Winter Term 2023/24

Lecture

Nano-Optics

Andreas Naber

KSOP

Organization

Tuesday: 2:00 – 3:30 pm

Friday: 9:45 – 11:15 am,
(including exercises)

Credit points: KSOP: 6 ; MPhys: 8

- If you need a certificate (no mark), you should present a paper (~20-30 min; required for credit points in „Nebenfach“)
- For credit points (KSOP, „Ergänzungsfach“, „Schwerpunktfach“) you have to pass an oral exam (30 min)

What is Nano-Optics?!

Google search "nano optics"

- Optoelectronics / Investigation of optoelectronic devices
- Innovative light sources for illumination
- Lenses and lens systems made with nanometer precision
- Quantum optics (entangled states, quantum computing)
- Lithography (EUV)
- Optical coherence tomography
- Optics of nanostructured systems
- Study of nanoscaled materials
- Optical properties of nano particles
- Ultra-precise optics
- Laser techniques
- Laser surgery

Objectives of nano-optics

Light as a tool for

- visualization
- analysis
- control
- manipulation

of matter (atoms, molecules, metallic particles, semi-conductor nano-crystals, quantum dots etc.)

on a scale clearly below the wavelength of light.

Specification

Length scale of conventional optical methods:

> Wavelength of visible light (350-650 nm)

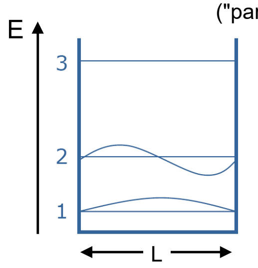
Classification / assignment:

Nano-Optics = Optical phenomena on a length scale below 100 nm

Relevance of visible light

Visible light interacts with charges which are confined to regions of a size of ~ 1 nm. ⇨ Electrons in large (organic) molecules

Illustration: energy states of electrons in a quantum well ("particle in a box")



$$E_n = \frac{h^2 n^2}{8mL^2} \qquad n = 1,2,\ldots$$

$$E_2 - E_1 = \frac{h^2}{8mL^2}(2^2 - 1^2) = \frac{hc}{\lambda}$$

$$L = \sqrt{\frac{3h\lambda}{8mc}} \sim 7\text{Å}$$ (for visible light)

Confinement of topics

This lecture

- Limitation to „visible“ light (200-800 nm) (e.g., no x-ray microscopy)
- Classical electrodynamics (Maxwell's equations)
- Discussion of experimental methods with exemplified applications

Lecture – Overview

I. Theoretical aspects
Maxwell's equations and boundary conditions; near- and far-field radiation; plasmons; surface plasmon polaritons; localized plasmons; Mie scattering; optical properties of molecules including absorption cross section and rate equations

II. Classical optical microscopy
Historical background; microscopic imaging process; primary aberrations and sine condition; microscopic techniques including interference contrast, phase contrast and fluorescence microscopy, confocal light scanning microscopy, total internal reflection microscopy

III. Near-field techniques in nano-optics
Nano-antennas and nano-apertures; photon scanning tunneling microscopy; scanning near-field optical microscopy; methodology including probe fabrication and surface distance control; single molecule microscopy & spectroscopy; selected applications & results

IV. Far-field techniques in nano-optics
Nano-scale dynamics of single molecules; single molecule tracking (SMT); fluorescence correlation spectroscopy (FCS); 4Pi microscopy; stimulated emission depletion (STED-) microscopy; stochastic optical reconstruction microscopy (STORM); applications in physics and biology)

Literature & Slides

Literature

Born & Wolf: Principles of Optics
Pergamon Press

L. Novotny & B. Hecht: Principles of Nano-Optics (eBook)
Cambridge University Press

J. B. Pawley: Handbook of Biological Confocal Microscopy
Springer

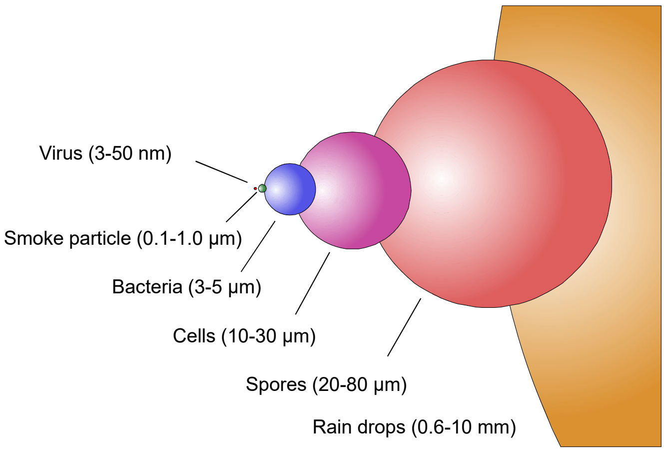
Slides & excercises
are uploaded to ILIAS after each lecture

Introduction

What is a nanometer?

1 nanometer =
10^{-9} m =
0.001 micrometer

Comparison

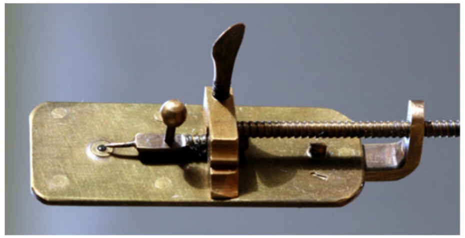


Antoni van Leeuwenhoek

1632 - 1723

… observed for the first time red blood cells and bacteria using a home-build microscope based on a single lens (1675).

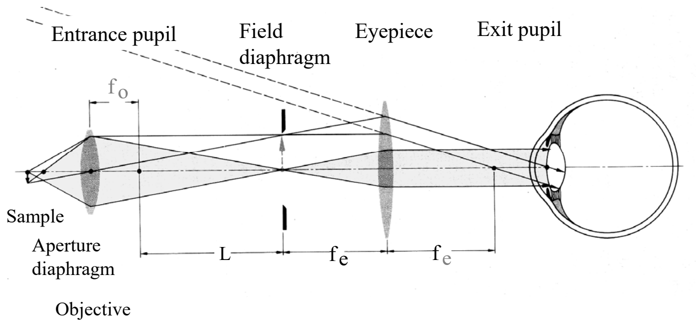
Leeuwenhoek's microscope



(Maximum magnification ~270)

Jeroen Rouwkema, http://www.flickr.com/photos/rouwkema/2262158965/

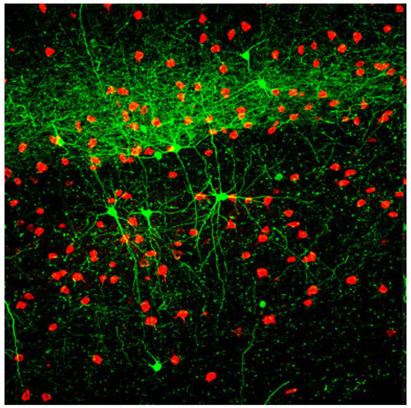
The classical optical microscope



E. Hecht, Optik (Addison-Wesley 1989)

Modern fluorescence microscope

Subtypes of Cortical Interneurons in GAD67-GFP Transgenic Mice



Dr. Hang Hu, Department of Neurobiology & Anatomy, West Virginia University

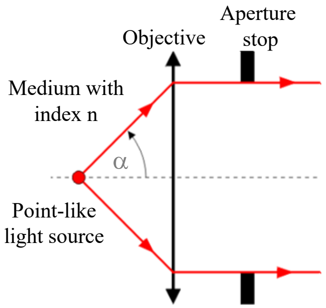
Resolution limit of classical microscopy

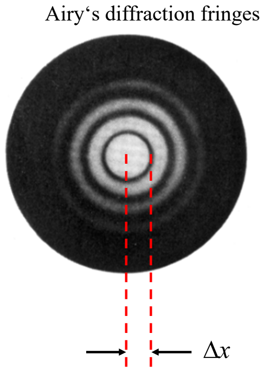
The lower limit of the resolving power of a microscope is given by

$$\Delta x \geq \frac{\lambda}{2\,n}$$ with index of refraction *n*

(Abbe's diffraction limit)

Resolving power

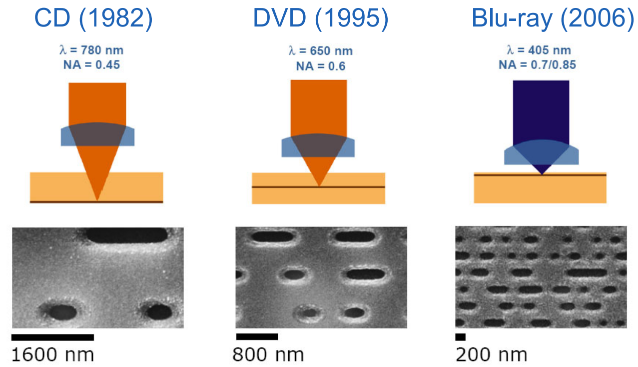




$$\Delta x = 0.61\frac{\lambda}{NA} \quad \text{with} \quad NA = n \sin\alpha$$

Born & Wolf, Principles of Optics (Pergamon Press 1993)

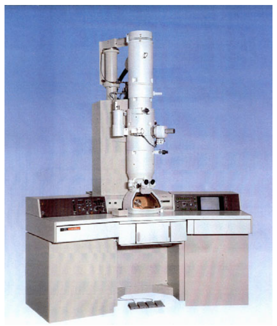
Optical data storage



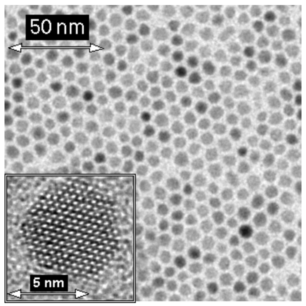
Pohl & Hecht (2003) (adapted)

Electron microscopy

TEM



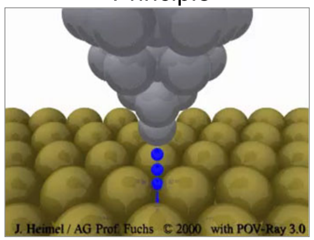
Nano-crystals



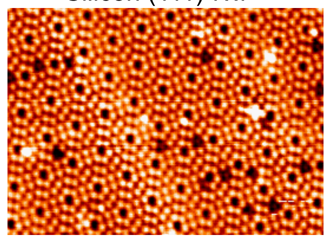
Uni Hamburg, AG Weller

Scanning tunneling microscopy (STM)

Principle



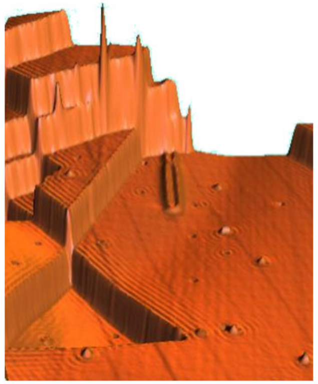
Silicon (111) 7x7



Uni Münster, AG Fuchs

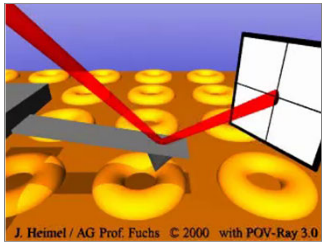
Scanning tunneling microscopy (STM)

Atomic steps

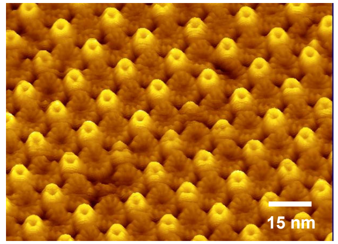


Scanning force microscopy (SFM)

SFM



Bacteriophagus Φ29



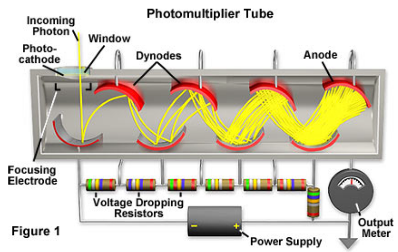
Müller et al., Embo J **16**, 2547-53 (1997)

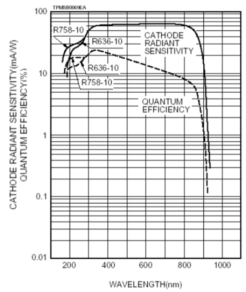
Benefits of optical methods

- **Sensitivity:** Single photons
- **Selectivity:** Very high spectral resolution, special light sources (laser), material contrast
- **Speed:** Very high temporal resolution
- **Diversity:** Interference, absorption, fluorescence, scattering, etc.

Sensitivity

Secondary electron multiplier



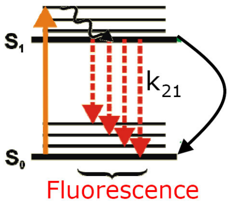


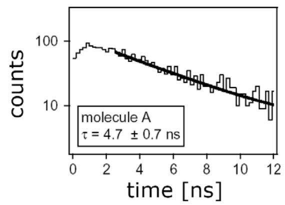
Dark count rate : < 10 Counts/s
Temporal resolution : < 150 ps

Hecht (2003)

Speed

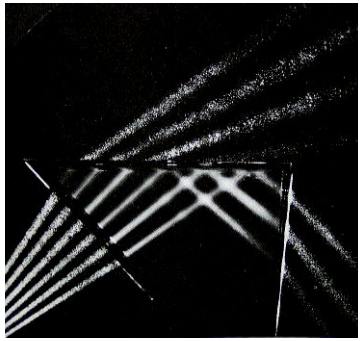
Excitation and fluorescence of a molecule





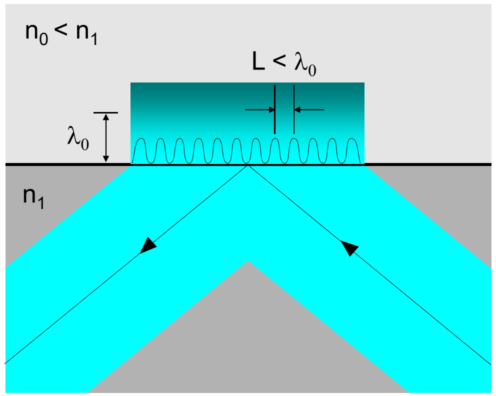
Hecht (2003)

Angle of total reflection



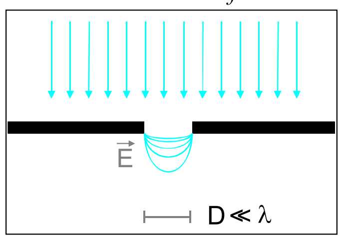
Hecht, Optik

Total reflection

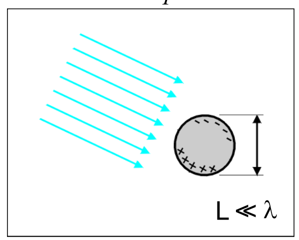


Evanescent fields

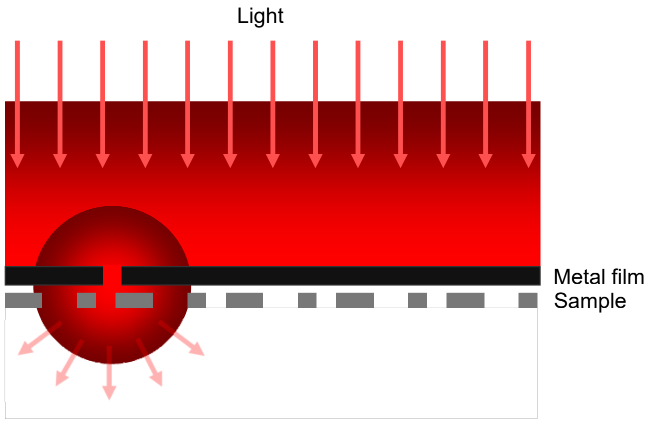
Hole in a metal film



Metallic nano particle

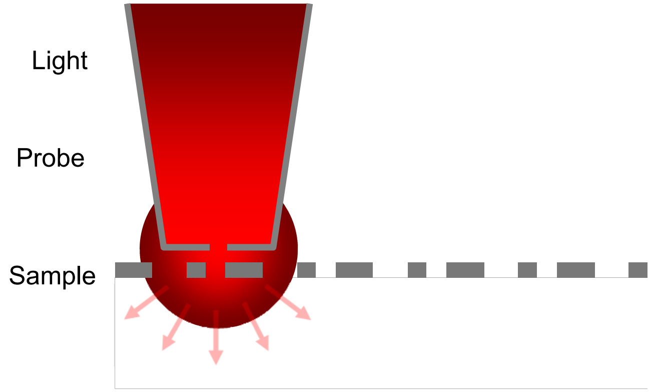


Microscopy with holes



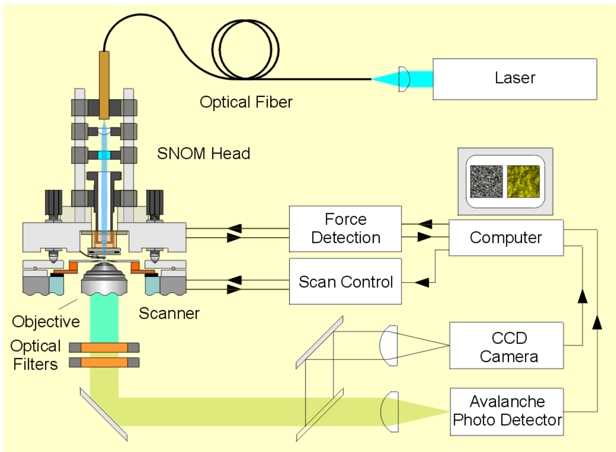
E. Synge (1928)

Scanning Near-field Optical Microscopy (SNOM)

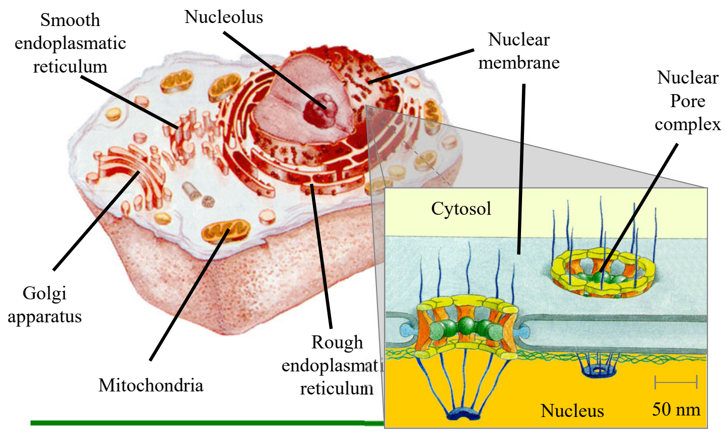


Pohl et al. (1984); Betzig et al. (1991)

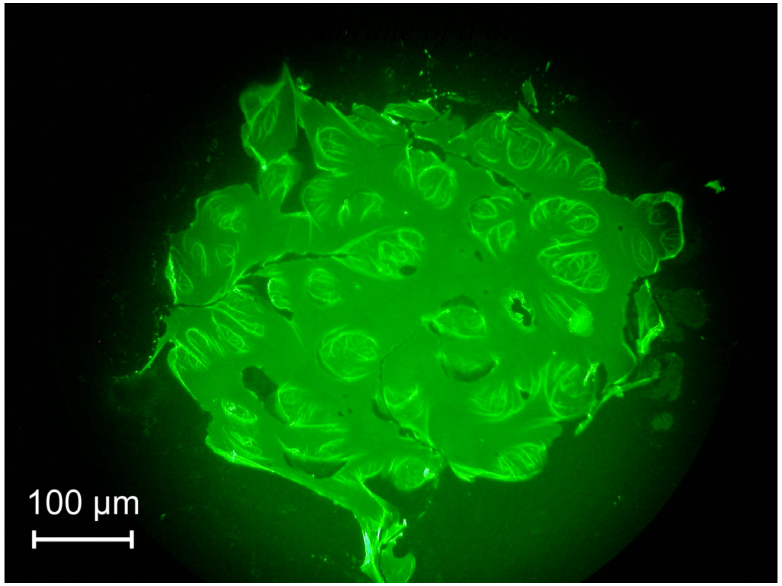
Set-up of a SNOM

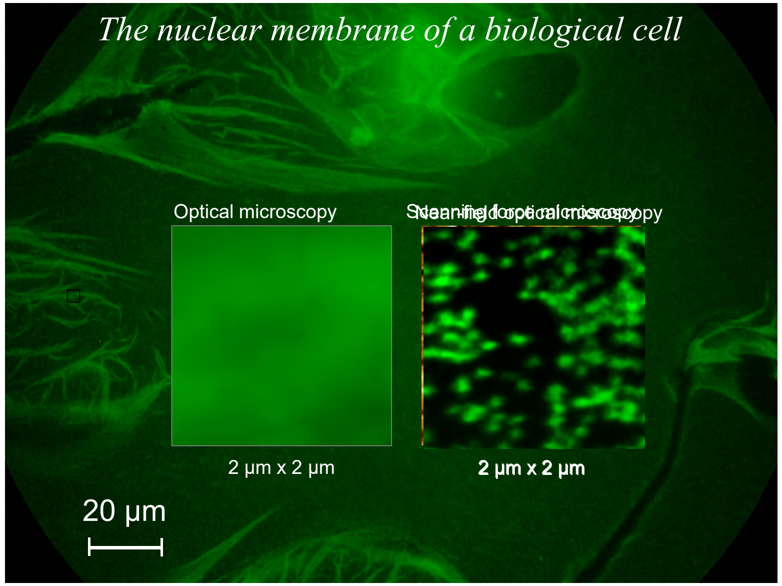


Organels in a biological cell



Alberts et al, VCH, 1995; Lehninger et al, Spektrum, Akad. Verl., 1994


100 µm


The nuclear membrane of a biological cell
Optical microscopy
Scanning force microscopy
Near-field optical microscopy
2 µm x 2 µm
2 µm x 2 µm
20 µm