Modern Analytical Microscopic Tools

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1. Introduction

Importance of Microscopy for our knowledge, science and technology:

Insights into a previously not accessible field (the smallest structures visible by the naked eye are ≈ 0.1 mm).

Invention of the optical microscope opened the way to the micro-world (micro-biology but also materials science, precision engineering and so on)

Direct imaging of the spatial topography is highly important for all practical influence on systems (applications)

The fabrication of microscopes became a self-standing part of economy (Carl Zeiss Jena in Germany as a vary early modern science-based high-tech factory)

2. Limitations of Conventional Optical Microscopy

Diffraction-based limitation: Each point of the original is imaged as an spatially extended diffraction-pattern

Lateral resolution: distance between two point of the original which can still be separated from each other in the image

$$\Delta x = 0.61\,\lambda / n \sin\sigma$$

(? – wave-length of light used; n – index of diffraction in the object space; s – angle by which the first lens is seen from the object)

Lateral resolution determines the useful magnification: 1000 x

Ways-out: Shorter wave-length (Electron microscopy, X-Ray microscopy)

Novel principles of operation (Scanning-Probe-Microscopies)

3. Electron Microscopies (EM)

Electron waves (de-Broglie-waves):

Wave-length can be adjusted by acceleration voltage

$$\lambda = h / p$$

$$p = \sqrt{2 m E} = \sqrt{2 e m U}$$

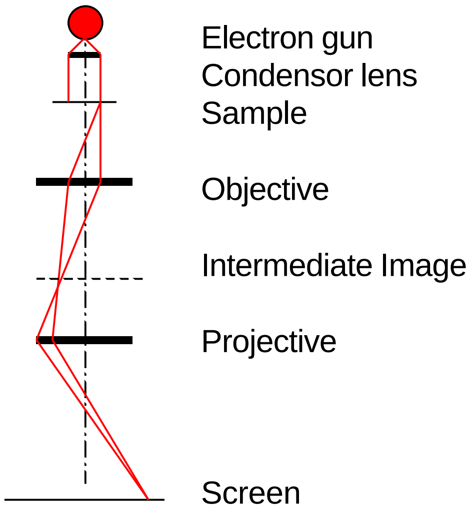
(for voltages higher than 100 kV relativistic effects have to be taken into account)

Electrons propagate freely only in vacuum and can be influenced by electromagnetic fields – electron lenses; electron sources: thermal or field-emission cathodes

Electron microscopy was developed to a large extent in Germany: E. Ruska (Nobel price); v.Borries, v.Ardenne, Recknagel, Heydenreich, Rose, Urban

Transmission Electron Microscopy (TEM)

General scheme (analogy to optical microscope in transmission using a two- or three-stage lens system).

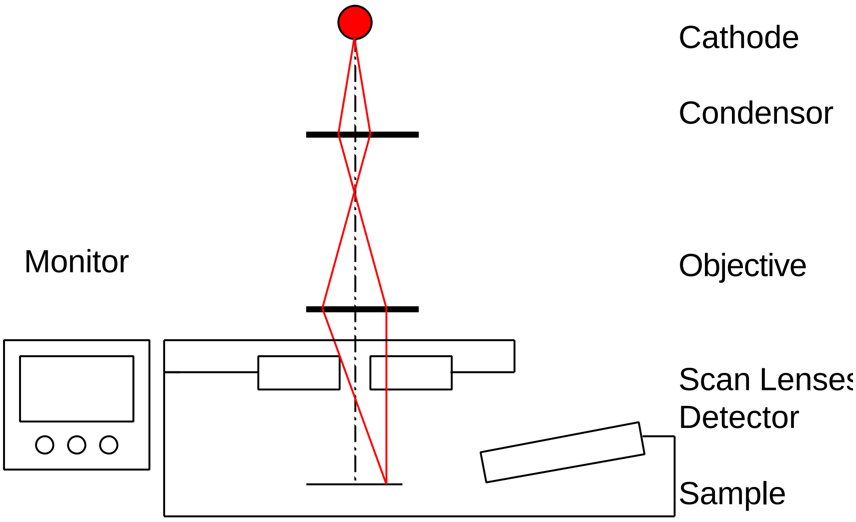


Very thin (electron transparent) samples. Image appears due to interaction of the electron beam with the sample (absorption, scattering, phase shift). Maximum lateral resolution ˜ 0.1 nm. Information about internal structure of the transmitted sample.

Lorentz-Microscopy: Special modifications allow the imaging of magnetic structures (Fresnel-mode, Foucault-mode)

Scanning-Electron-Microscopy (SEM)

General scheme



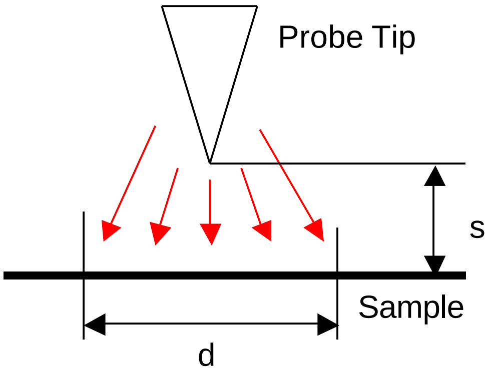
Measured is the yield of secondary electrons at each scanned point. Lateral resolution limit 1 ... 10 nm. Imaged are the surface and near-surface properties (there are also detected X-Rays, photons, backscattered and Auger electrons).

Photoelectron-Emission-Microscopy (PEEM)

Sample is illuminated by a photon beam. Photoelectrons are collected and their distribution over the surface is imaged. Images reflect the distribution of work function. Magnetic structures can be imaged using the magnetic X-Ray circular dichroism.

4. Scanning-Probe-Microscopies

General principle



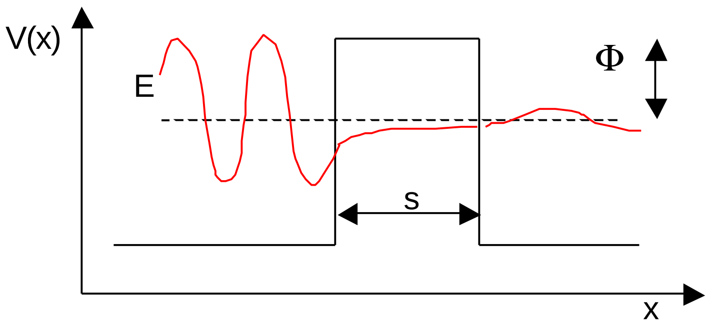
Resolution is not longer diffraction-limited; limitation due to geometry and type of interaction

$\Delta x \approx d(s)$.

3-dimensional investigation of surface profile becomes possible !

Scanning-Tunneling-Microscope

Quantum-mechanical tunneling through a potential barrier:



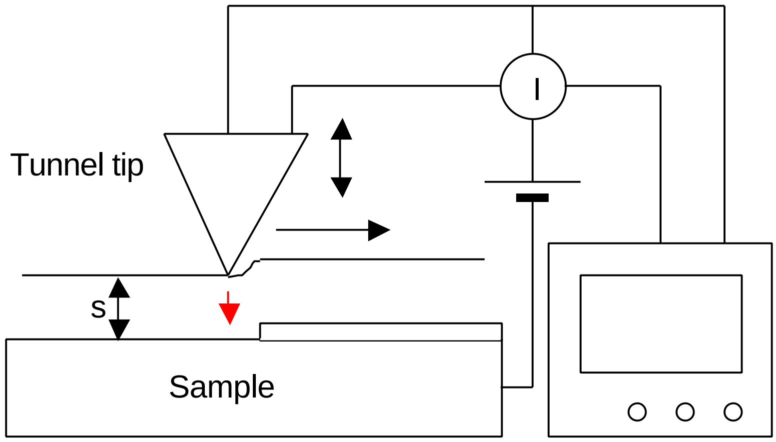
Tunneling probability

$P \sim \exp\{-\text{const.}\sqrt{\Phi}\ s\}$; const. $= 4\pi\sqrt{2m_e}\ / h$.

Typical values for metals: s = 1 nm, Φ = 3 eV, U = 0.1 V, I = 1 nA.

STM: 1981 (G.Binnig, H.Rohrer – Nobel price in physics)

General principle of STM



Lateral resolution ˜ 0.1 nm; vertical resolution in the order of 1 pm!

Spin-Polarized Scanning-Tunneling-Microscopy:

A magnetized tunnel tip enables tunnelling of electrons belonging mainly to one spin orientation. Due to Pauli-principle, the tunnel current reflects magnetic structures on the sample surface.

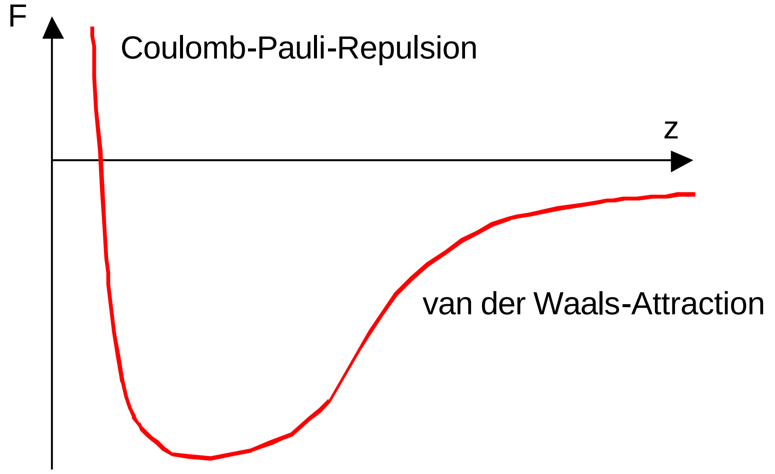
Scanning-SQUID-Microscopy: STM tip within the detecting loop of a SQUID enables highly localized mapping of weak magnetic fields on the sample surface.

Scanning-Hall-Probe-Microscopy: STM tip is equipped by a special semiconductor probe using the Hall effect in a two-dimensional electron gas. The mapping of the magnetic field component vertical to the surface is possible.

Scanning-Force-Microscopies

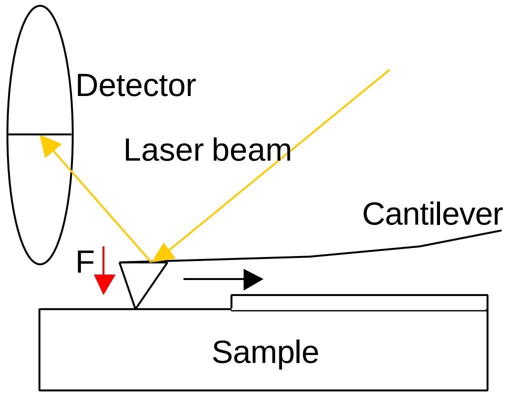
Atomic-Force Microscopy:

General Force-Distance characteristics



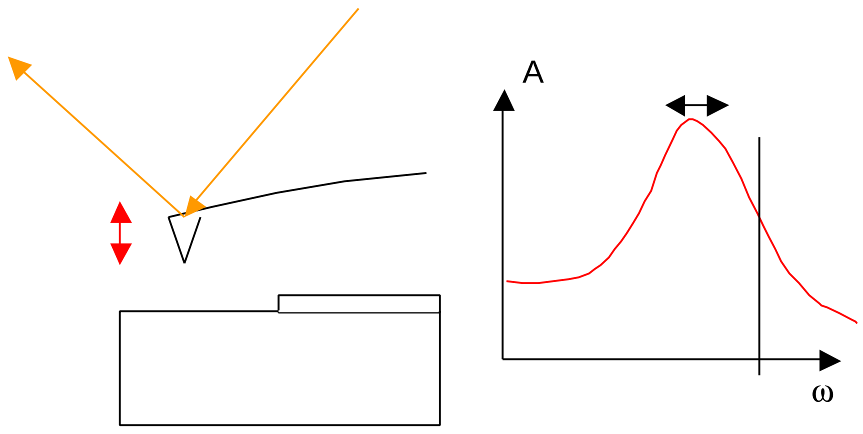
General principles:

Contact modus (1986: Binnig, Rohrer, Quate)



Acting force ~ 1 nN

Dynamical modus



Cantilever is excited to vibrations near to its eigenfrequency; additional external force gradients change the effective force constant of the cantilever and so its resonance frequency. A feedback controls either the amplitude or the phase shift of the vibration.

Atomic-force microscopy is presently most broadly used. Resolution is possible till into the atomic range.

Variations using electric and magnetic stray-fields::

Scanning –Electrical-Force-Microscopy:

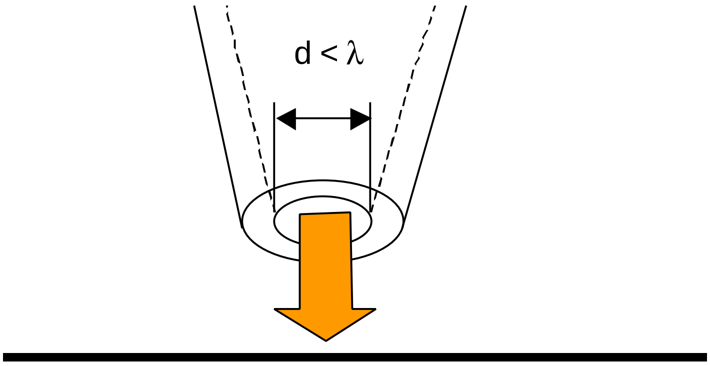
An electrical bias between tip and sample allows mapping of the surface potential and of the local tip-sample capacitance.

Magnetic-Force-Microscopy:

Tip is magnetized and in its influence on the sample idealized by a magnetic monopole.

Optical Near-Field-Microscopy

General principle



Subwavelength aperture; propagating and evanescent parts of the electromagnetic field.

D.Pohl (1984); lateral resolution ~ 10 nm.

5. Final Remarks

Modern microscopies extremely important for micro- and nano-technologies

Today atomic structures are accessible to direct imaging, spatially resolved investigation and manipulation.