

Wintersemester 2022/23

Lecture

Nano-Optics

Andreas Naber



KSOP



Organization

Tuesday: 2:00 – 3:30 pm

Friday: 10:00 – 11:30 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)
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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:

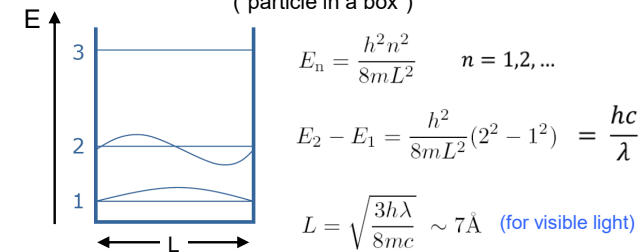
Nano-Optics = Optical phenomena on a length scale below 100 nm



Relevance of visible light

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

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



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



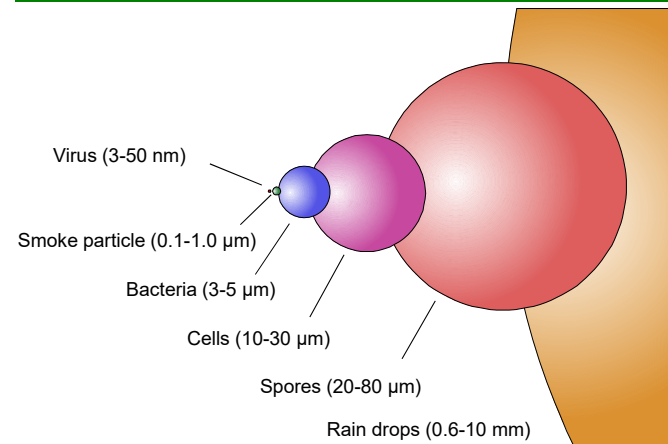
Introduction

What is a nanometer?

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



Comparison



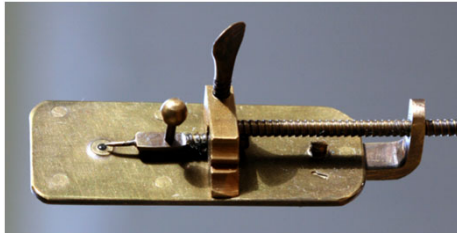
Antoni van Leeuwenhoek



1632 - 1723

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

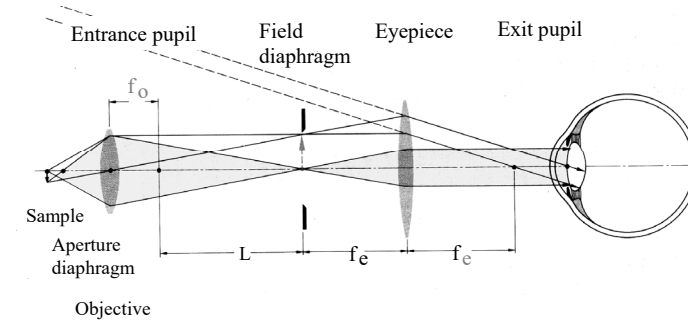
Leeuwenhoek's microscope



(Maximum magnification ~270)

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

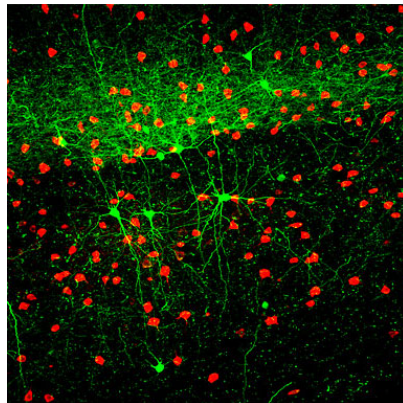
The classical optical microscope



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

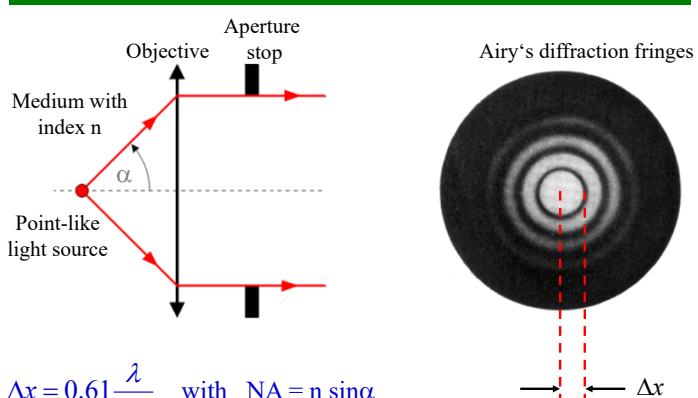
Resolution limit of classical microscopy

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

$$\Delta x \geq \frac{\lambda}{2n} \quad \text{with index of refraction } n$$

(Abbe's diffraction limit)

KIT **Resolving power**



Medium with index n

Point-like light source

Objective

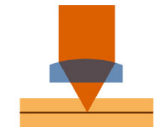
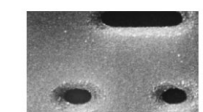
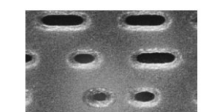
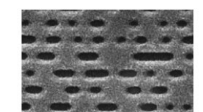
Aperture stop

Airy's diffraction fringes

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

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

KIT **Optical data storage**

CD (1982)	DVD (1995)	Blu-ray (2006)
$\lambda = 780 \text{ nm}$ $NA = 0.45$	$\lambda = 650 \text{ nm}$ $NA = 0.6$	$\lambda = 405 \text{ nm}$ $NA = 0.7/0.85$
		
		
1600 nm	800 nm	200 nm

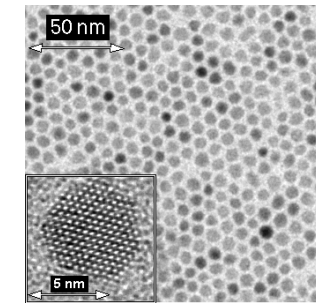
Pohl & Hecht (2003) (adapted)

KIT **Electron microscopy**

TEM



Nano-crystals



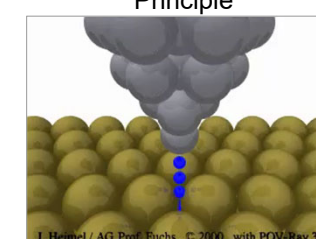
50 nm

6 nm

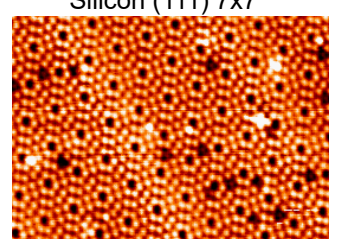
Uni Hamburg, AG Weller

KIT **Scanning tunneling microscopy (STM)**

Principle



Silicon (111) 7x7

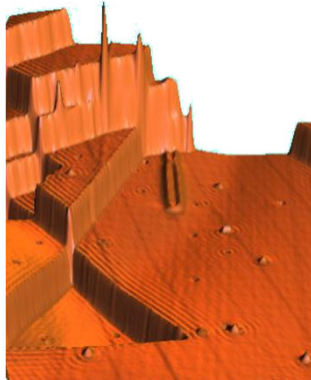


J. Heimeel / AG Prof. Fuchs © 2000 with POV-Ray 3.0

Uni Münster, AG Fuchs

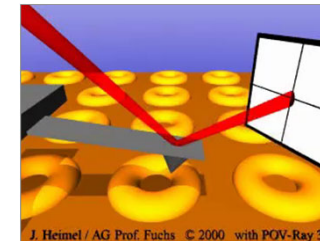
Scanning tunneling microscopy (STM)

Atomic steps

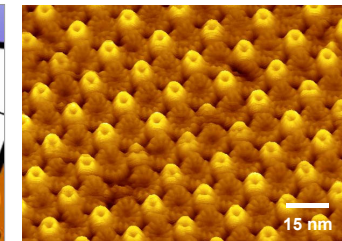


Scanning force microscopy (SFM)

SFM



Bacteriophages $\Phi 29$



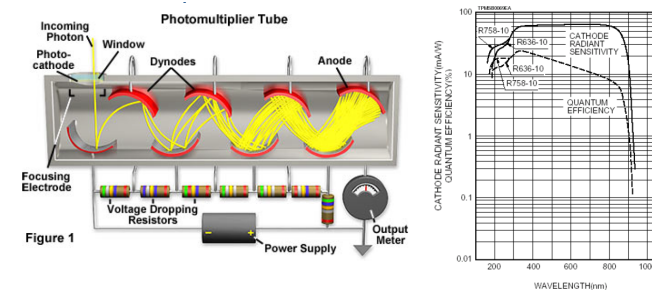
Müller et al., *Embo J* **16**, 2547-53 (1997)

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

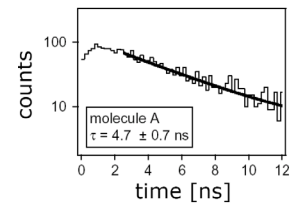
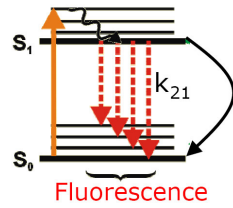
Secondary electron multiplier



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

Hecht (2003)

Excitation and fluorescence of a molecule



Hecht (2003)