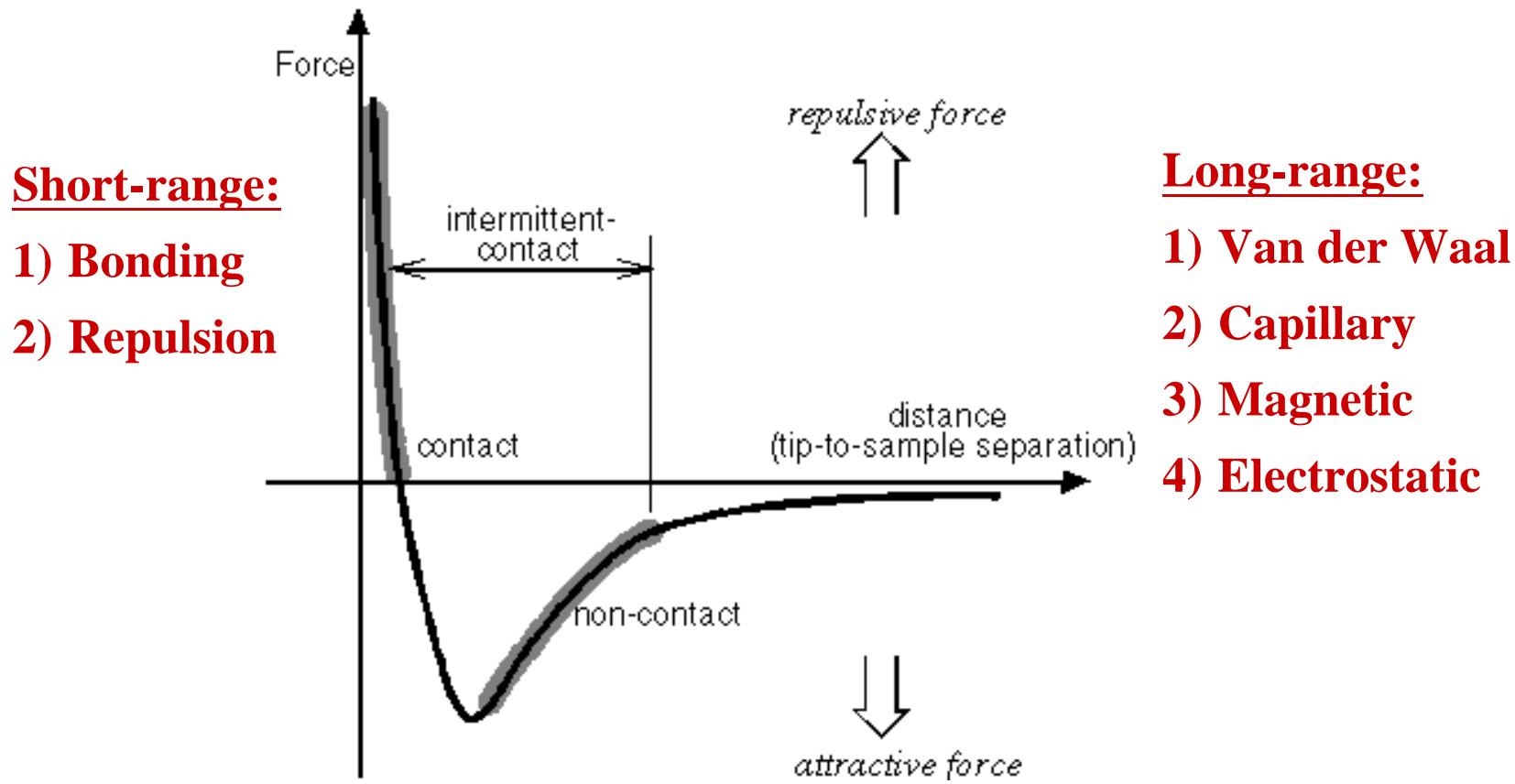
Sulfate adsorption on Cu (111)



Core components of AFM

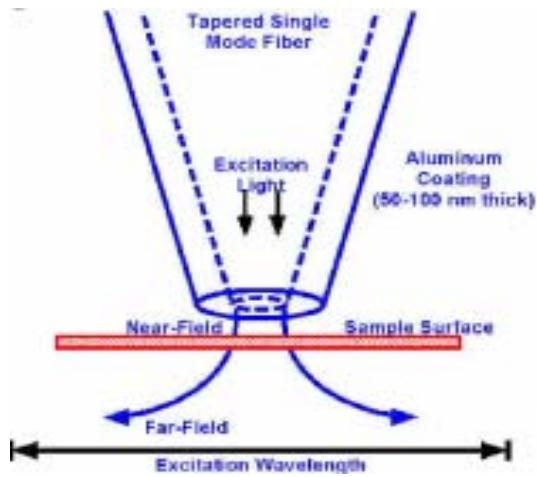
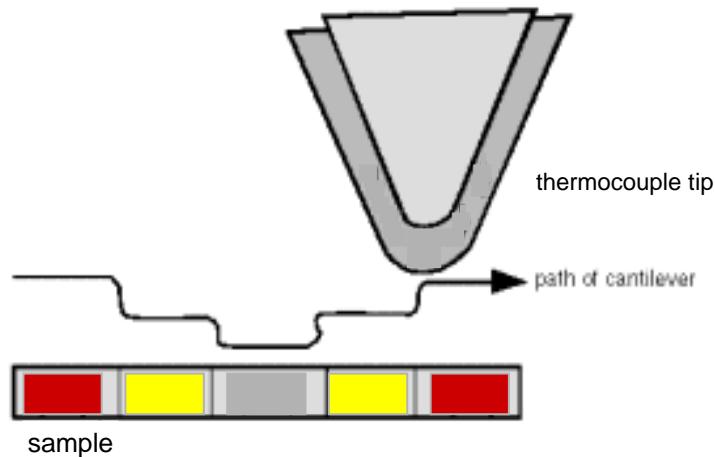
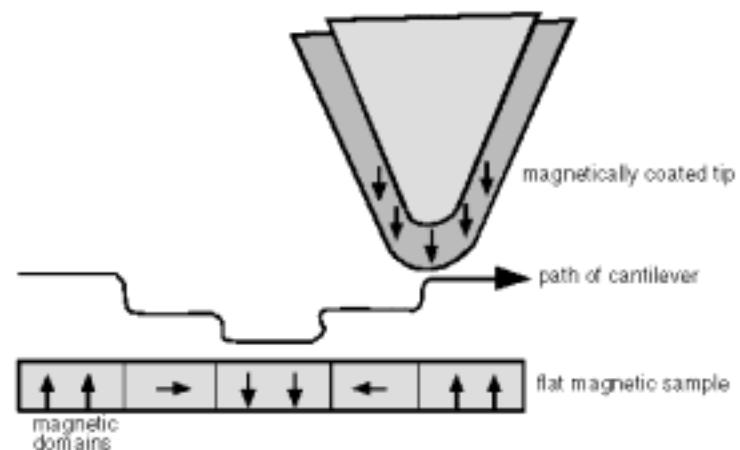
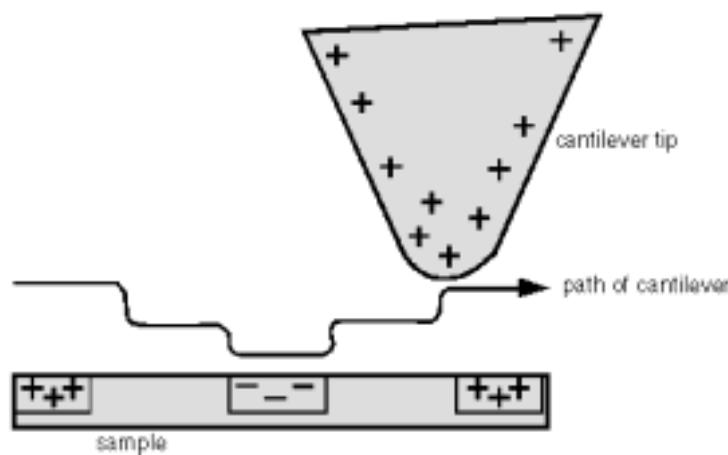


Interaction between the probe and sample

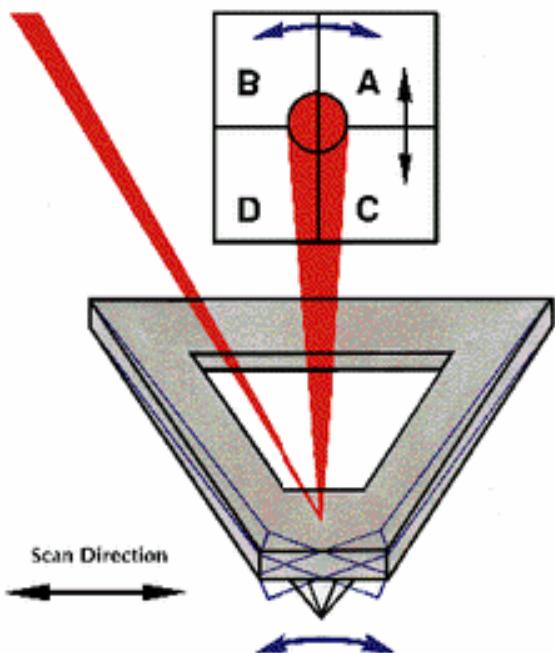


$$\text{Lennard-Jones potential } \phi(r) = - A/r^6 + B/r^{12}$$

Probes of various functions

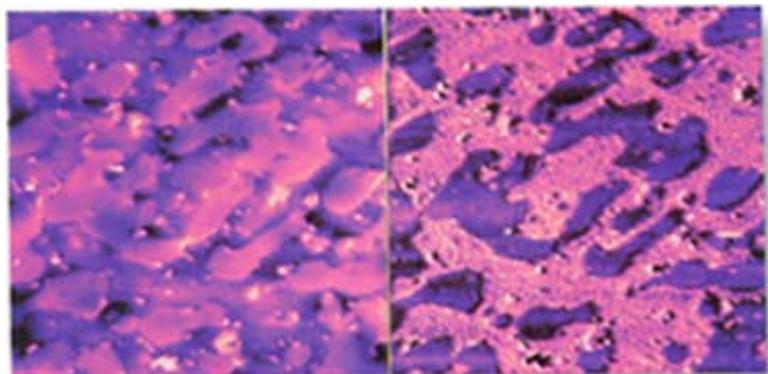


Lateral Force Microscopy



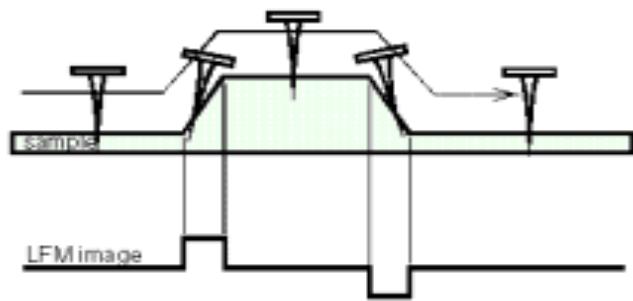
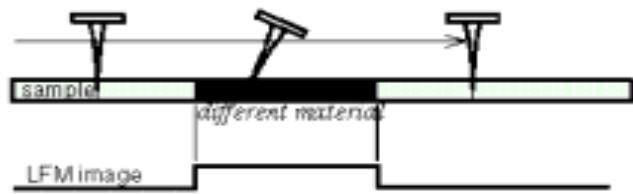
$$(A+C) - (B+D)$$

- LFM is sensitive to friction and chemical forces.
- Image contrast depends on the scanning direction.
- Surface roughness will contribute to the contrast.



Topography LFM

Nature rubber/EDPM blend

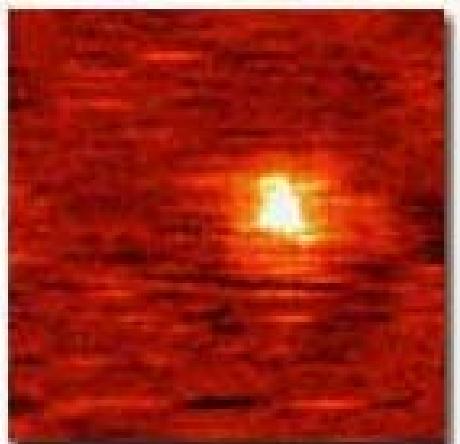
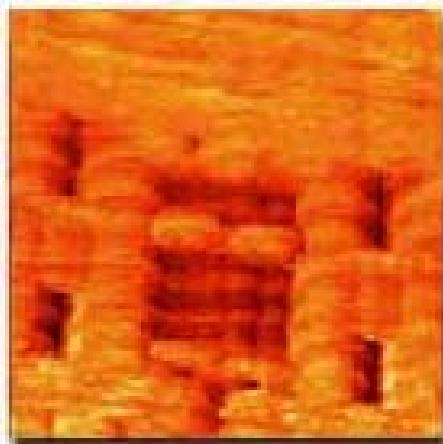
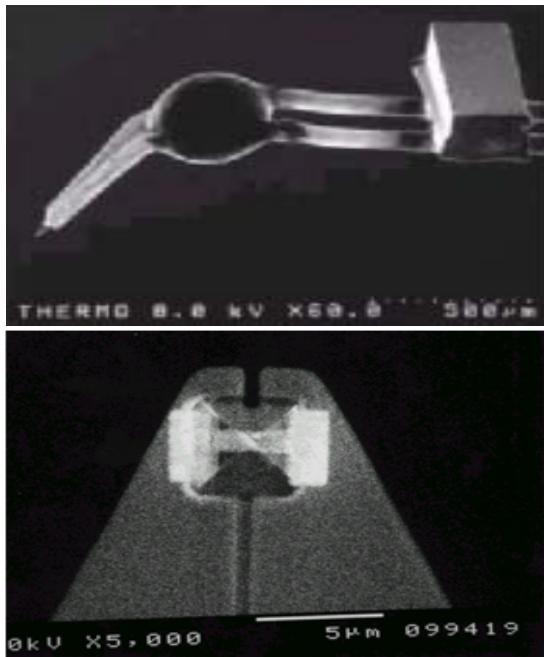
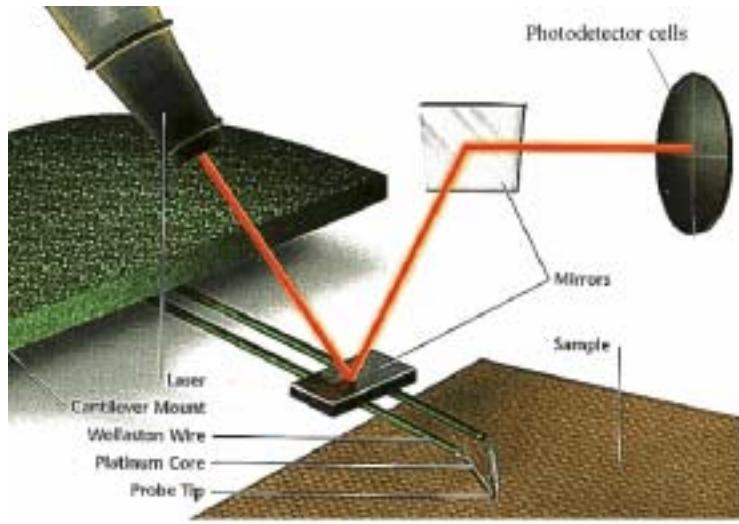


Chemical Force Microscopy



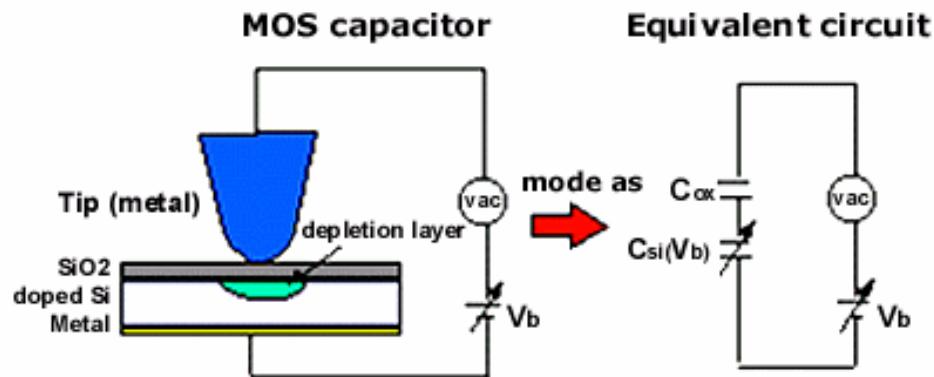
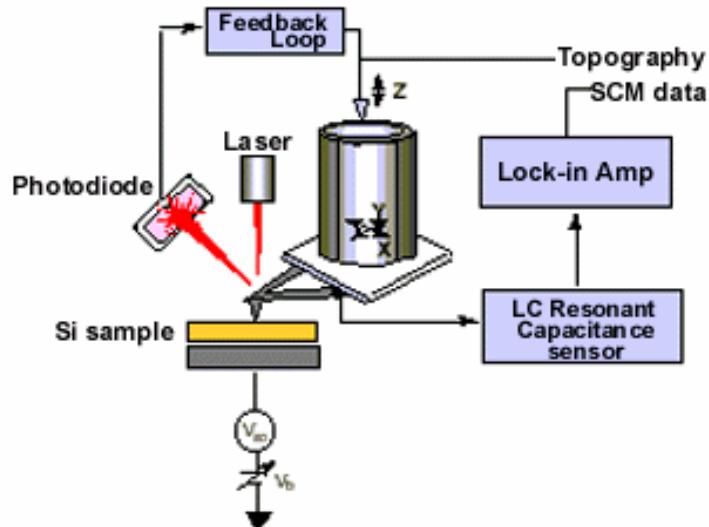
CFM scan of well-defined regions that terminate in either methyl or carboxylic acid groups. When a carboxylic acid-terminated tip is used for imaging (left), the carboxylic acid-terminated regions exhibit greater frictional force (lighter color) than the methyl-terminated regions. When a methyl-terminated tip is used (right), the friction contrast is reversed. No differences are revealed by the topographic AFM scan (not shown) since the functional groups are structurally quite similar. Image courtesy of Dr. C. Lieber, Harvard University.

Scanning Thermal Microscopy (SThM)

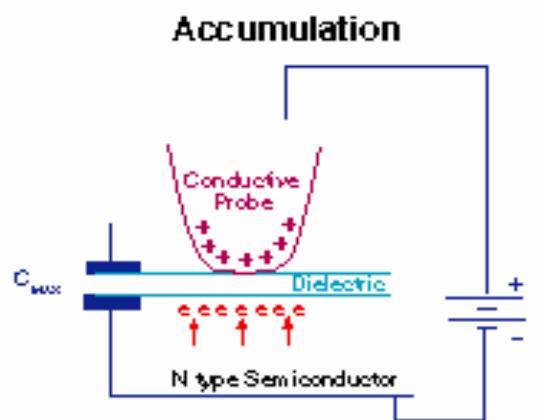
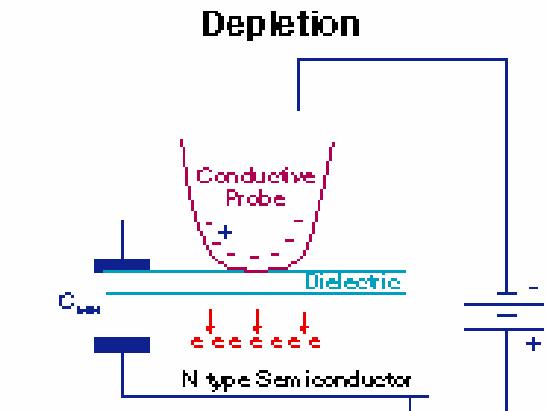
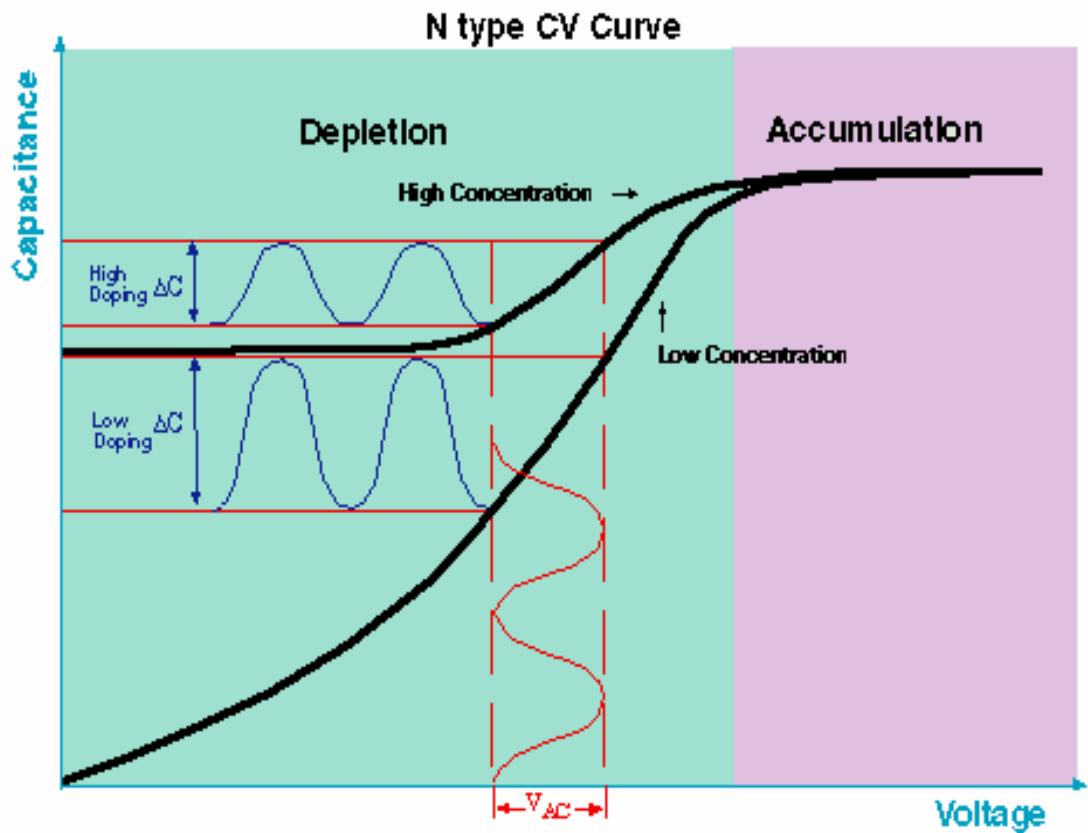


Scanning Capacitance Microscopy (SCM)

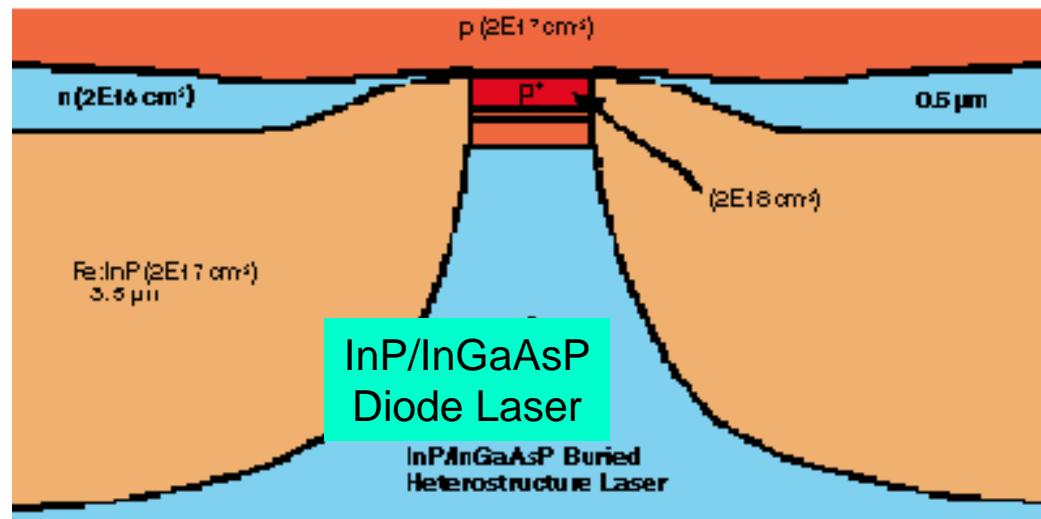
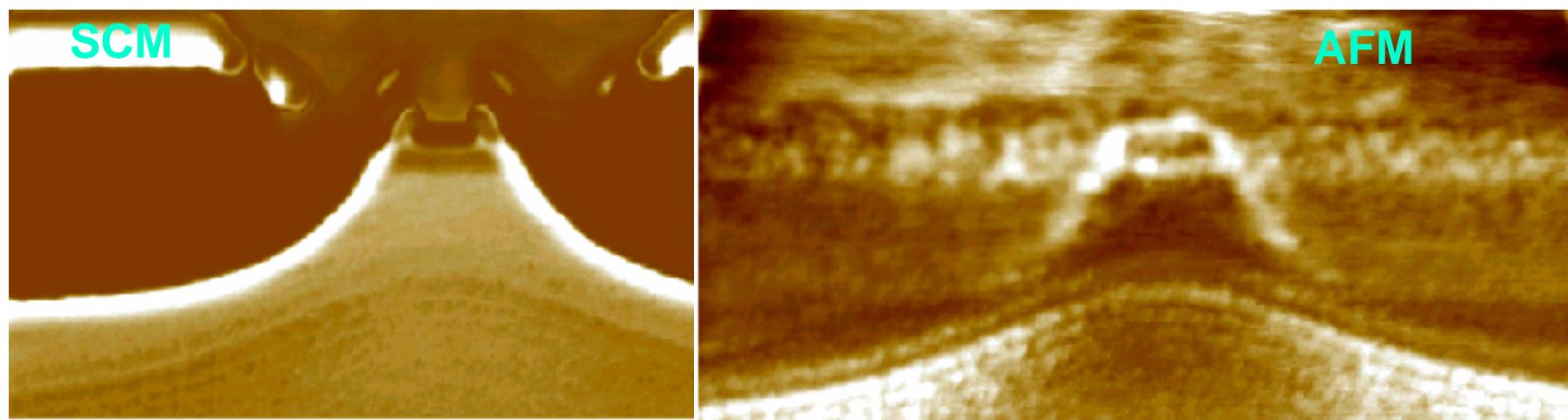
Operational principle of the SCM



SCM CV Curve



Scanning Capacitance Microscopy



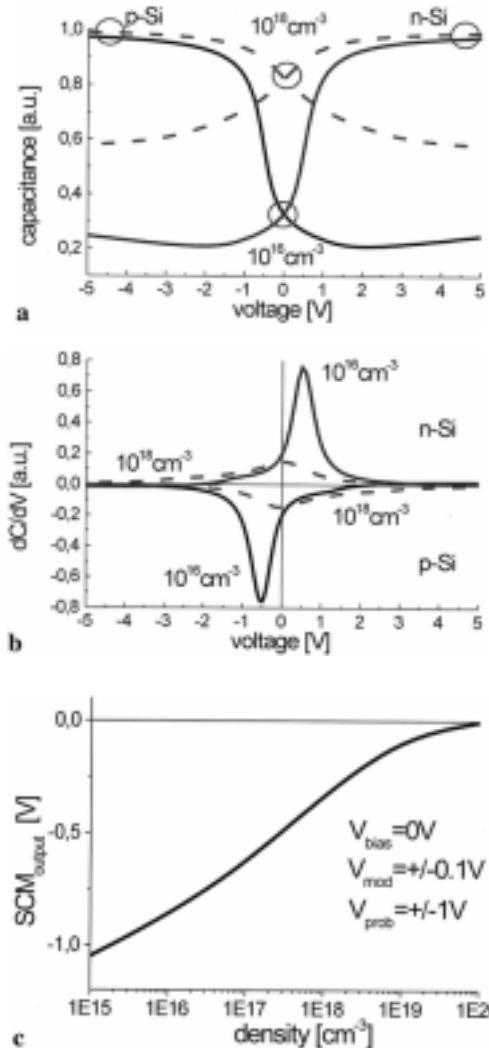


Fig. 2a-c. 3D simulations of SCM on homogeneously doped samples. The tip ($r_s = 25 \text{ nm}$, $r_t = 25 \text{ nm}$, $\alpha = 20^\circ$) is modelled in cylindrical coordinates; $d_{\text{tip}} = 10 \text{ nm}$. **a** $C(V)$ curves on p- and n-doped silicon with dopant concentrations of 10^{16} cm^{-3} and 10^{18} cm^{-3} , respectively. **b** The corresponding $dC/dV(V)$ curves are calculated analytically. **c** The calibration curve is calculated from $C(V)$ -curve simulations. The SCM output is calculated as $\Delta C/\Delta V(V)$ at $V_{\text{bias}} = 0 \text{ V}$ taking $V_{\text{mod}} = \pm 0.1 \text{ V}$ and $V_{\text{prob}} = \pm 1 \text{ V}$ into account.

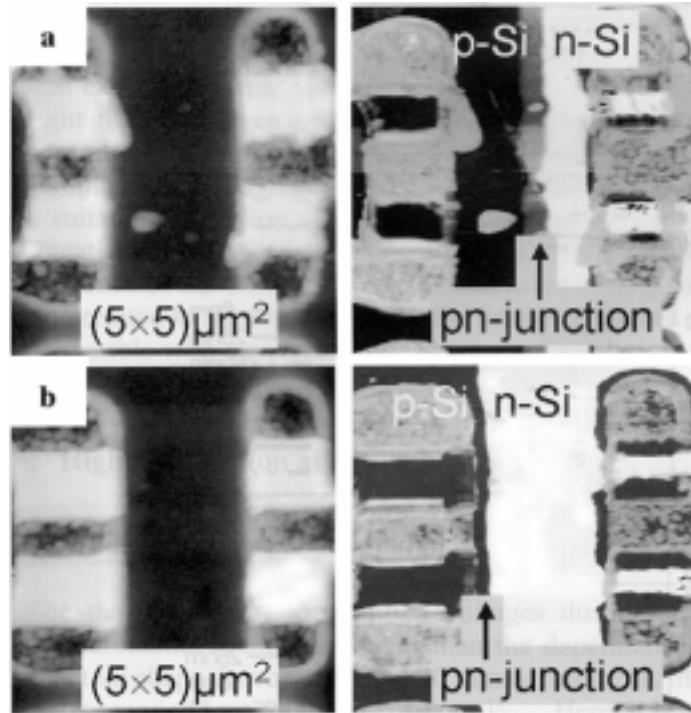


Fig. 3a,b. Failure analysis of an industrial device by means of SCM. Topography (left-hand side) and SCM image (right-hand side) are taken simultaneously. **a** Well-operating device with the pn junction implanted in the middle between the poly-silicon contacts. **b** Defective device with the pn junction shifted to the left-hand contacts. Both devices were measured at the same V_{bias} corresponding to the "zero voltage" (see text)

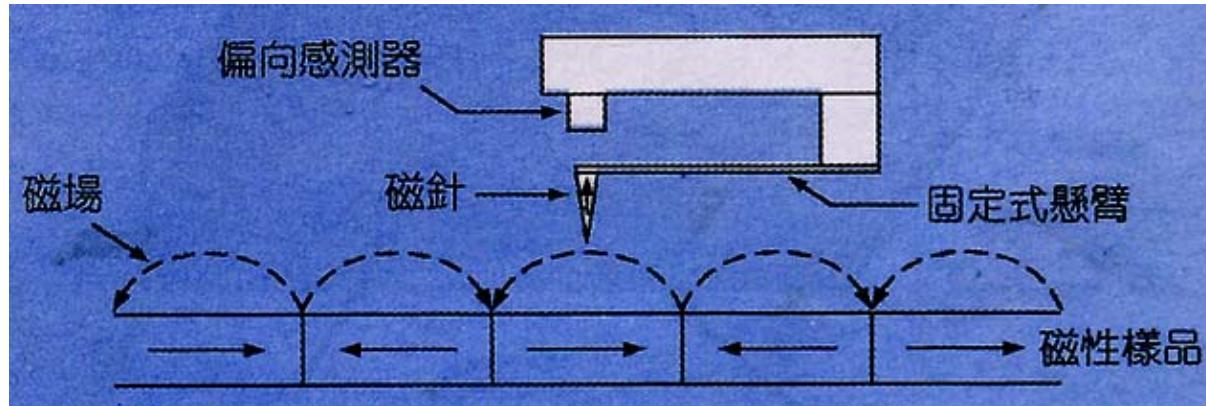
J. Isenbart et al., Appl. Phys. A 72, S243 (2001).

1. **Most SCMs are based on contact-mode AFM with a conducting tip.**
2. **In SCM, the sample (or the metallic tip) is covered with a thin dielectric layer, such that the tip-sample contact forms a MIS capacitor, whose C-V behavior is determined by the local carrier concentration of the semiconductor sample.**
3. **By monitoring the capacitance variations as the probe scans across the sample surface, one can measure a 2D carrier concentration profile.**
4. **One usually measures the capacitance variations (dC/dV), not the absolute capacitance values.**
5. **No signal is measured if the probe is positioned over a dielectric or metallic region since these regions cannot be depleted.**

References:

1. C.C. Williams, *Annu. Rev. Mater. Sci.* **29**, 471 (1999).
2. P.D. Wolf et al., *J. Vac. Sci. Technol. B* **18**, 361 (2000).
3. R.N. Kleiman et al., *J. Vac. Sci. Technol. B* **18**, 2034 (2000).
4. H. Edwards, et al., *J. Appl. Phys.* **87**, 1485 (2000).
5. J. Isenbart et al., *Appl. Phys. A* **72**, S243 (2001).

Magnetic Force Microscopy (MFM)



$$\mathbf{F} = \nabla(\mathbf{m} \cdot \mathbf{H})$$

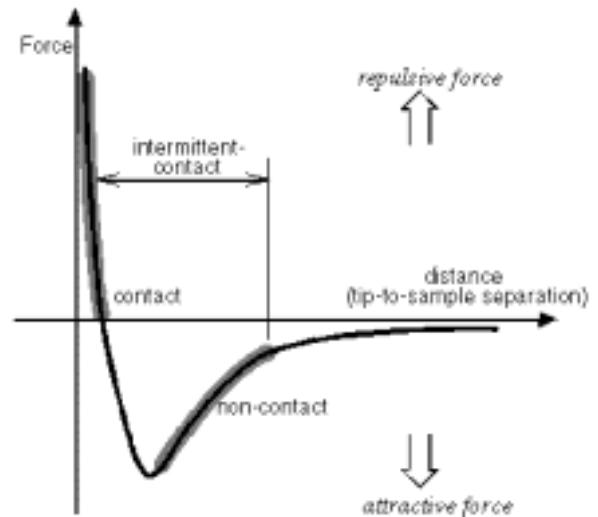
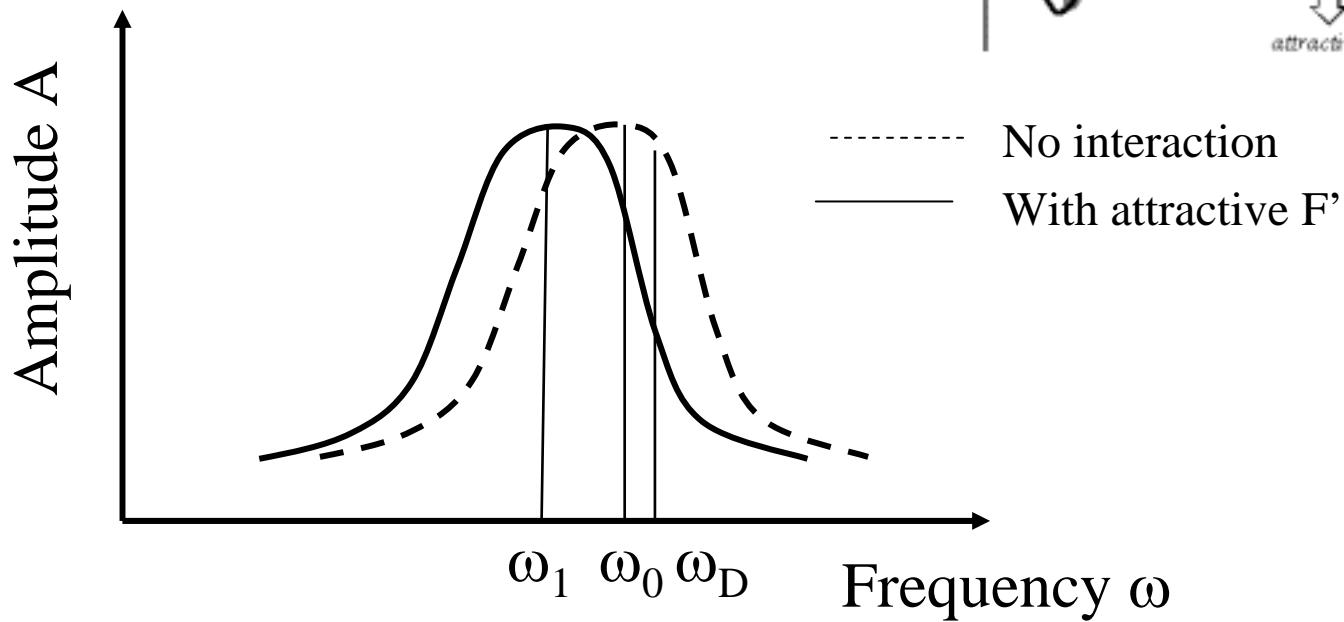
Tips: silicon probes are magnetically sensitized by sputter coating with a ferromagnetic material.

Resolution: 10 ~ 25 nm.

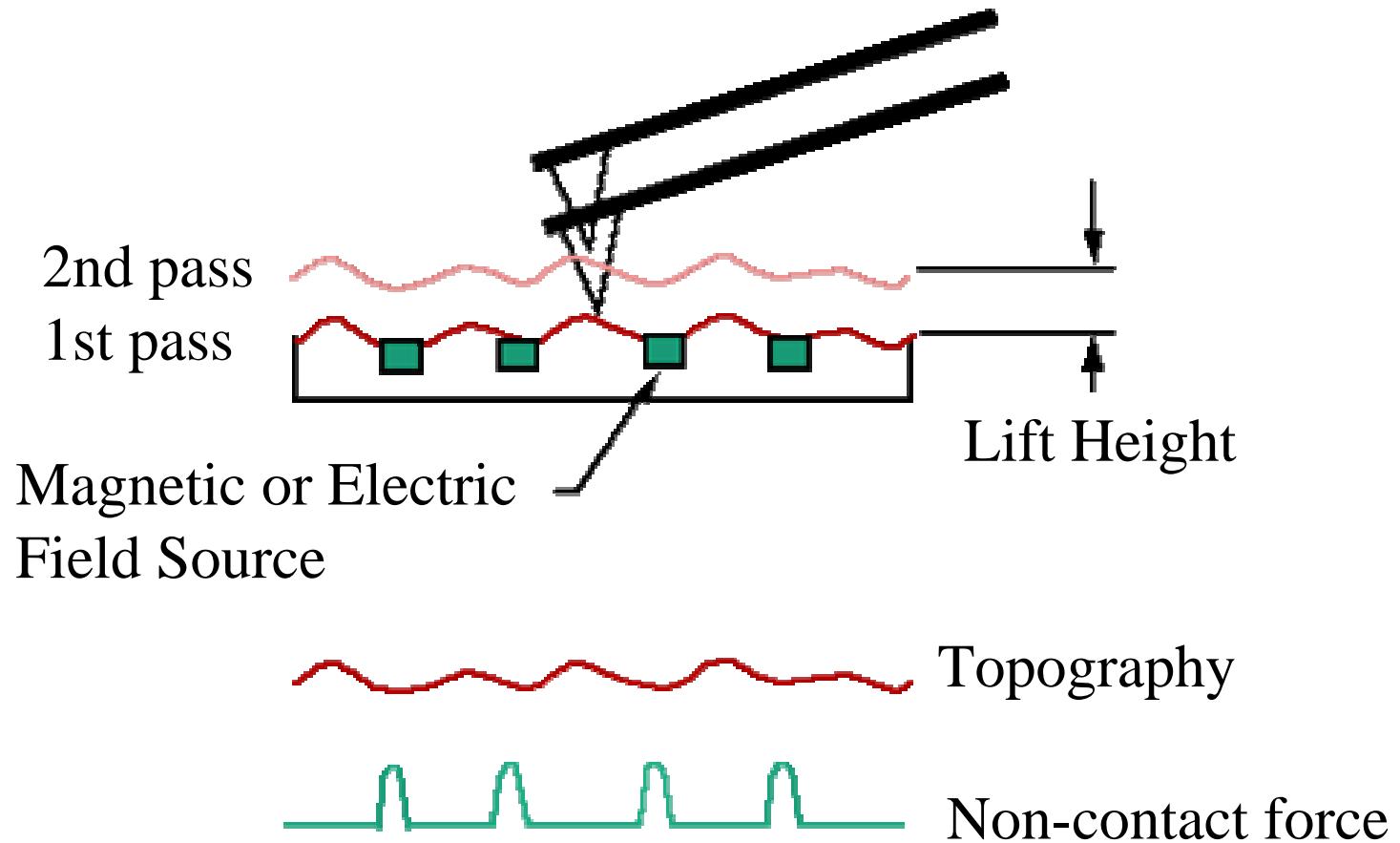
Applications: hard disks, magnetic thin film materials, micromagnetism.

AC imaging mode

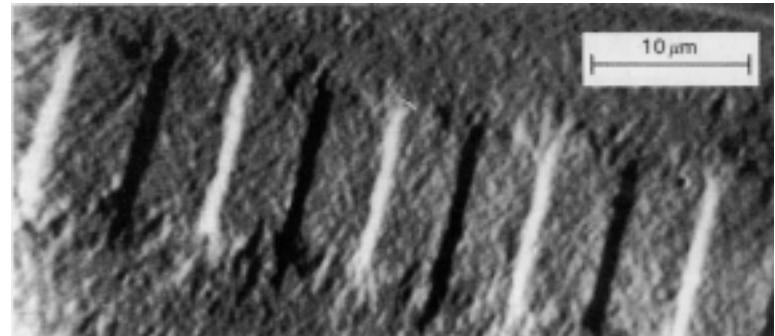
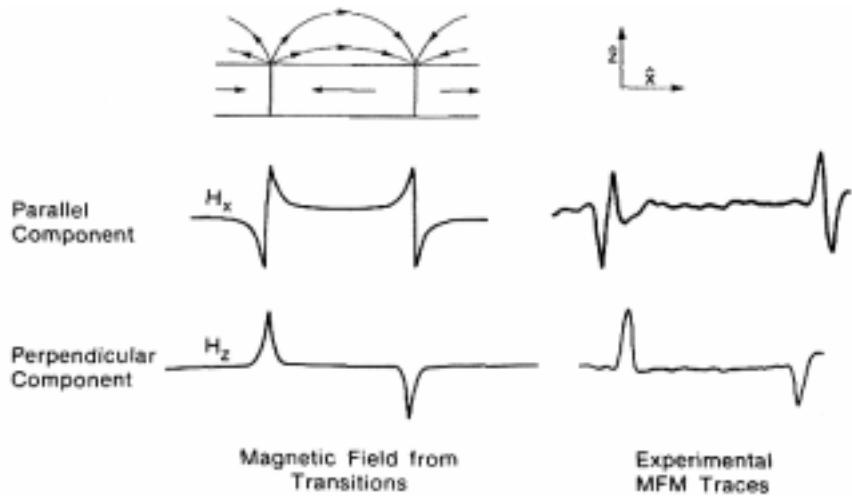
$$\omega_1 = \omega_0 (1 - F'/2k)$$



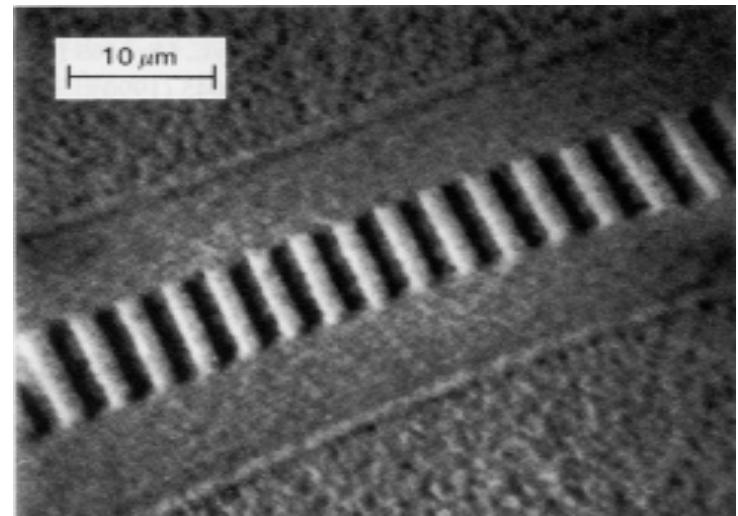
Lift mode of AFM



MFM Images



$$\mathbf{m}^T = m_z$$



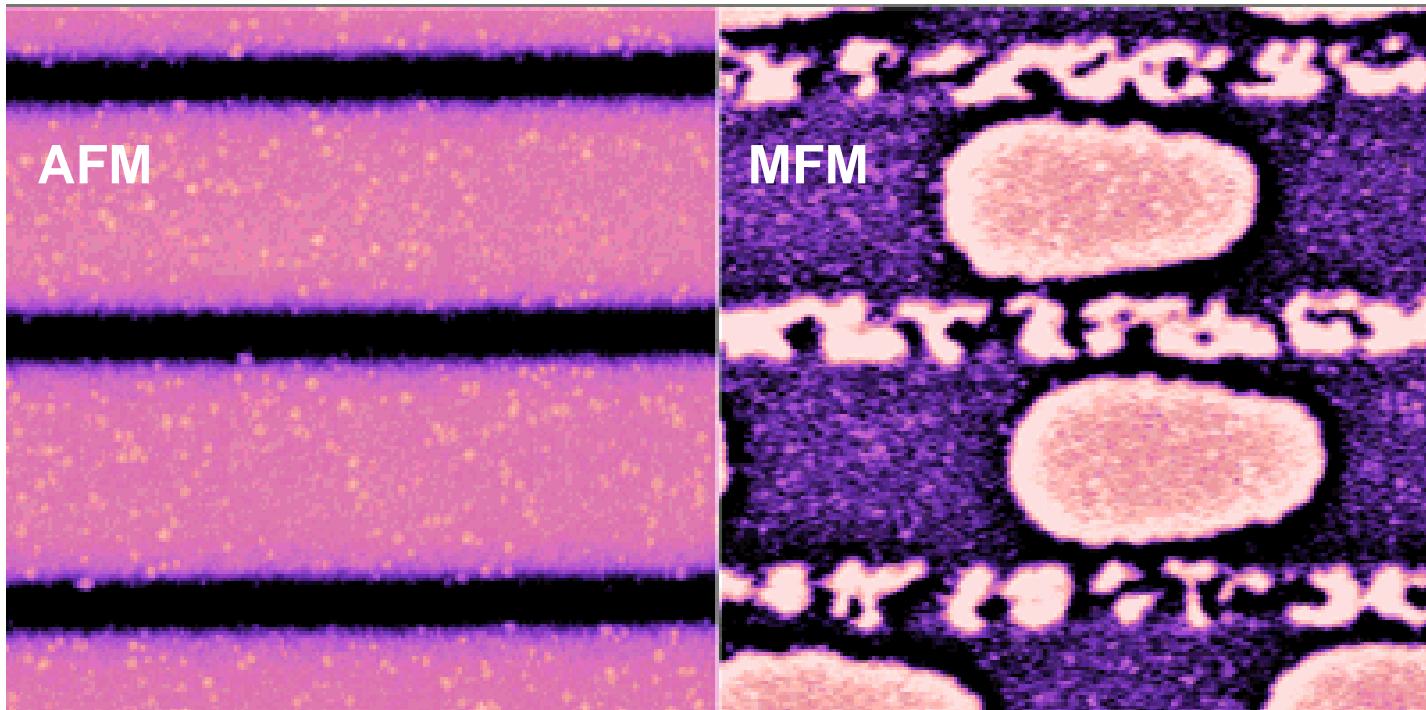
Tip as a point dipole

$$F_z = \partial(m_x H_x + m_y H_y + m_z H_z)/\partial z$$

Tip as a long rod

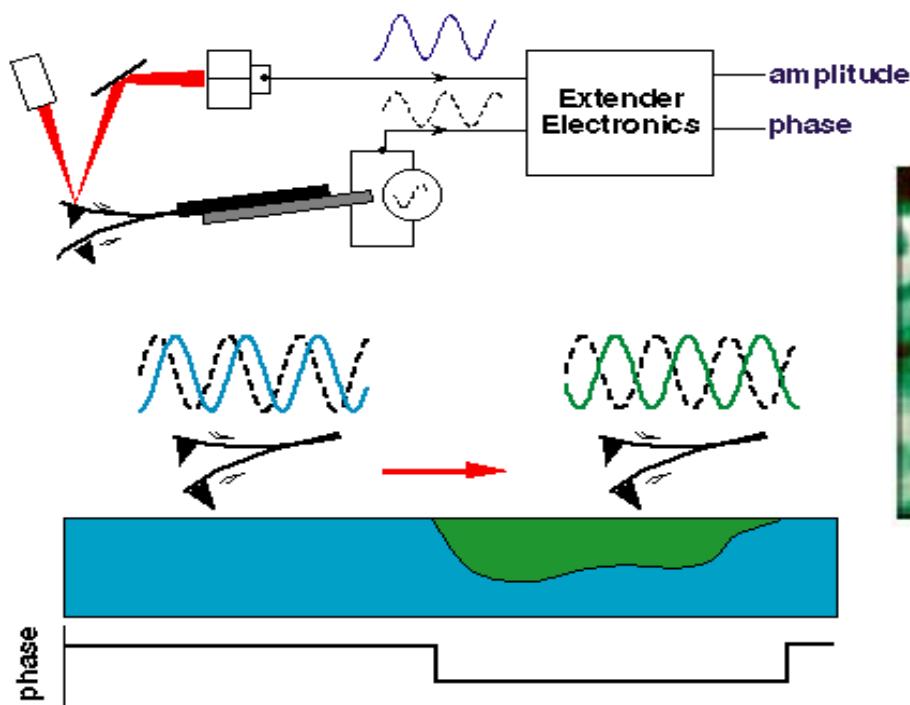
$$F_z = m_z H_z$$

$$\mathbf{m}^T = m_x + m_z$$



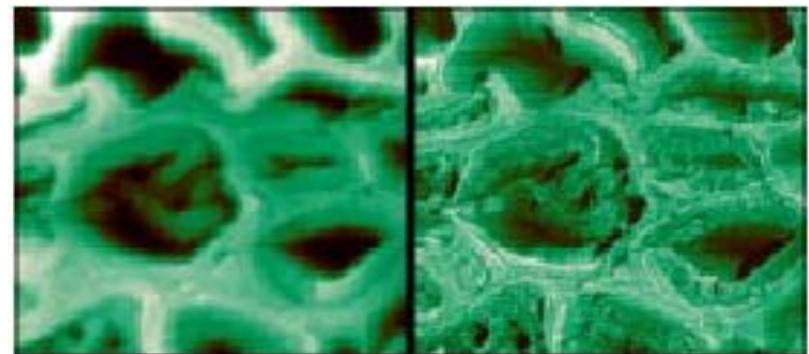
Bits (50 nm) on a magneto-optical disk
Scan area (5 μ m x 5 μ m)

Images by tapping mode



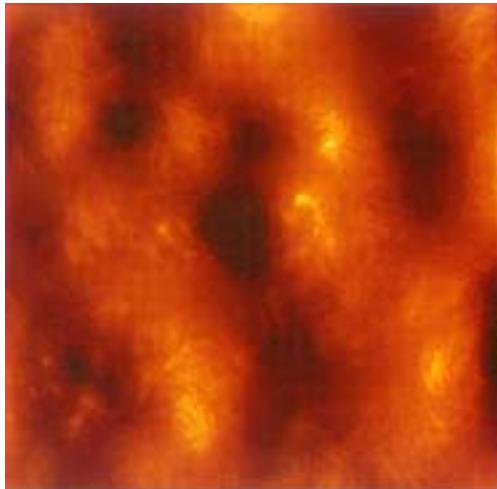
Topography

Phase

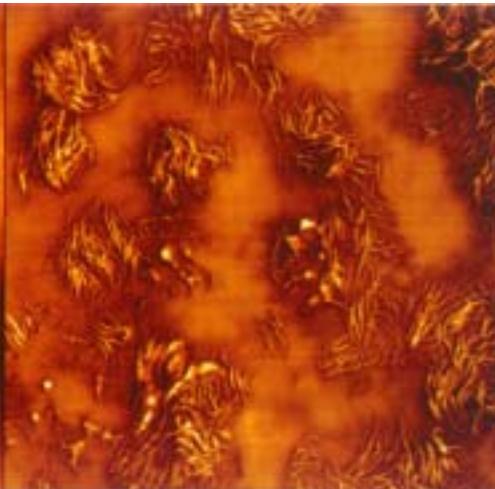


AFM image of a fresh
Alfalfa root section

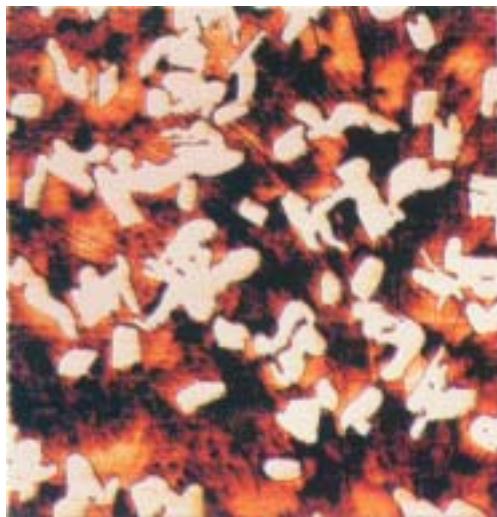
Height image



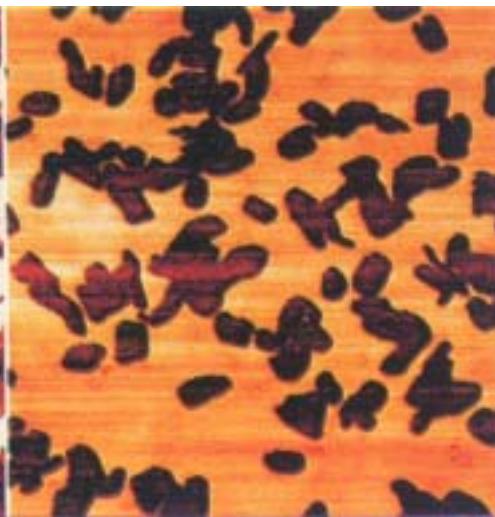
Phase Image



Phase image



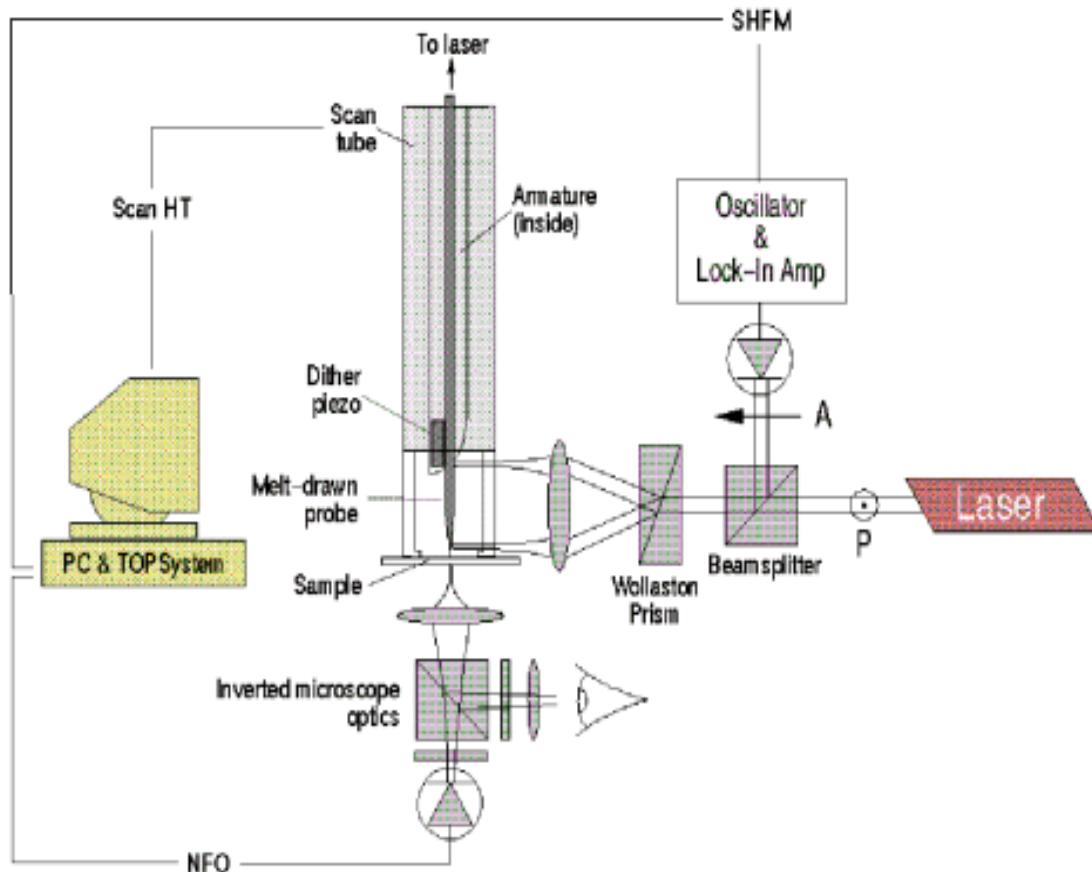
Lateral force Image



MoO_3 on
 MoS_2

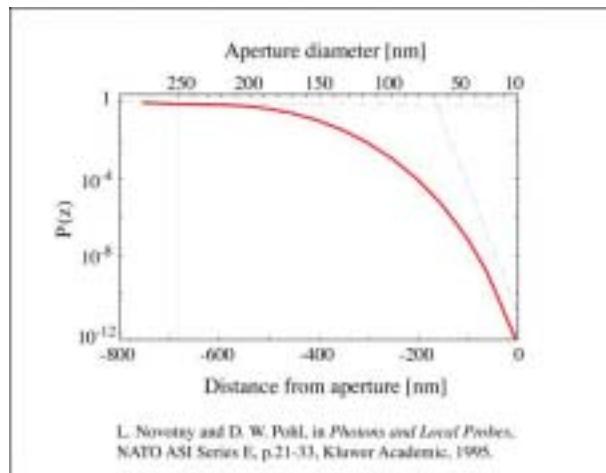
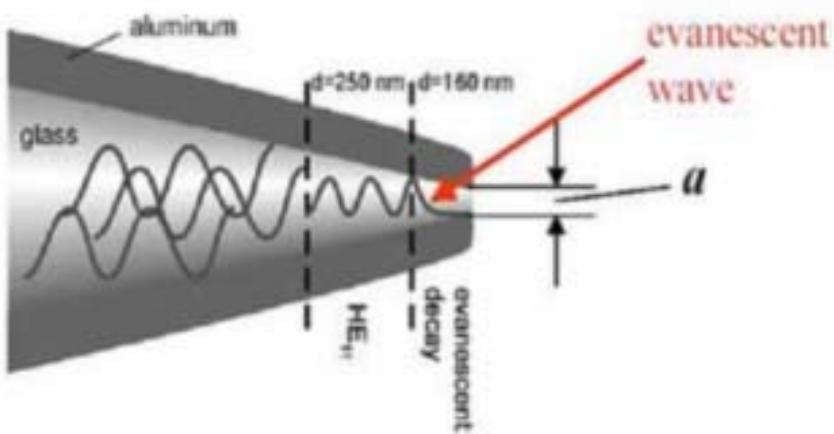
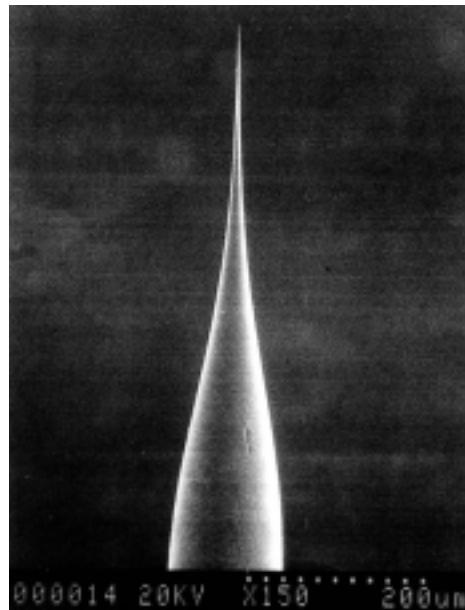
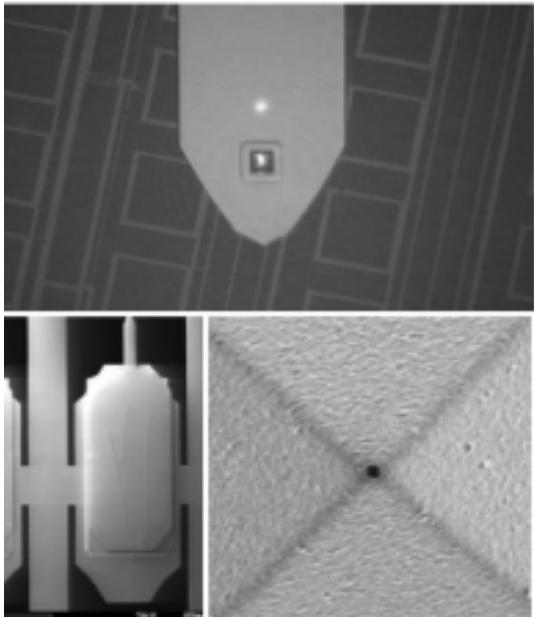
1. The SCM has proven its potential for the analysis of 2D dopant profiles on a scale down to less than 50 nm.
2. The quantification of a measured dopant profile is still difficult due to the influence of parameters of the sample, the tip shape, and the capacitance sensor including the applied voltages.
3. The properties of the sample, e.g. the roughness of the surface (fluctuation of the oxide thickness), the density of charged impurities and traps in the oxide layer and mobile surface charges, are mainly determined by the sample-preparation procedure.
4. The most important influence on the measurements is due to the probing voltage of the capacitance sensor and the applied bias voltage.
5. In SCM, not the dopant concentration, but rather the local charge-carrier concentration is measured because only the mobile carriers can contribute to $C(V)$ and thus only the local charge-carrier distribution can be detected.

Near-field Scanning Optical Microscopy (NSOM)

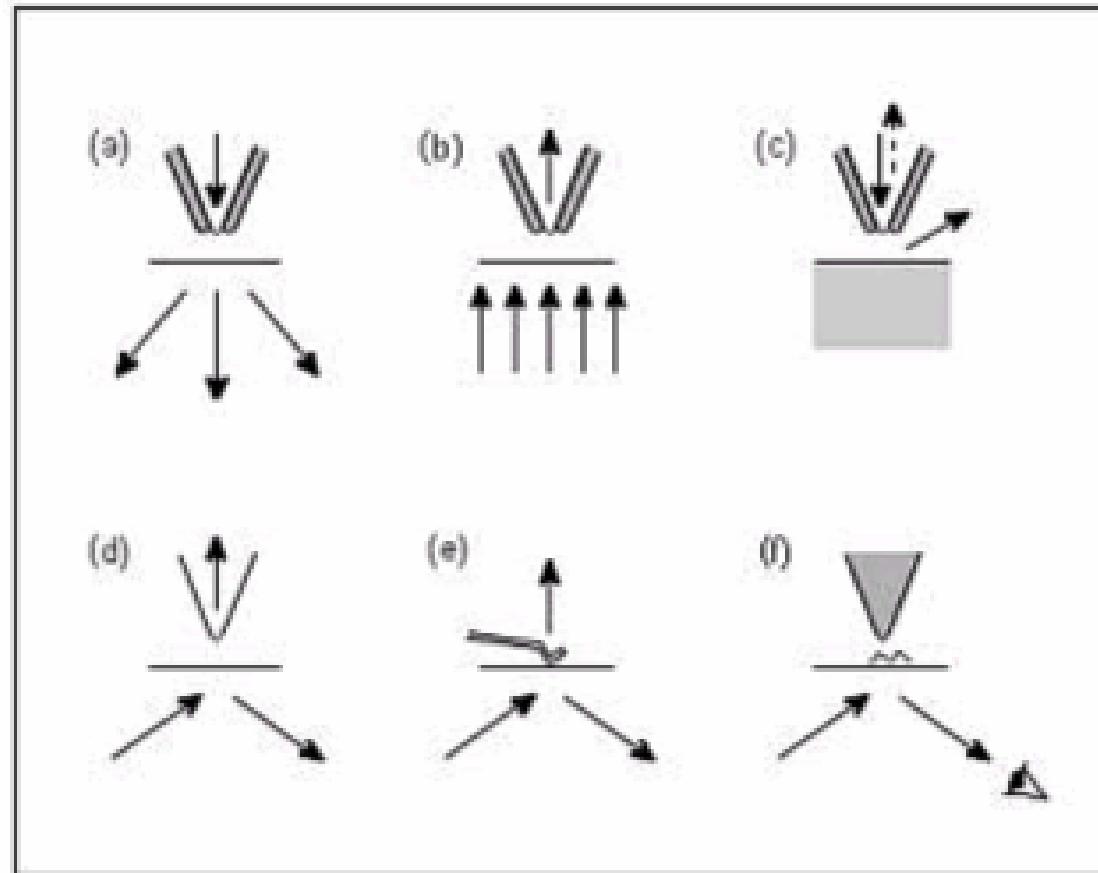


Shear force detection is used to regulate the tip/sample separation

Probes for NSOM

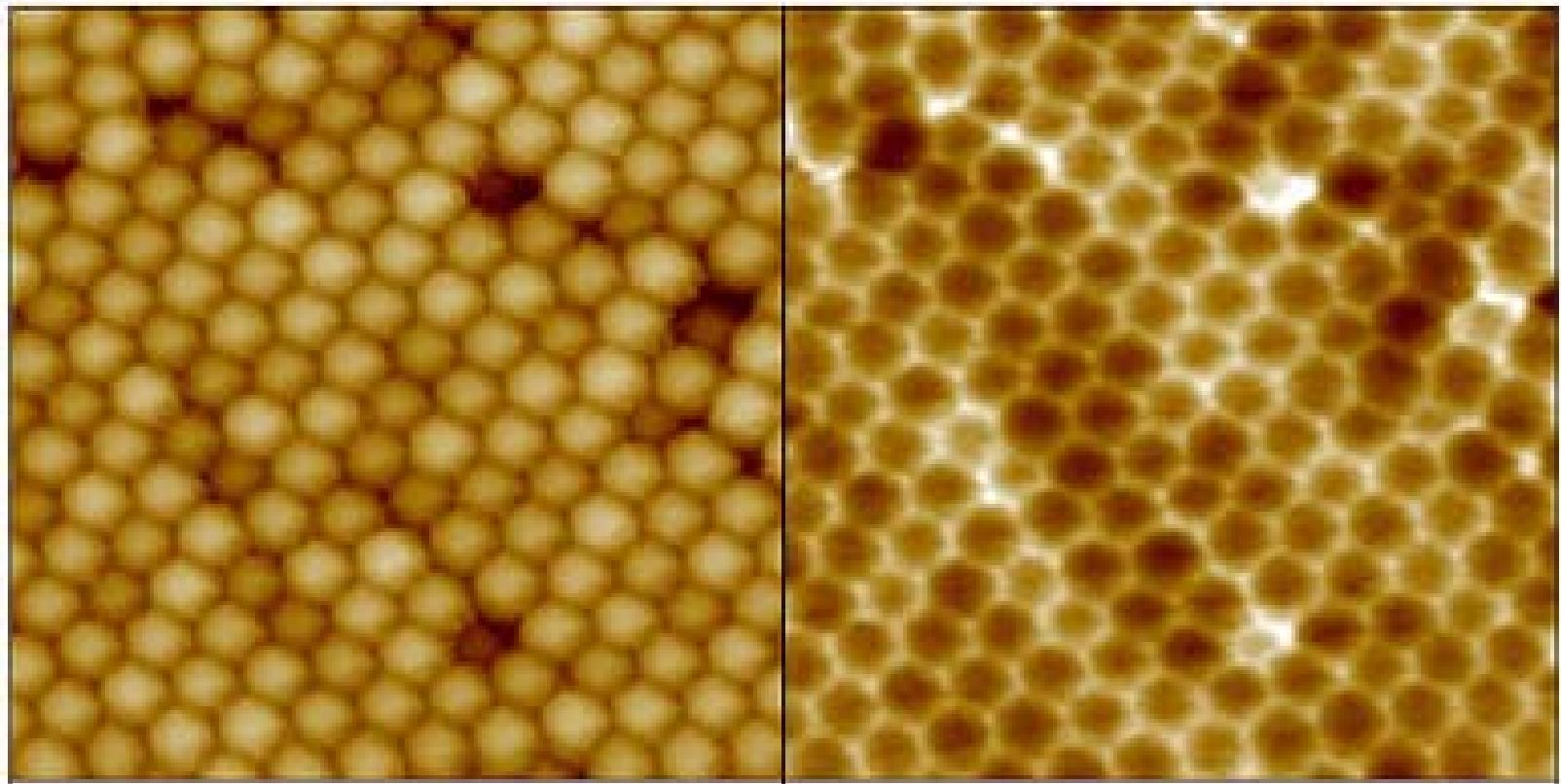


Imaging modes for NSOM



Topography

NSOM Image



0

1.05 μm 0

Data type
Z range

Height
60.3 nm

1.05 μm

Data type
Z range

Aux B
0.0370 U

Polystyrenes of 100 nm on glass

TABLE II. Summary of the different scanning probe microscopy techniques which can be used for 2D carrier profiling of semiconductor devices. The "mode" reflects the scanning mode which is being used to control the movement of the probe (NC=noncontact; C=contact).

Technique	Mode	Probe	Measured quantity
Scanning tunneling microscopy/spectroscopy (STM/STS)	STM	Metallic needle	No. doping atoms $I-V$ spectra
Selective etching+atomic force microscopy	NC-AFM	Ultrasharp Si	Topography after chemical etch
Scanning capacitance microscopy/spectroscopy (SCM/STS)	C-AFM	Metal-coated Si or metallic	Depletion capacitance $C-V$ spectra
Scanning spreading resistance microscopy (SSRM)	C-AFM	Diamond-coated Si or diamond	Electrical resistance $I-V$ spectra
Kelvin probe force microscopy (KPM)	NC-AFM	Metal-coated Si or metallic	Electrostatic potential (electric field)
Scanning surface harmonic microscopy (SSHM)	STM	Metallic needle with microwave cavity	Depletion capacitance

P.D. Wolf et al., J. Vac. Sci. Technol. B 18, 361 (2000).

TABLE III. Intercomparison of two-dimensional doping (D) and carrier (C) profiling methods (NA=not available).

Method	Ref.	Resol. (nm)	Range (cm^{-1})	Cone. resol.	D/C	Quantifiable	Comments and problems
SPM techniques							
SCM	(43-59)	10	$1e15-1e20$	Power	C	Limited	Uncertainties at junctions, poor quantification procedure
SSHM	(60-62)	5	NA	Power	C	No	No quantification procedure
STM-atom counting	(20-23)	Atomic	$1e18-1e20$	Linear	D	Yes	Only on GaAs, not on Si
STM-STS/CITS	(24-26) (31,32)	10	NA	Log.	C	Limited	Only junction delineation and type (<i>n</i> or <i>p</i>) identification
STM-STP	(27-30)	10	NA	Limited	C	Limited	Only junction delineation
KPM	(66,67)	100	$1e15-1e20$	Limited	C	Limited	Poor quantification procedure, stray-fields limit the resolution
SSRM	(68-73)	20	$1e15-1e20$	Linear	C	Yes	Availability diamond probes
Chemical etch+AFM/STM	(37-39)	10-20	$1e17-1e20$	Limited	C	Limited	Difficult to quantify, poor reproducibility

1. All SPMs are based on the ability to position various types of probes in very close proximity with extremely high precision to the sample under investigation.
2. These probes can detect electrical current, atomic and molecular forces, electrostatic forces, or other types of interactions with the sample.
3. By scanning the probe laterally over the sample surface and performing measurements at different locations, detailed maps of surface topography, electronic properties, magnetic or electrostatic forces, optical characteristics, thermal properties, or other properties can be obtained.
4. The spatial resolution is limited by the sharpness of the probe tip, the accuracy with which the probe can be positioned, the condition of the surface under study, and the nature of the force being detected.