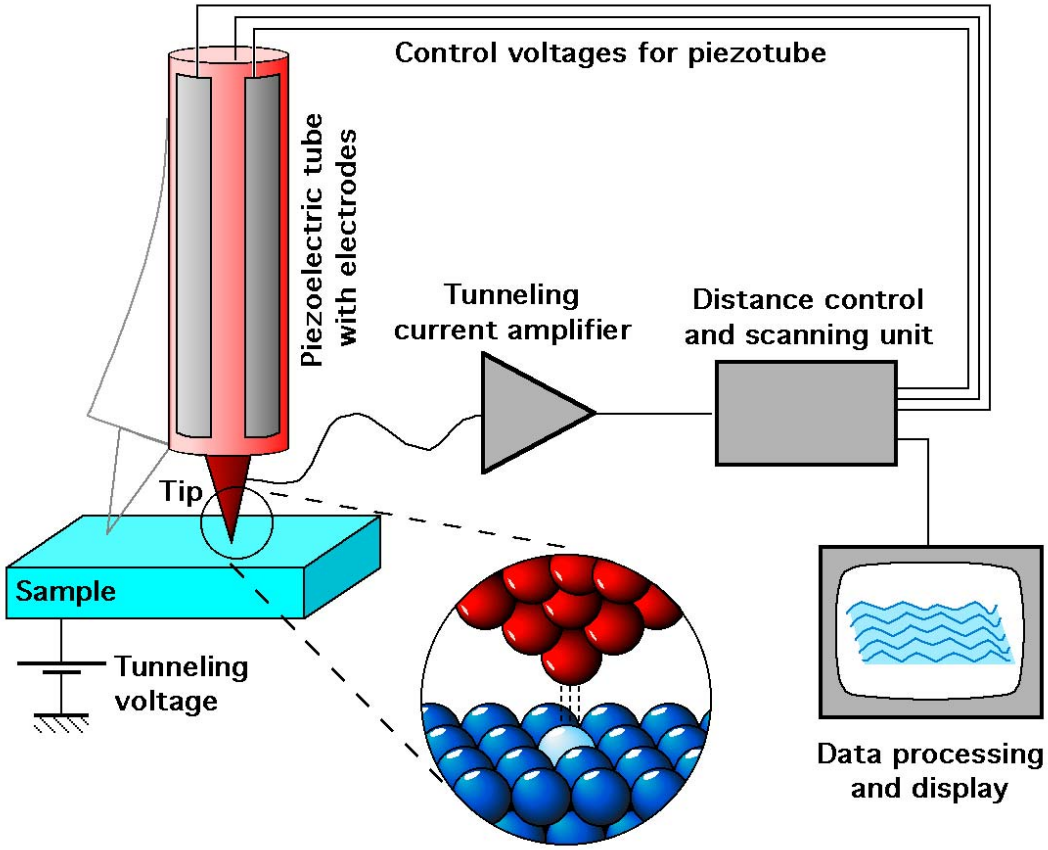
Scanning Tunneling Microscopy



References:

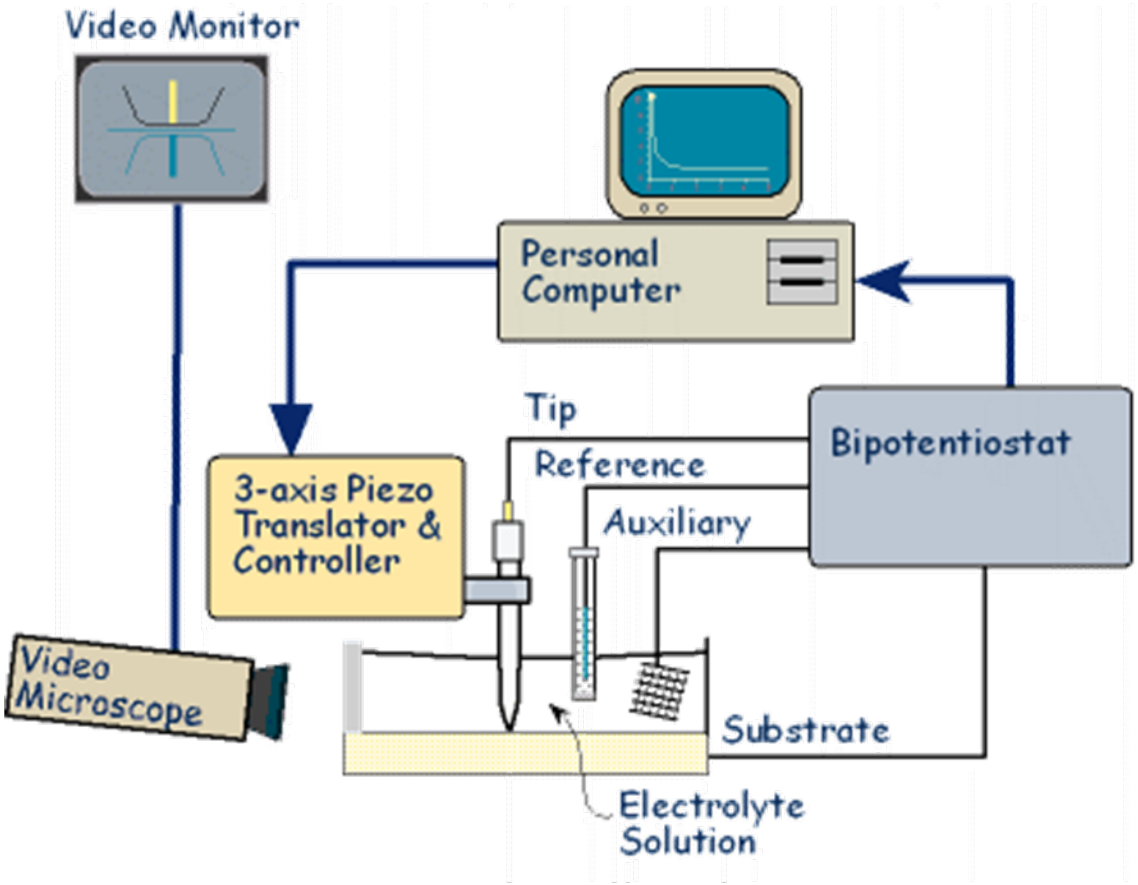
1. G. Binnig, H. Rohrer, C. Gerber, and Weibel, Phys. Rev. Lett. **49**, 57 (1982); and ibid **50**, 120 (1983).

2. J. Chen, *Introduction to Scanning Tunneling Microscopy*, New York, Oxford Univ. Press (1993).

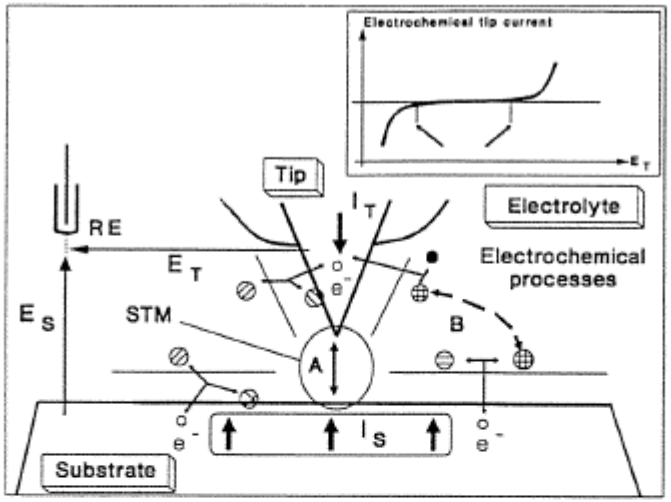
Electochemical STM

- STM studies in electrolyte
  - Surface topography in electrolyte
  - Adsorption and desorption of molecules
  - Initial stage of dissolution and passivation
  - STM study on electroplating process
    - Initial stage of electro-deposition
  - Tip-induced nano-structuring in electrolyte
    - Local potential control
    - Tip position control
      - Jump-to-contact

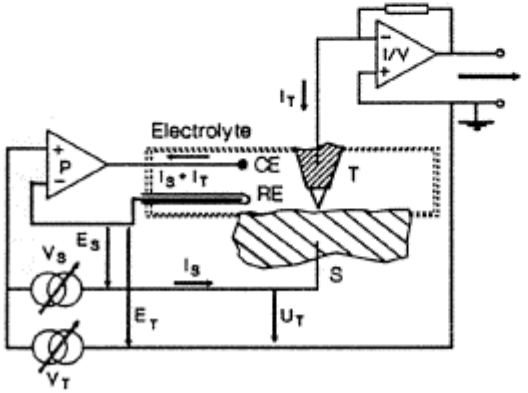
Setup of ECSTM



Bipotentiostat



(a)



(b)

Demands:

Control Tip and specimen's potential independently

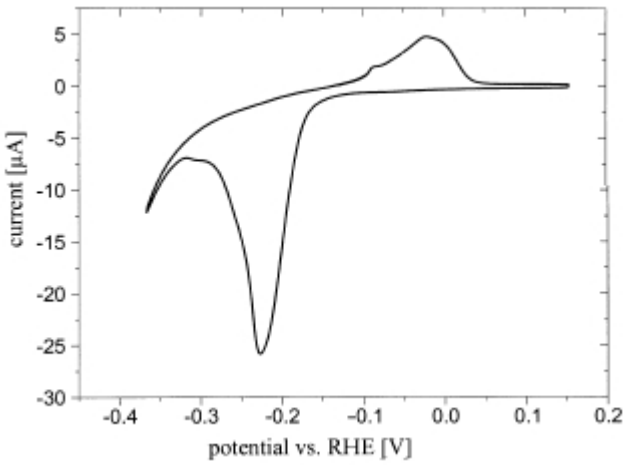
Z-axis direction can displace freely if needed

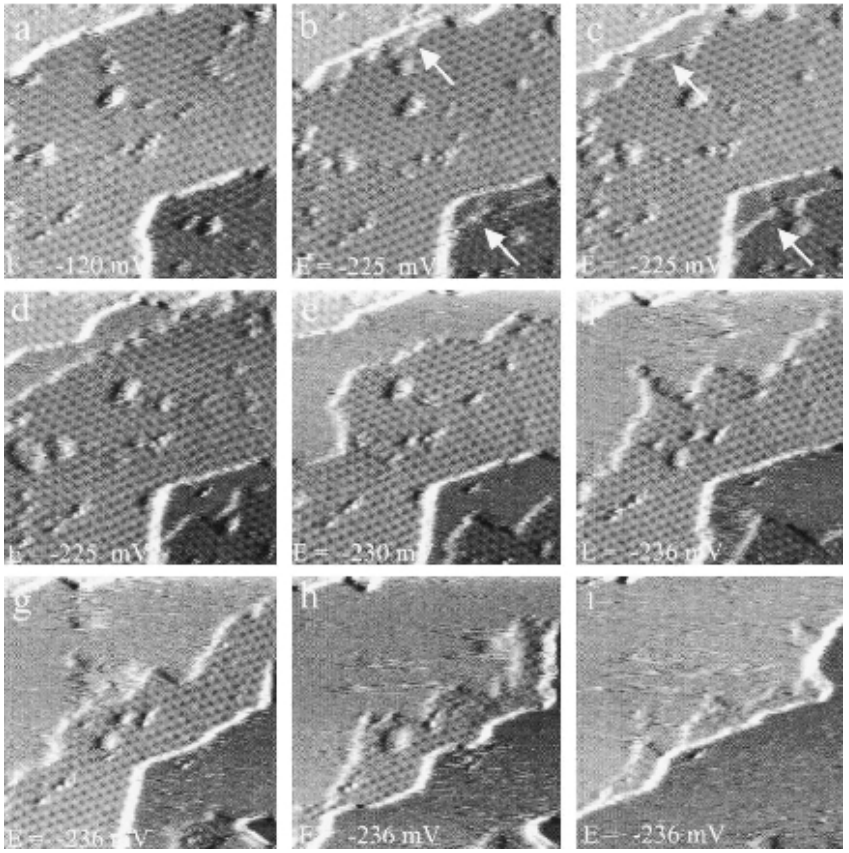
Tip bias connect with frequency function generator, in order to give different pulse

Potentiostat combine with Electrochemical impedance spectroscopy

Adsorption and Desorption -inorganic molecules

- Sulfate adsorption on Cu (111)





Starting at –120 mV, then –225 mV (3 frames), -230 mV (1 frame), and –236 mV (4 frames)

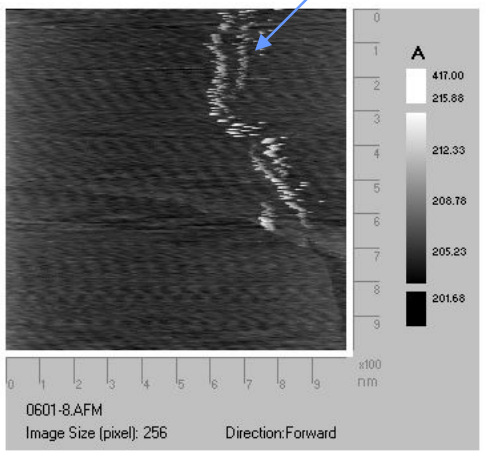
The sulfate adlayer always appears deeper in STM than bare Cu, due to electronic effect

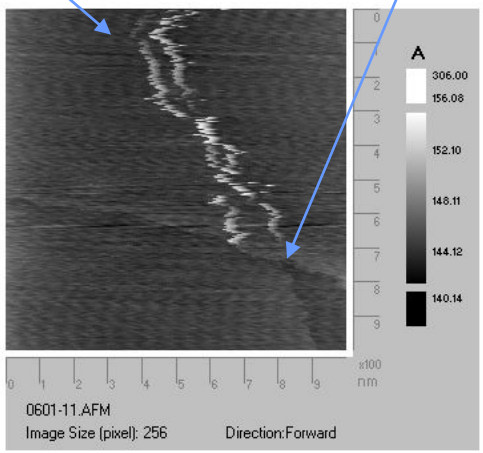
Ref. 11

Adsorption and Desorption -DNA

Double Strands DNA

HOPG steps- a marker

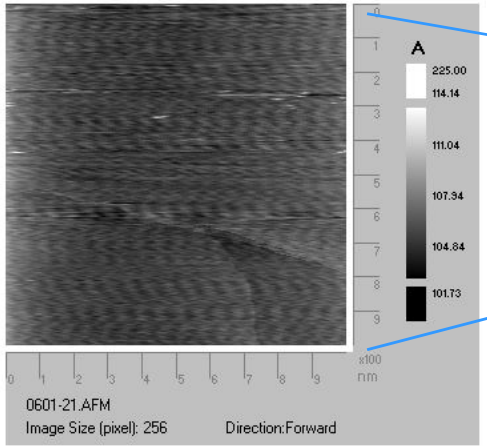




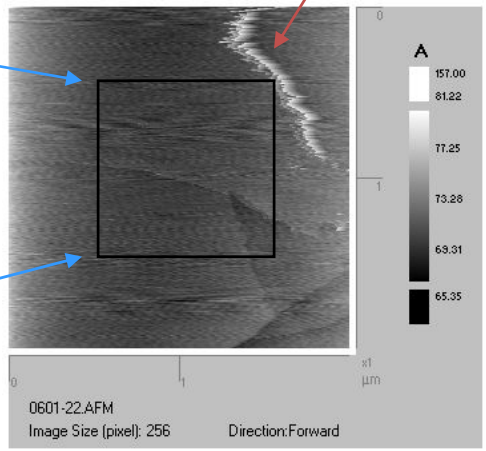
(1)~(2) DNA has been immobilized on graphite surface in chloride solution

Now, DNA is here

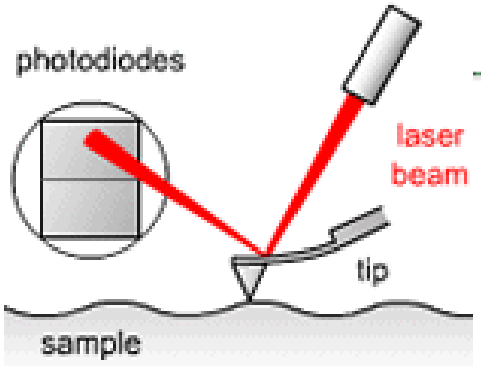
(3)~(4) Move DNA out of the imaging frame

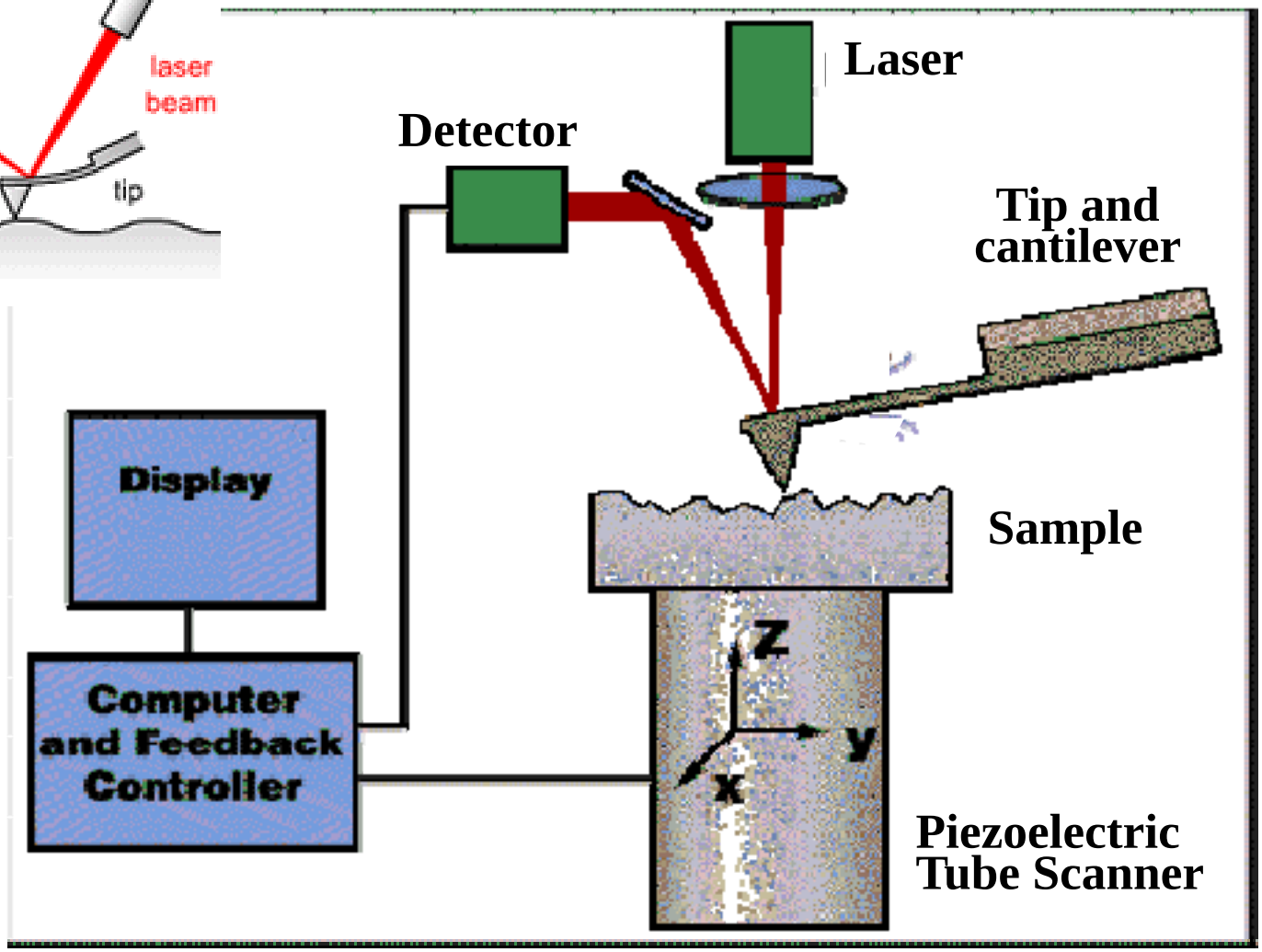


Zoom Out

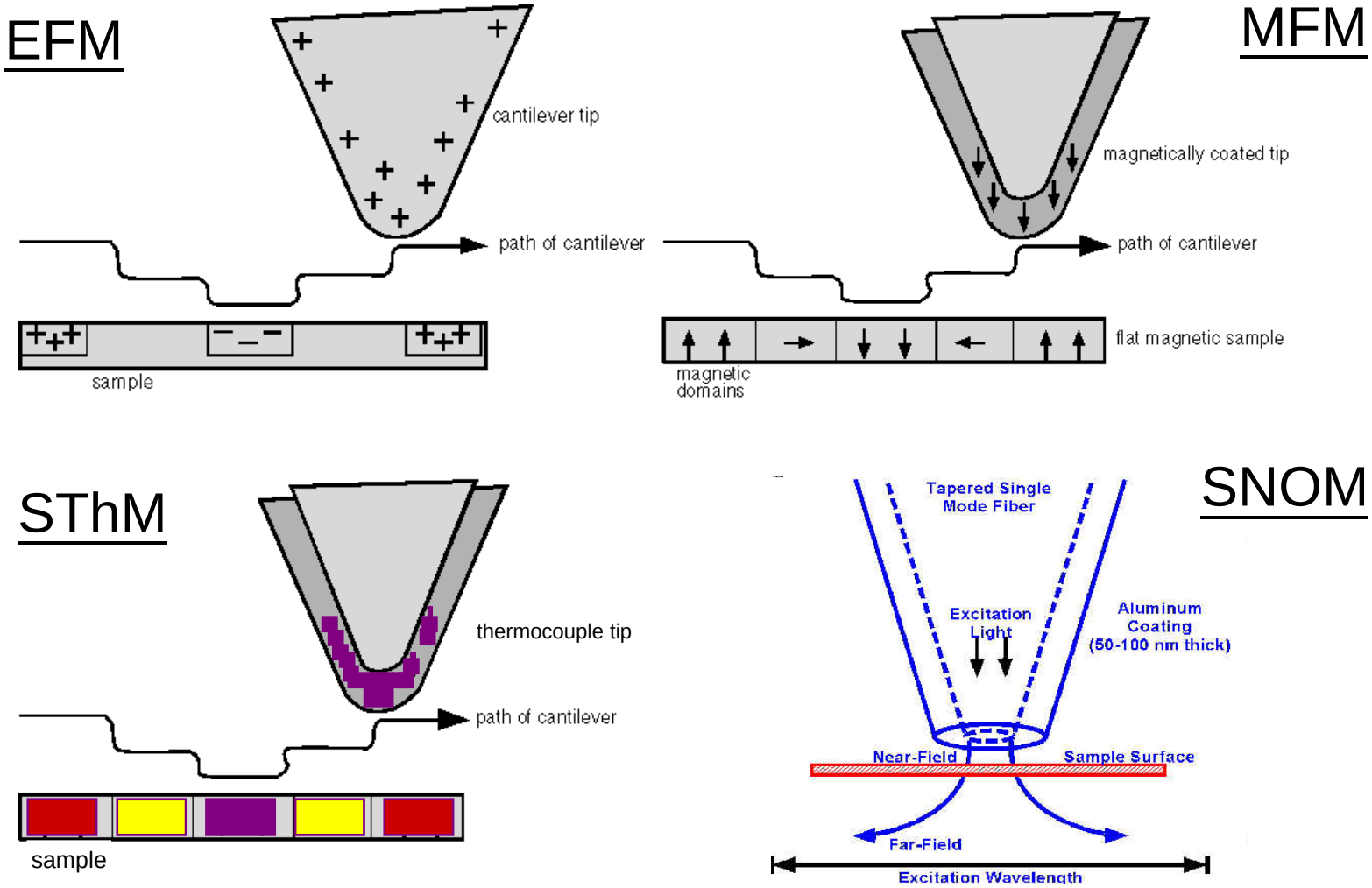


Atomic Force Microscopy

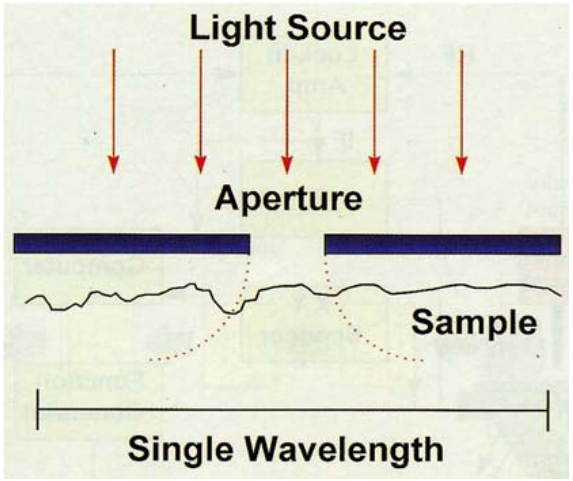


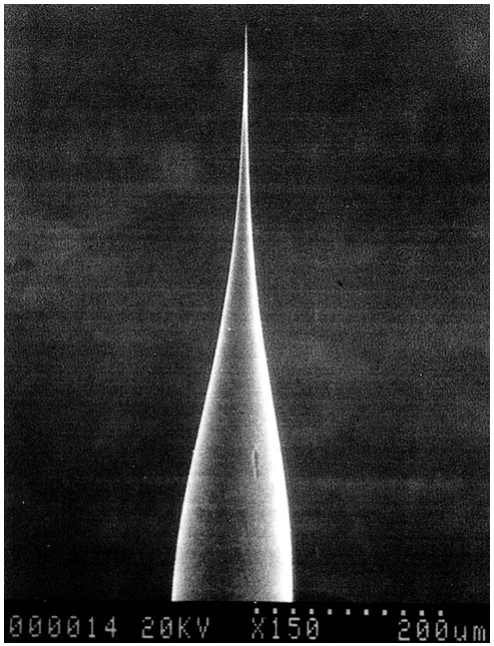


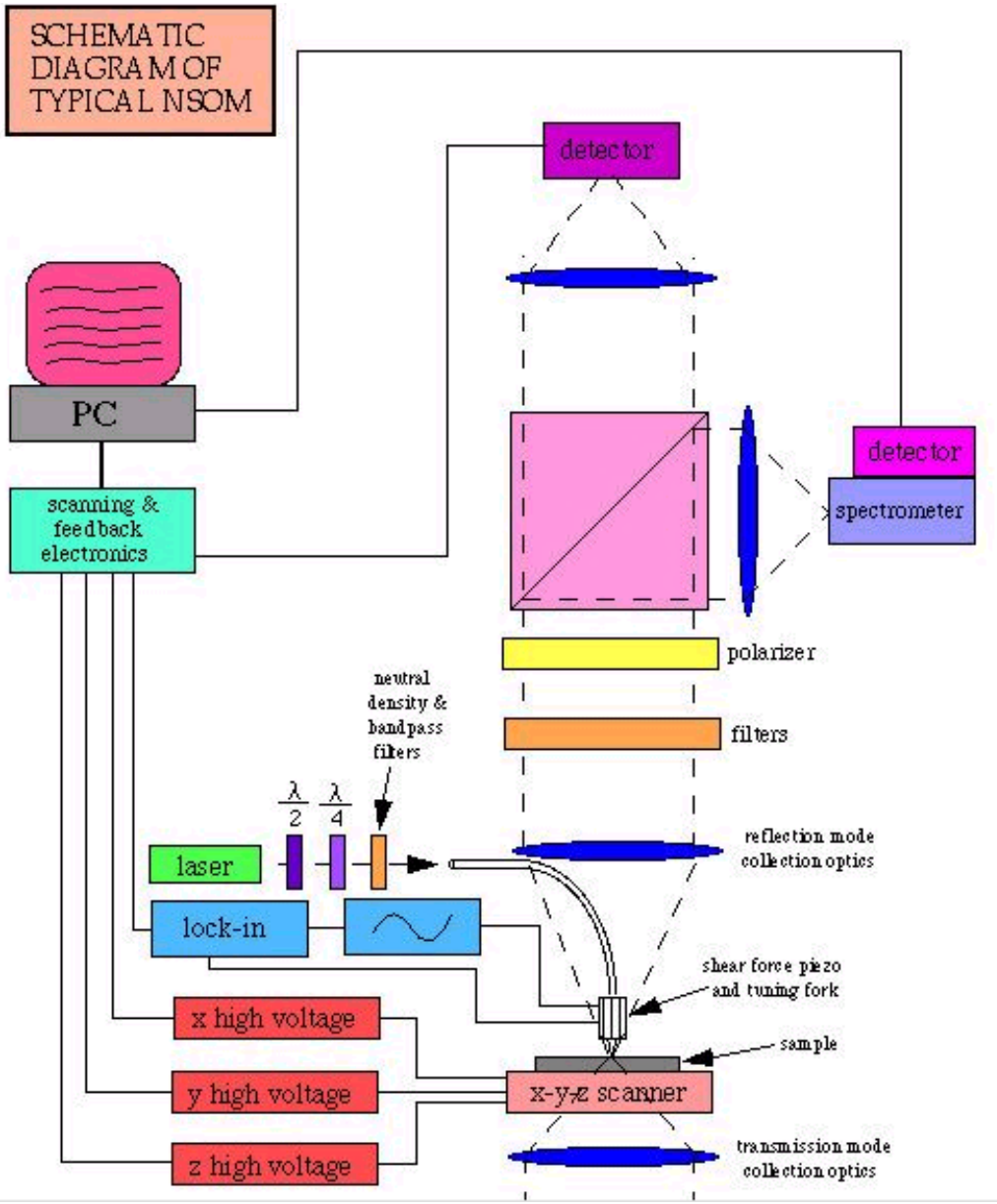
Probes of various functions



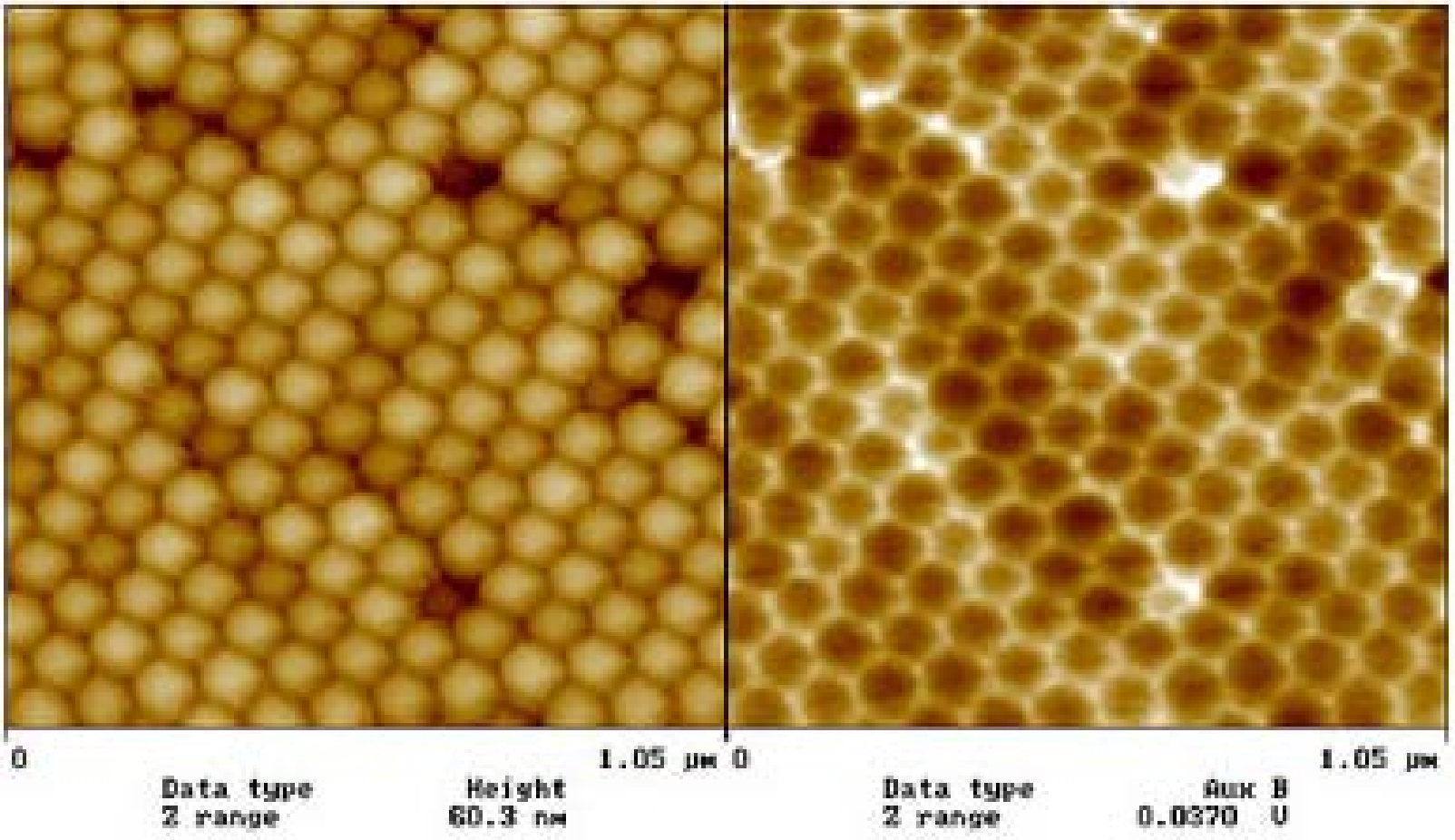
Near-field Scanning Optical Microscopy (NSOM)





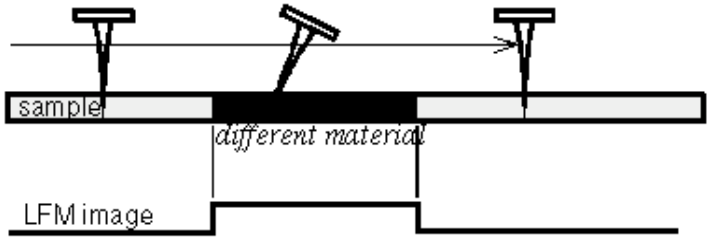


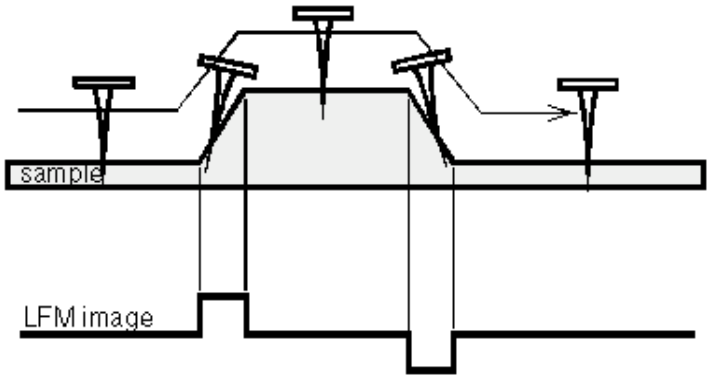
Topography **NSOM Image**

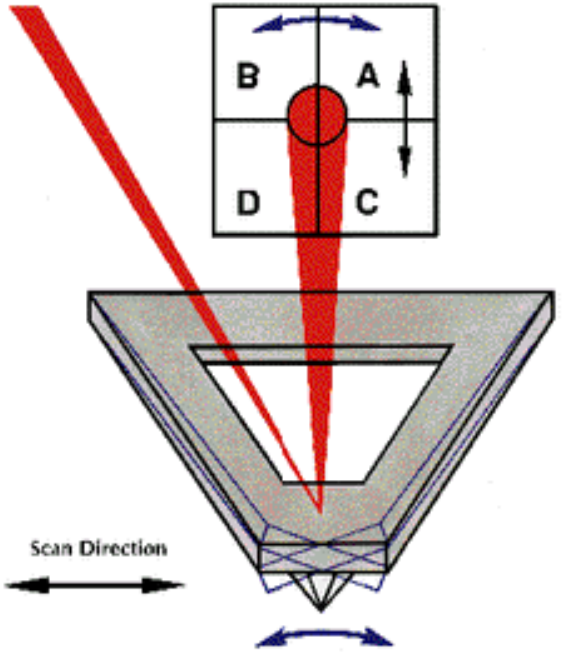


Polystyrenes of 100 nm on glass

Lateral Force Microscopy



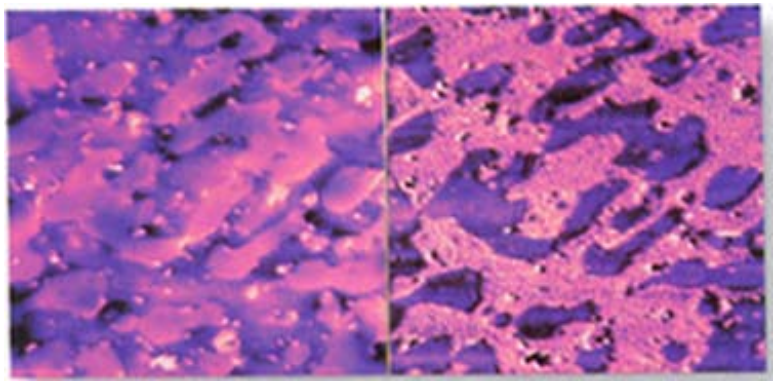




(A+C) – (B+D)

Topography

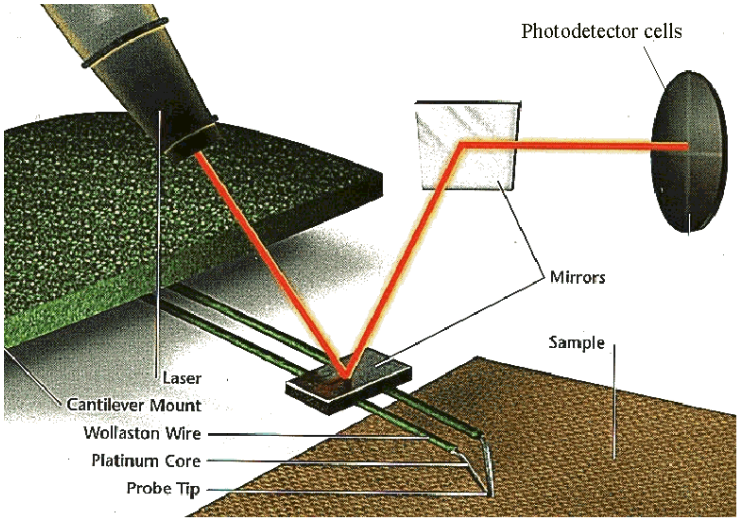
12 μm

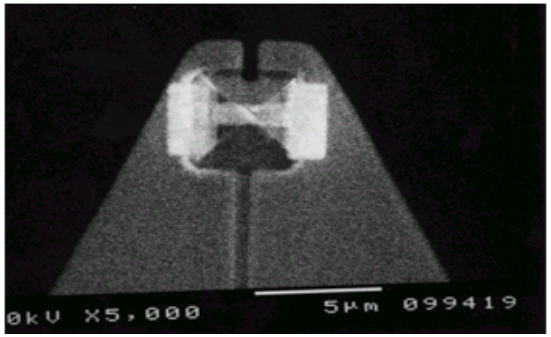


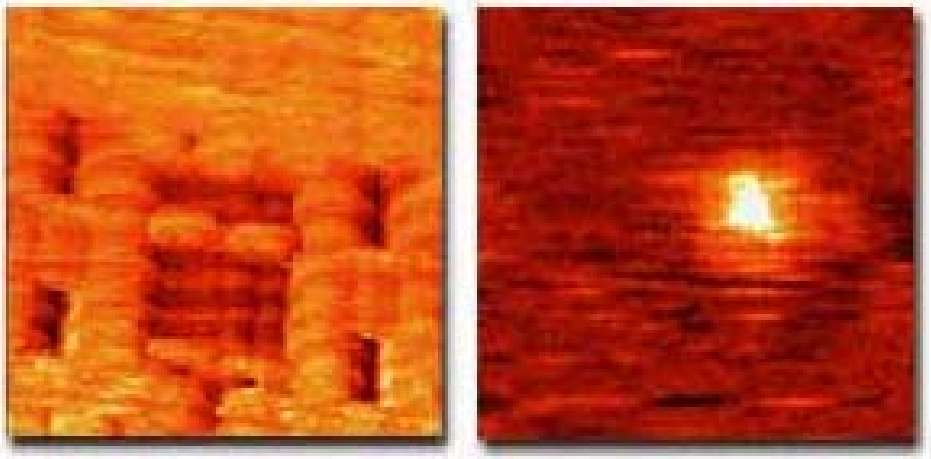
LFM image

Nature rubber/EDPM blend

Scanning Thermal Microscopy (SThM)

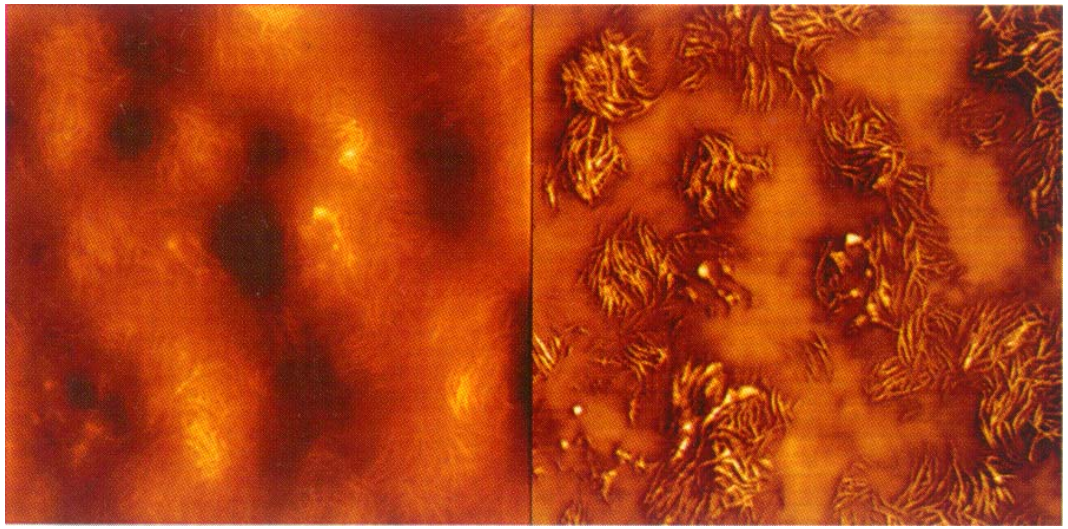






Height image

Phase Image

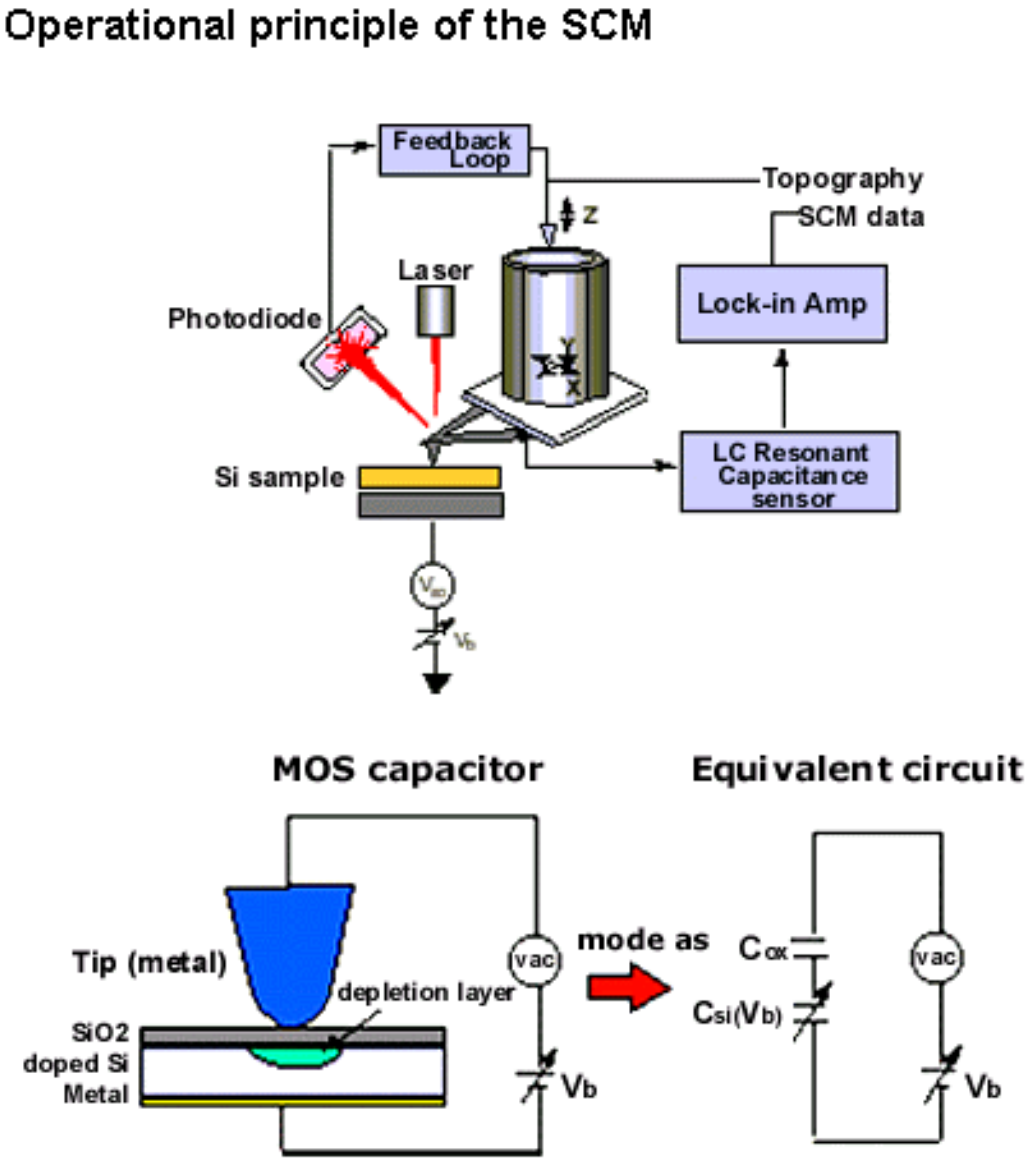


Phase image

Lateral force Image

MoO_3 on MoS_2

Scanning Capacitance Microscopy (SCM)

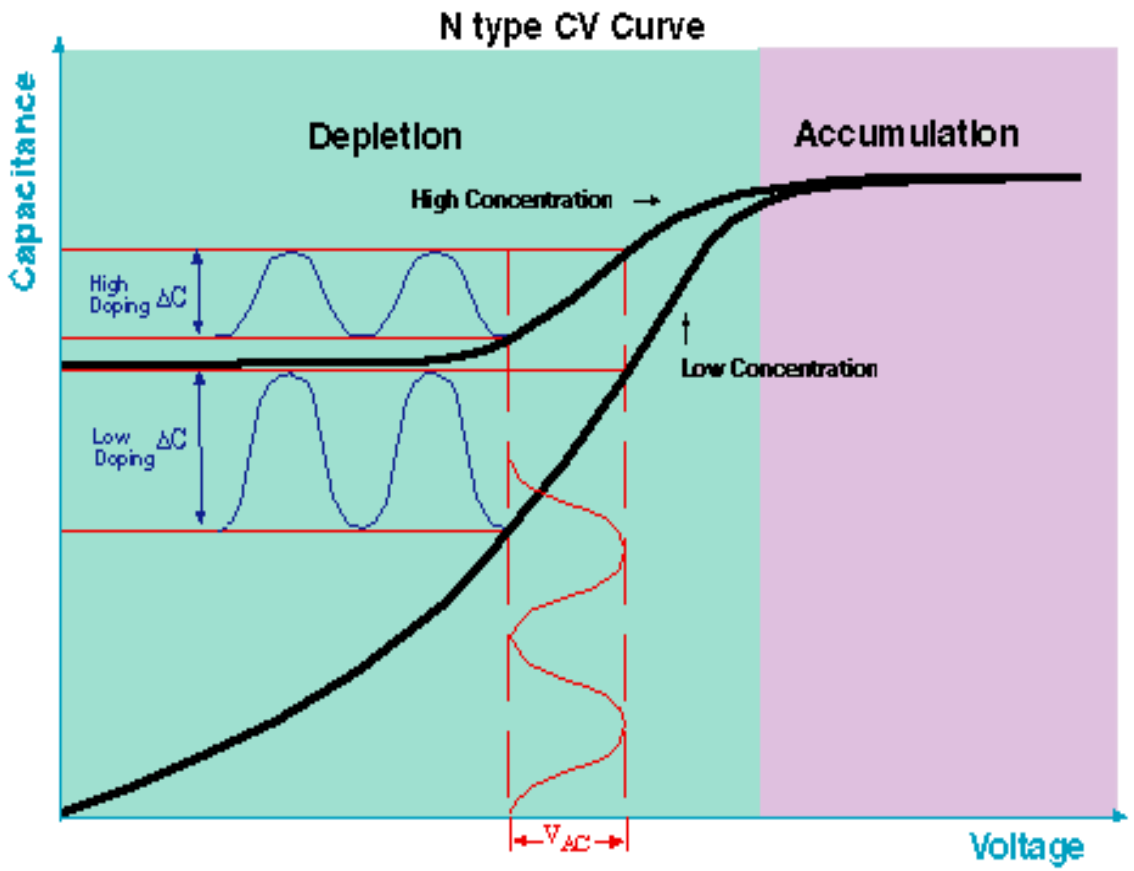


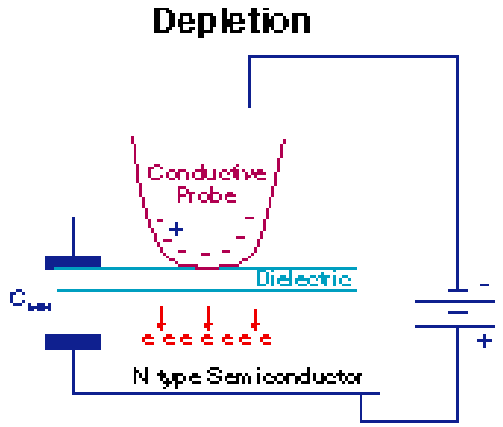
1. **Most SCMs are based on contact-mode AFM with a conducting tip.**
2. **In SCM, the sample (or the metallic tip) is covered with a thin dielectric layer, such that the tip-sample contact forms a MIS capacitor, whose C-V behavior is determined by the local carrier concentration of the semiconductor 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.**

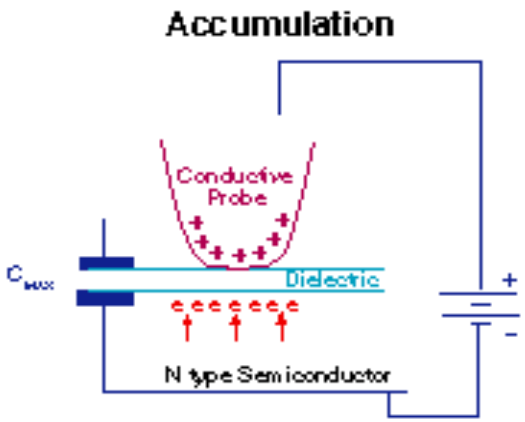
References:

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).

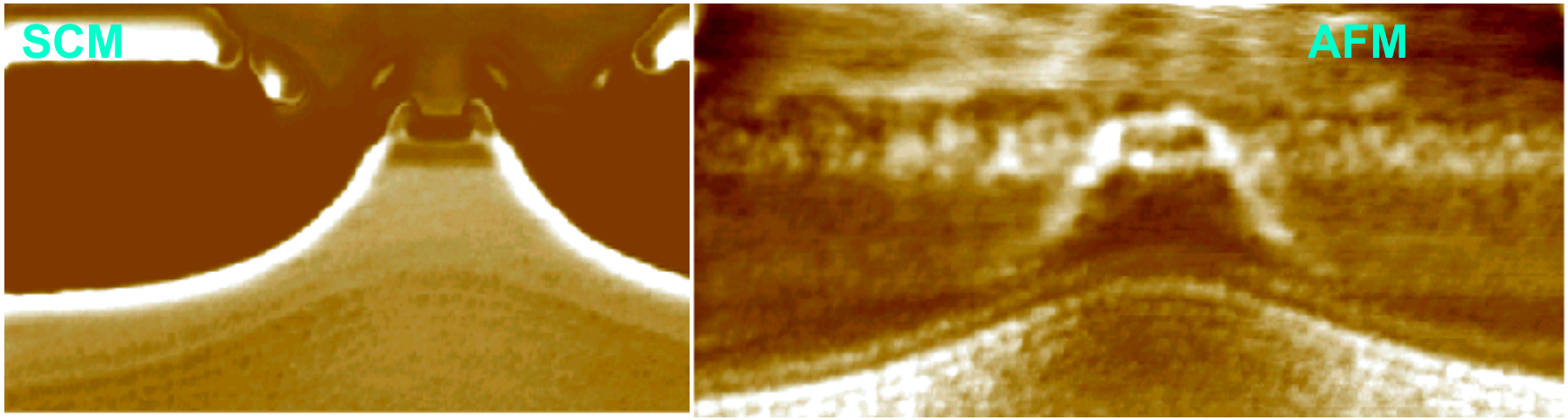
SCM CV Curve

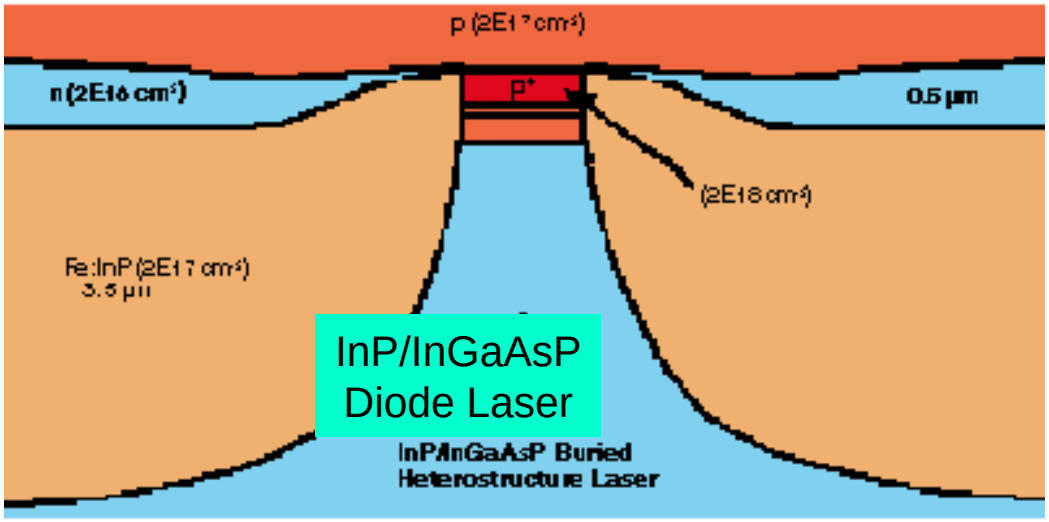

N type CV Curve
Capacitance
Depletion
Accumulation
High Concentration
Low Concentration
High Doping ΔC
Low Doping ΔC
V_{AC}
Voltage


Depletion
Conductive Probe
Dielectric
C_{max}
N type Semiconductor


Accumulation
Conductive Probe
Dielectric
C_{max}
N type Semiconductor

Scanning Capacitance Microscopy





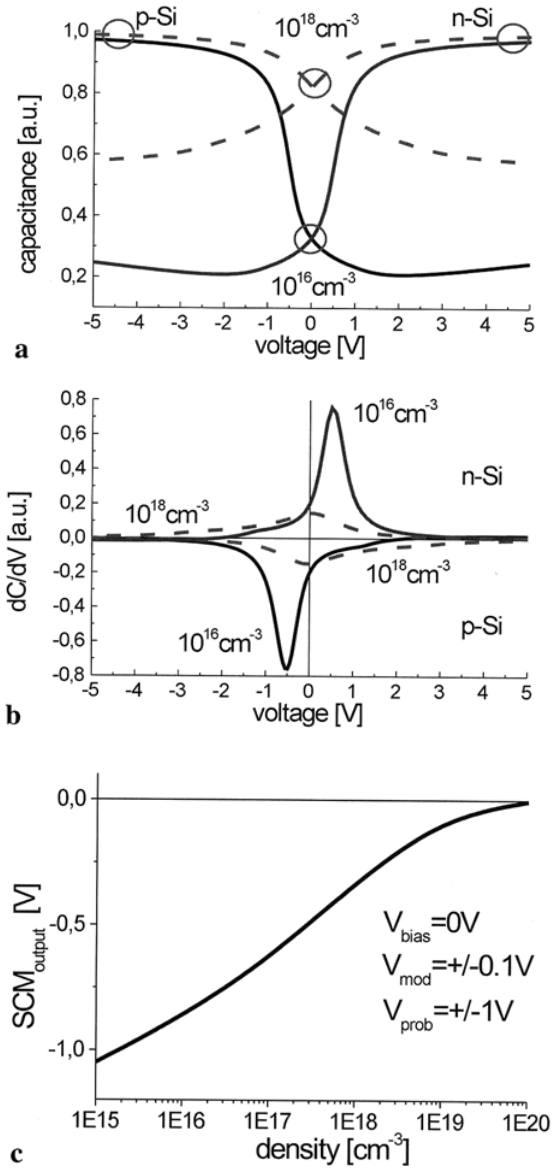


Fig. 2a–c. 3D simulations of SCM on homogeneously doped samples. The tip ($r_a = 25$ nm, $r_i = 25$ nm, $\alpha = 20°$) is modelled in cylindrical coordinates; $d_{Ox} = 10$ nm. **a** $C(V)$ curves on *p*- and *n*-doped silicon with dopant concentrations of 10^{16} cm^{-3} and 10^{18} cm^{-3}, respectively. **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 $V_{bias} = 0$ V taking $V_{mod} = \pm 0.1$ V and $V_{prob} = \pm 1$ V into account

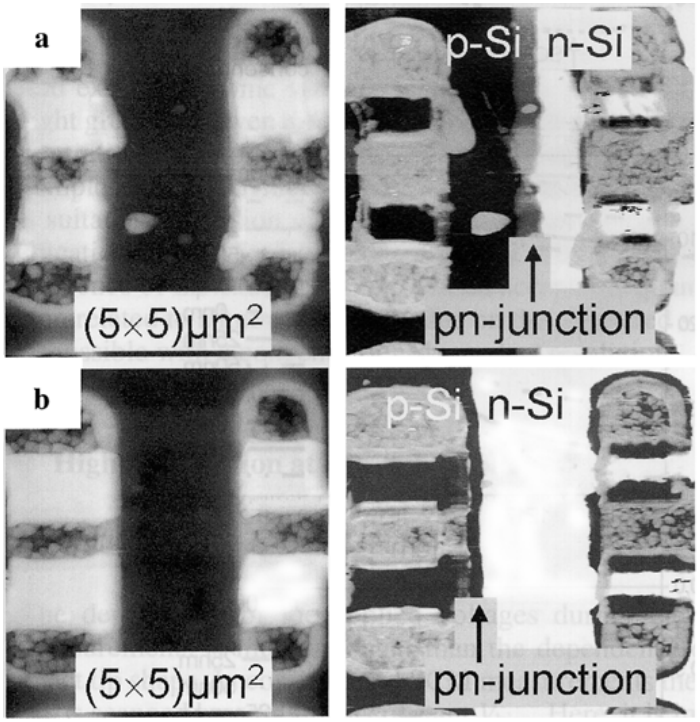
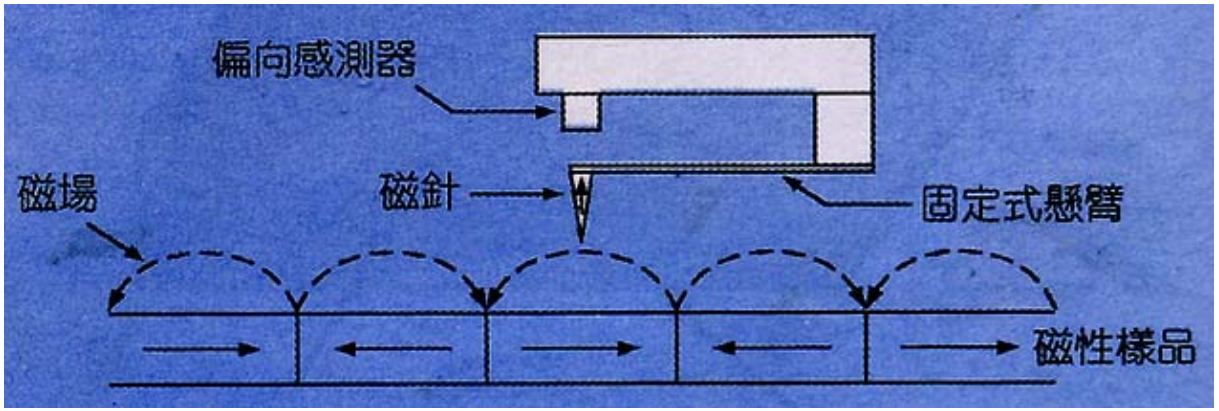


Fig. 3a,b. Failure analysis of an industrial device by means of SCM. Topography (*left-hand side*) and SCM image (*right-hand side*) are taken simultaneously. **a** Well-operating device with the *pn* junction implanted in the middle between the poly-silicon contacts. **b** Defective device with the *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. **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.**

Magnetic Force Microscopy (MFM)



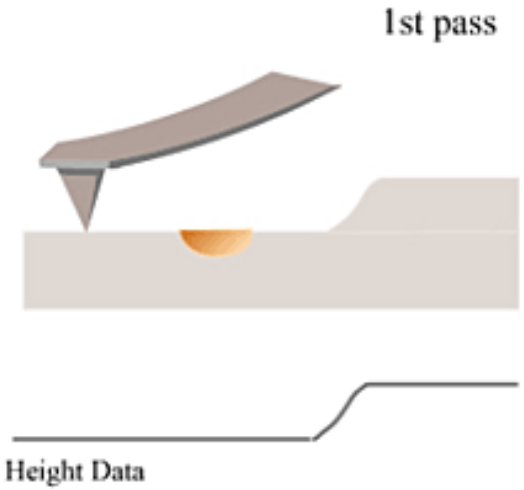
$$F = (m \bullet \nabla)H$$

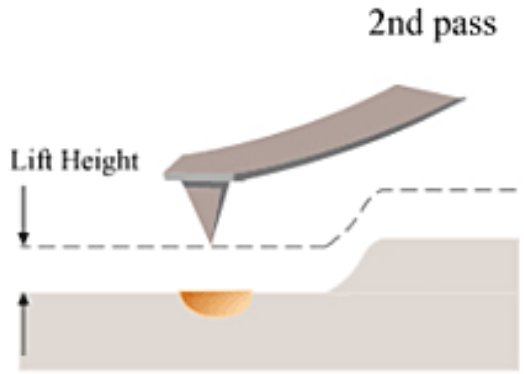
Tips: silicon probes are magnetically sensitized by sputter coating with a ferromagnetic material.

Resolution: 10 ~ 25 nm.

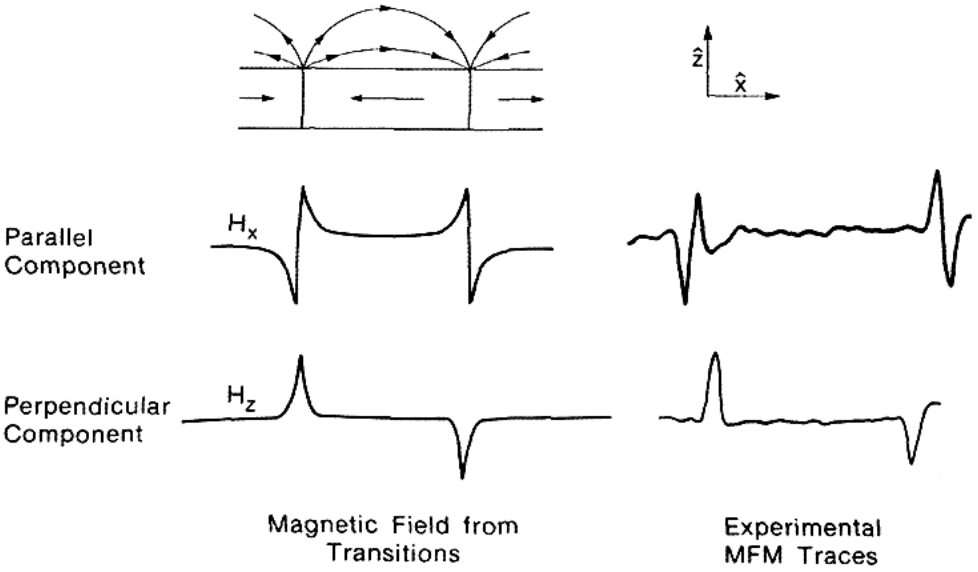
Applications: hard disks, magnetic thin film materials, micromagnetism.

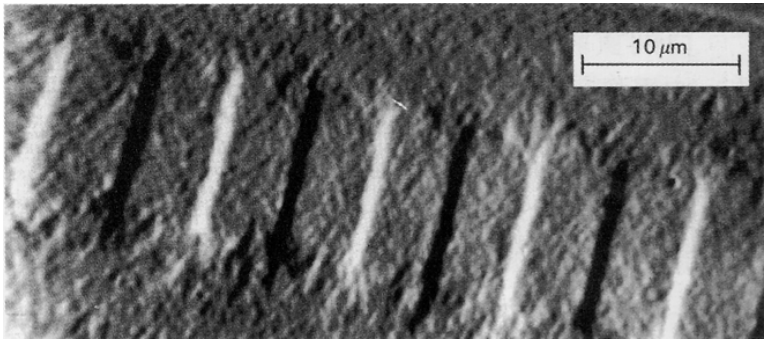
Lift mode

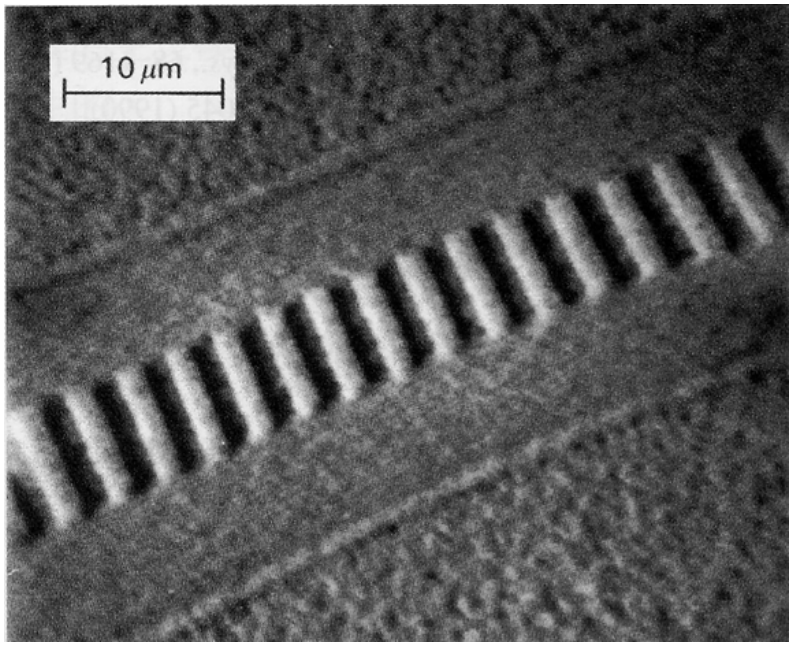


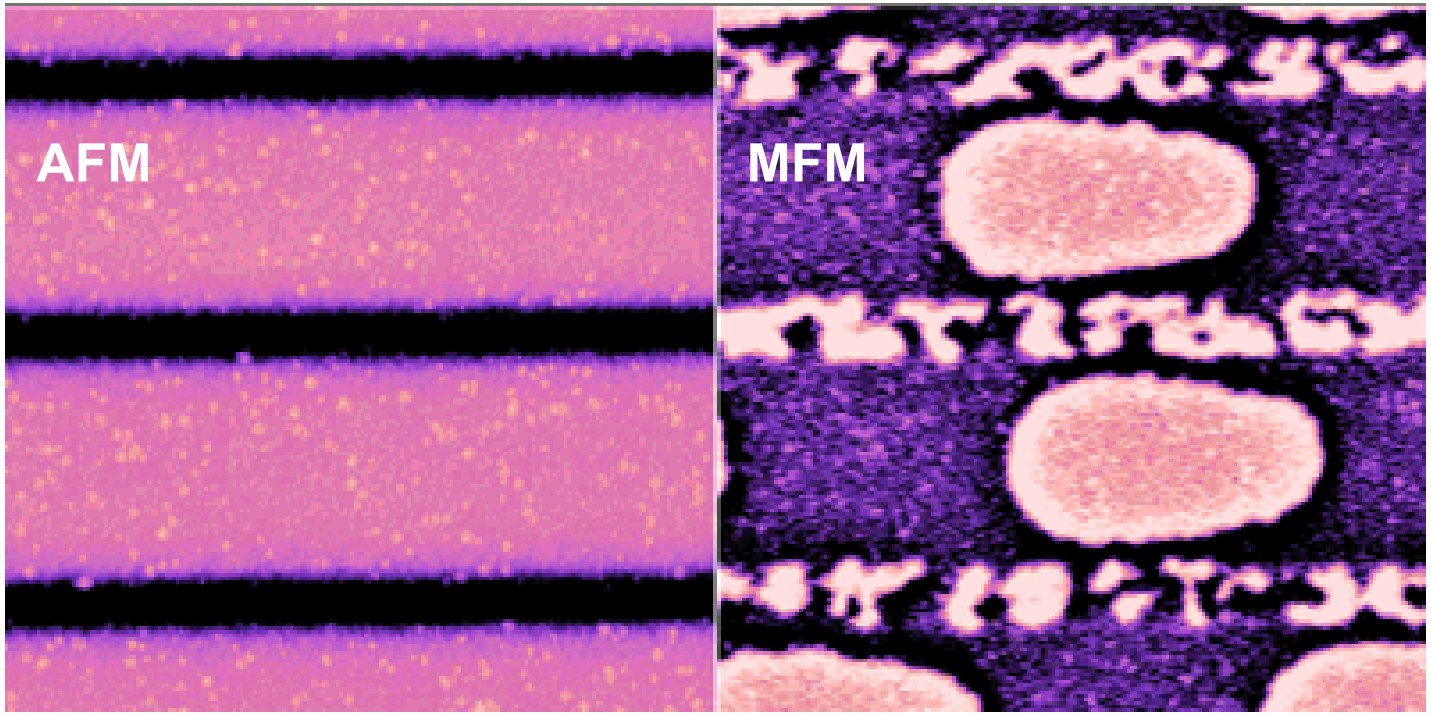


MFM Images


Parallel Component
Perpendicular Component
H_x
H_z
$\hat{z}$
$\hat{x}$
Magnetic Field from Transitions
Experimental MFM Traces


10 μm


10 μm



Bits (50 nm) on a magneto-optical disk

Scan area (5μm× 5μm)

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^{-3})	Conc. 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 (n or p) 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.**