Laboratory for Electron Microscopy

Electron Microscopy I
Lecture 01

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Content

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Content

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Electron Microscopy

Transmission electron microscopy (TEM)

Electron Microscopy I

Scanning electron microscopy (SEM)

Electron Microscopy II

Scanning transmission electron microscopy

Electron Microscopy II

Analytical methods in electron microscopy
(chemical analysis, electronic properties)

Electron Microscopy II

Relevance as an examination subject

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Electron Microscopy I: Transmission Electron Microscopy (2 SWS)
(WS 23/24) and accompanying lab course with 4 exercises

Electron Microscopy II: Scanning electron microscopy and analyt. Methods (2 SWS)
(SS 2024) and accompanying lab course with 4 exercises
possible only in SS2024

Elective subject in the Master Physics
Electron Microscopy I (4 ECTS) with lab course (4 ECTS)
Electron Microscopy II (4 ECTS) with lab course (4 ECTS)
EM for specialization and supplementary subjects in the field of
"Condensed Matter" and "Nanophysics".

Elective for Master MatWerk: EM I and EM II oral exam (16 LP)
Applied geosciences, business mathematics, chemistry....

Attendance certificate for lecture
Attendance list (Eligible for certificate with a minimum of 2 absences)

Attendance certificates necessary for exam registration

Requirements and documents

Requirements

Optics
Solid state physics/materials science
Most important elements of quantum mechanics: Particle-wave duality

Lecture Notes:

Slides →

Permanent Zoom Link →

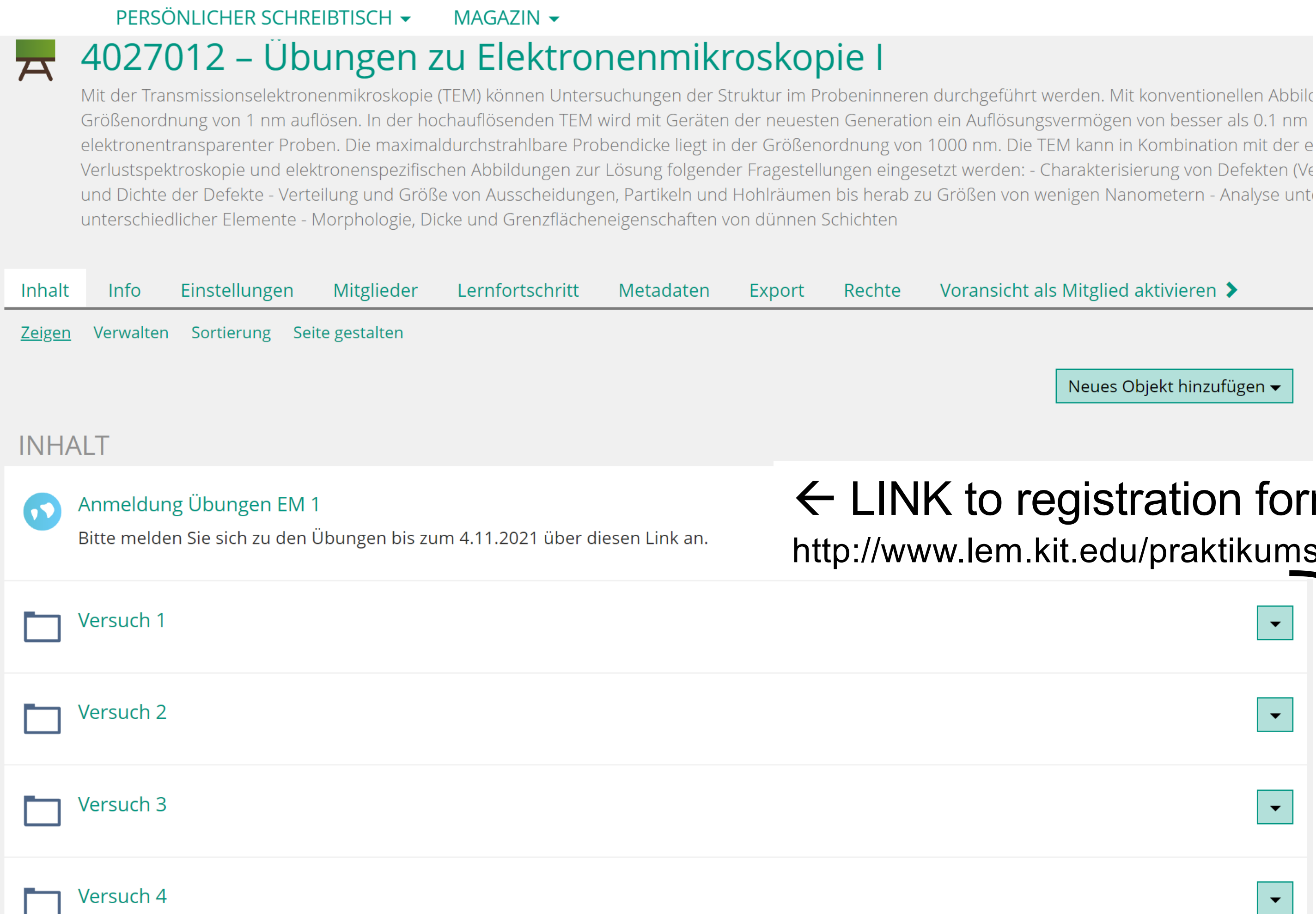
Link: Exercise and internships →

Lab Course

Laboratory for Electron Microscopy

ILIAS Course: Exercises in Electron Microscopy I WS23/24

- **Registration for the lab course until 07.11.2023.**



← LINK to registration form
http://www.lem.kit.edu/praktikumsanmeldung.php

4 exercises,

Documents will be provided 2 weeks prior to the exercise

Lab Course

Laboratory for Electron Microscopy

4 Exercises

1. Basic imaging modes of transmission electron microscopy I.
Sample: Semiconductor heterostructure

2. Basic imaging modes of transmission electron microscopy II
Sample: Polycrystalline metal alloy
Imaging of defects

3. Scanning transmission electron microscopy (STEM)
Sample: Dispersion strengthened aluminum, silicon

4. High-resolution transmission electron microscopy, digital image processing. and image simulation
Sample: Semiconductor heterostructure: GaAs layer on Si substrate

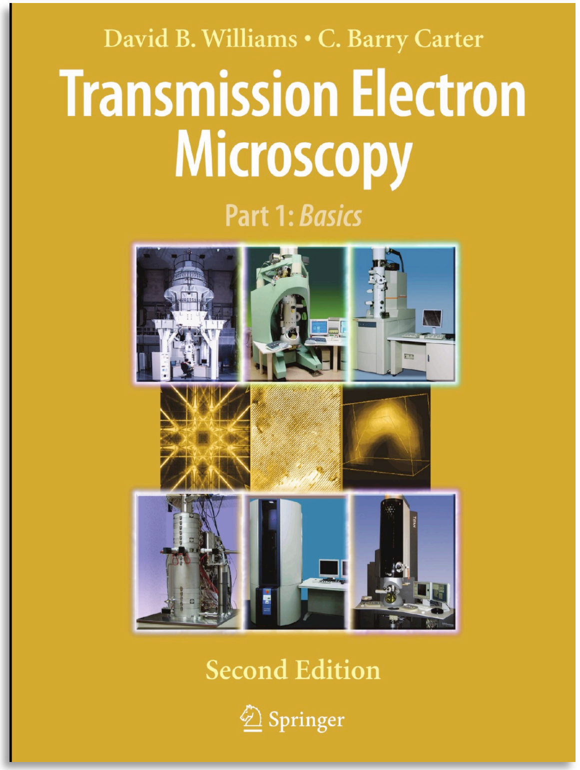
Registration **until 07.11.2023 at the latest:**

Study and Teaching → Electron Microscopy I → Lab Course Registration

Anmeldung Übungen EM 1
Bitte melden Sie sich zu den Übungen bis zum 4.11.2021 über diesen Link an.

← LINK to registration form
http://www.lem.kit.edu/praktikumsanmeldung.php

Literature



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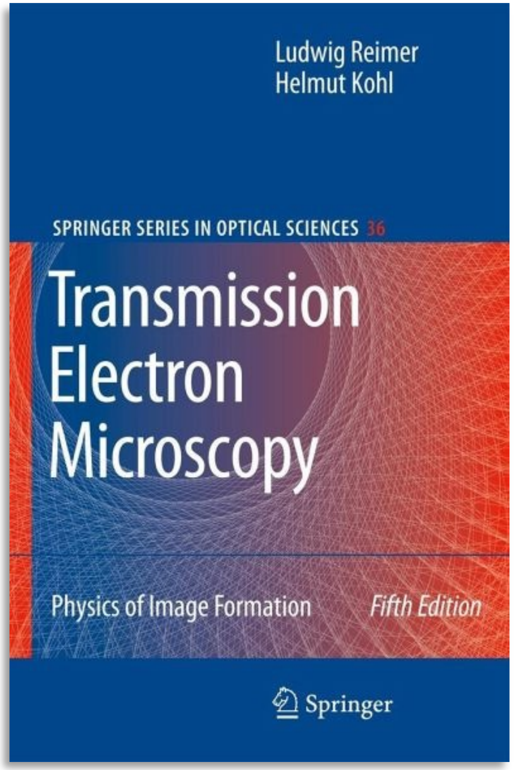
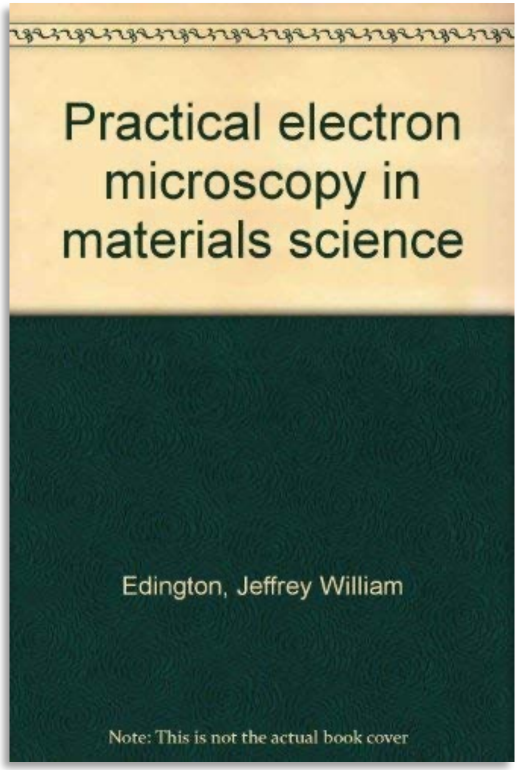


L. Reimer, H. Kohl, Transmission Electron Microscopy, Springer Series in Optical Sciences vol. 36, Springer Verlag 2008, 5th edition



J.W. Edington, Practical electron microscopy in material science, 1991
ISBN 13: 9780442222307

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Laboratory for Electron Microscopy

Optic
E. Hecht, A. Zajac, Optics, Addison-Wesley Publishing Company

Transmissionelectronmicroscopy and electron diffraction
H. Alexander, Physikalische Grundlagen der Elektronenmikroskopie
Teubner 1997

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ca. 40 EU (vergriffen)

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P. Hirsch, A. Howie, R.B. Nicholson, D.W. Pashley, J. Wheelan, Electron Microscopy of Thin Crystals,
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E. Fuchs, H. Oppolzer, H. Rehme, Particle Beam Microanalysis, VCH Verlag 1990

Literature

R. Erni, Aberration-Corrected Imaging in Transmission Electron Microscopy: An Introduction, Imperial College Press 2010

X. Zou, S. Hovmoller, P. Oleynikov, Electron Crystallography: Electron Microscopy and Electron Diffraction, Oxford University Press 2011

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Applications in solid state physics/materials research/materials science.

E. Hornbogen, B. Skrotzki, Werkstoffmikroskopie, Serie Werkstoff-Forschung und -Technik, Band 11, Herausgeber B. Ilschner, 2. Auflage Springer Verlag 1993

G. Thomas, M. J. Goringe, Transmission Electron Microscopy of Materials, John Wiley & Sons Inc 1987

Additional Textbooks:

M.H. Loretto, Electron Beam Analysis of Materials, Chapman and Hall

J.H.C. Spence, J.M. Zuo, Electron Microdiffraction, Plenum Press

A. Tonomura, Electron Holography, Springer Series in Optical Sciences 70, 1993

Motivation

Laboratory for Electron Microscopy

- Examination of objects with a ***resolution of 0.05 nm in*** comparison to conventional light microscopy (few 100 nm) due to low electron wavelength
- Transillumination of thin specimens ⟶ View inside the specimen
- Combination of mapping (structure in real space), diffraction (reciprocal space), chemical analysis and investigation of electronic properties on sub-nm (sub-Å) scale
- In particular, study of defects, interfaces, non-periodic structures.
- in-situ observation of plastic deformation, chemical reactions, ...
- Tomography (three-dimensional object reconstruction)
- Electron holography (reconstruction of amplitude and phase), imaging of electric and magnetic fields, ...

Application in:

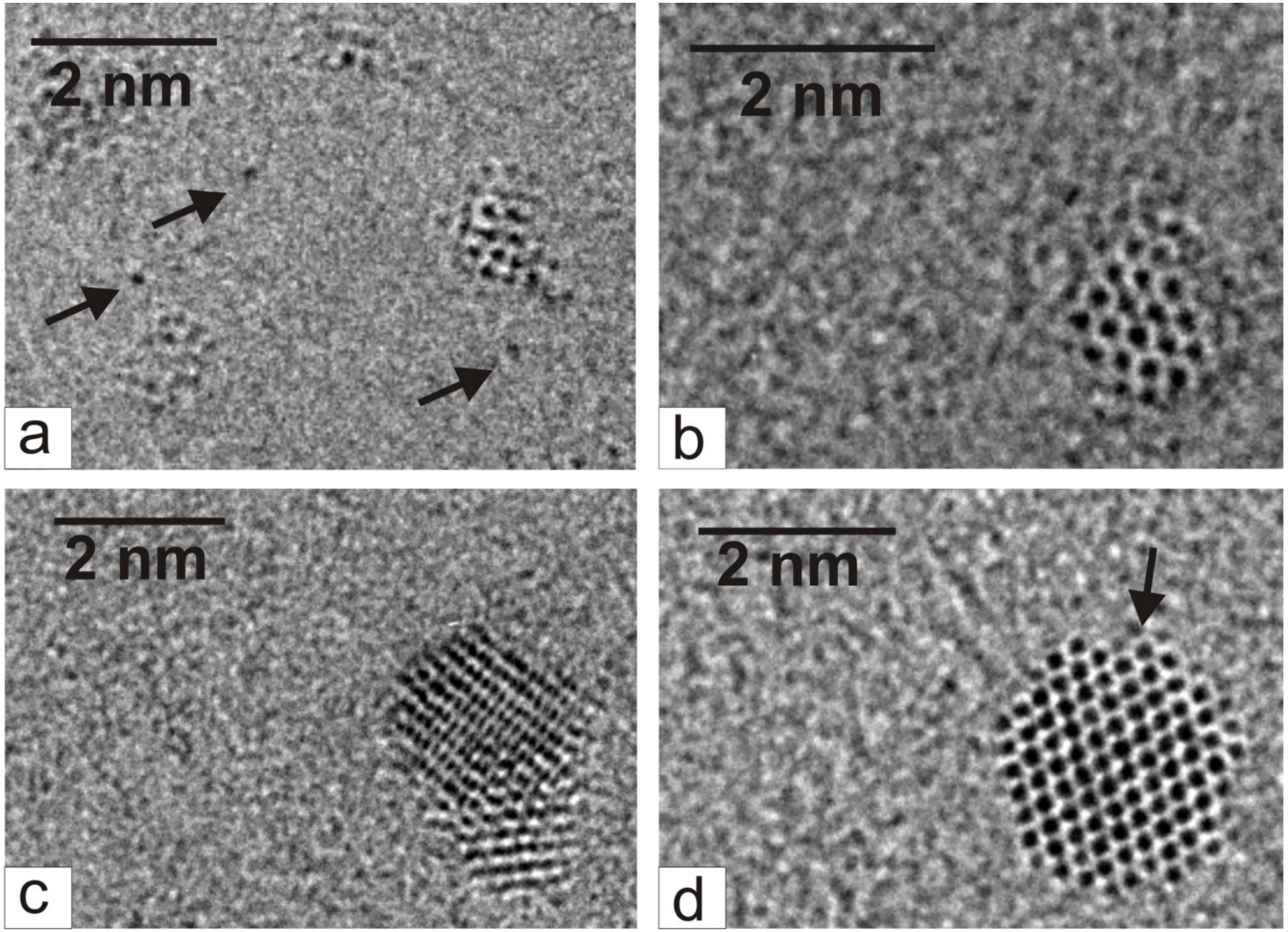
Solid state physics, materials research
Chemistry, catalysis research
Nanotechnology
Geology/Mineralogy
Biology/Zoology/Medicine
Archaeology
Art

Nobel Prize for Ernst Ruska in 1986 for design of first electron microscope

Nobel Prize for Dubochet, Frank and Henderson in 2017 for Cryo-EM

Laboratory for Electron Microscopy

Platinum clusters and single platinum atoms on a thin carbon film



R. Schneider, Laboratory for Electron Microscopy (LEM)

Motivation

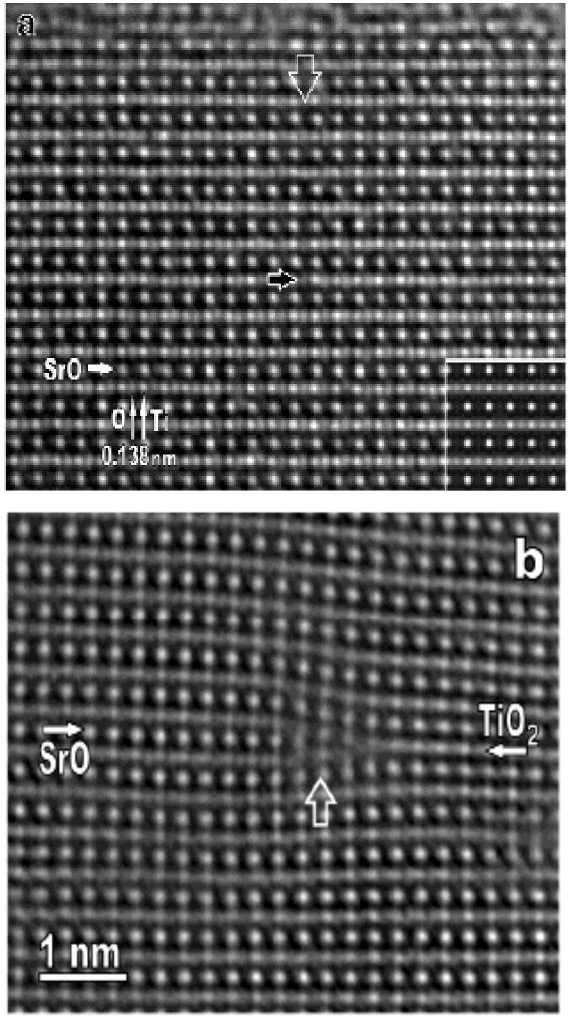


Figure 8. Experimental images of two different edge dislocations in $SrTiO_3$ [110] with a spherical aberration of −40 μm and a defocus of around 8 nm.

C.-L. Jia et al, Microsc. Microanal. 10, 174 (2004)

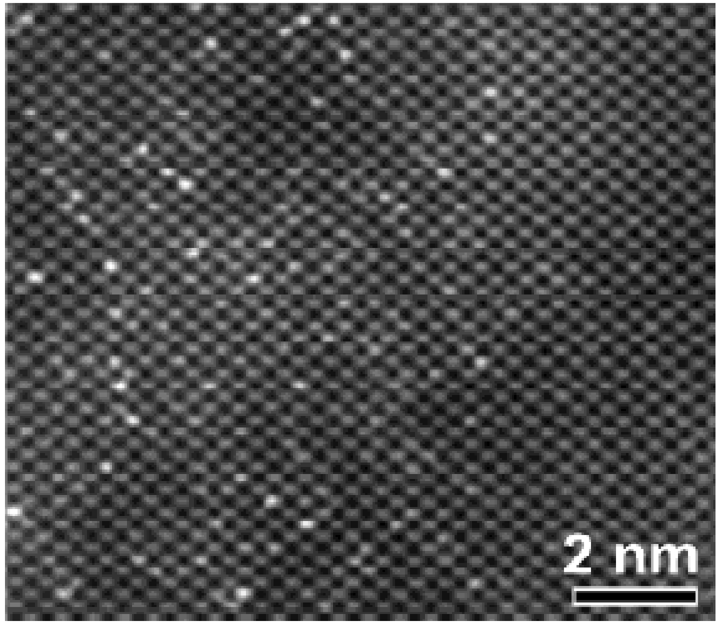


Figure 1. An atomic-resolution ADF-STEM image of a ⟨110⟩ projection of Si doped with Sb by low-temperature MBE showing contrast from single atoms. The right-hand side is the Si substrate, in which there is no Sb and all the atomic columns are the same intensity (atomic columns are white in this imaging mode). The left-hand side is the doped material. Most of the brightest atomic columns on the left contain a single Sb atom. A few (~15%) contain two Sb atoms. The image was acquired at room temperature in a 200-kV JEOL 2010F-ARP STEM with 10-mrad incident convergence angle and 50-mrad detector inner angle. We estimate this region of the sample is ~50 Å thick. The image was smoothed and background corrected.

P.M. Voyles, Microsc. Microanal. 10, 291 (2004)

Motivation

Wide range of applications at medium magnifications

Electron holography

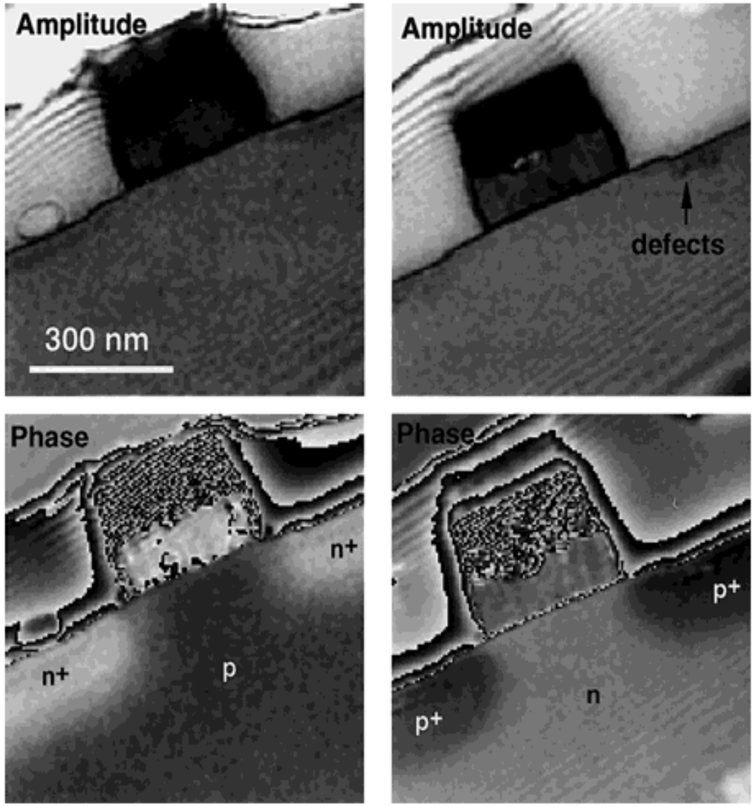
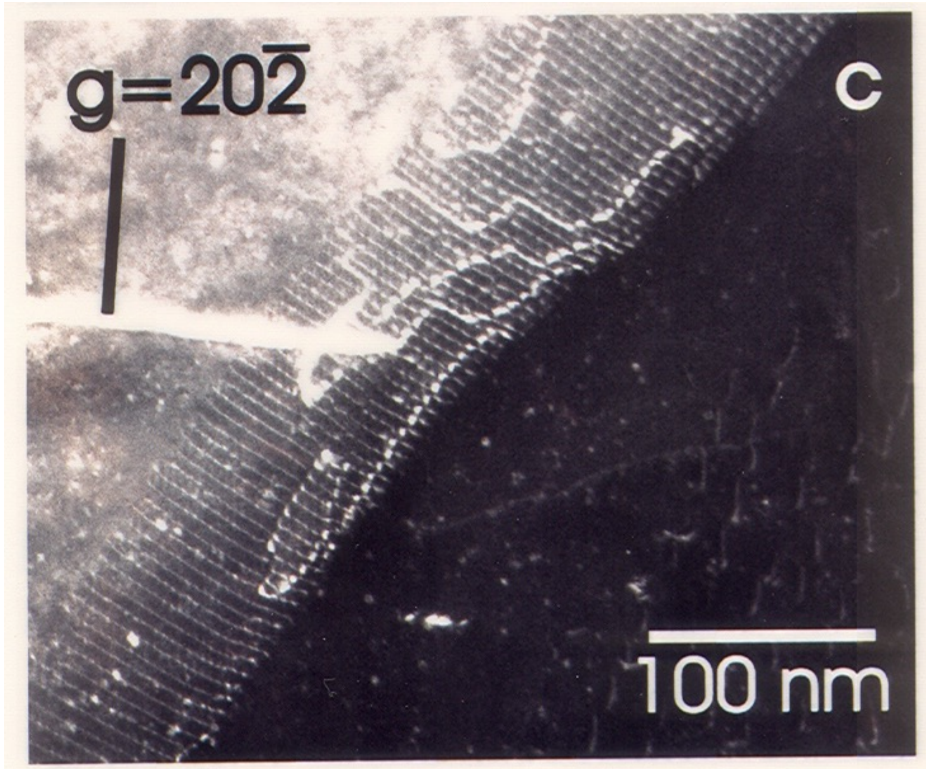


Fig. 4. Amplitude and phase image of 0.3 µm NMOS (left) and PMOS (right) transistors. The source and drain areas are revealed in the phase images. Sharp black-white contrast lines are due to phase changes larger than 2π

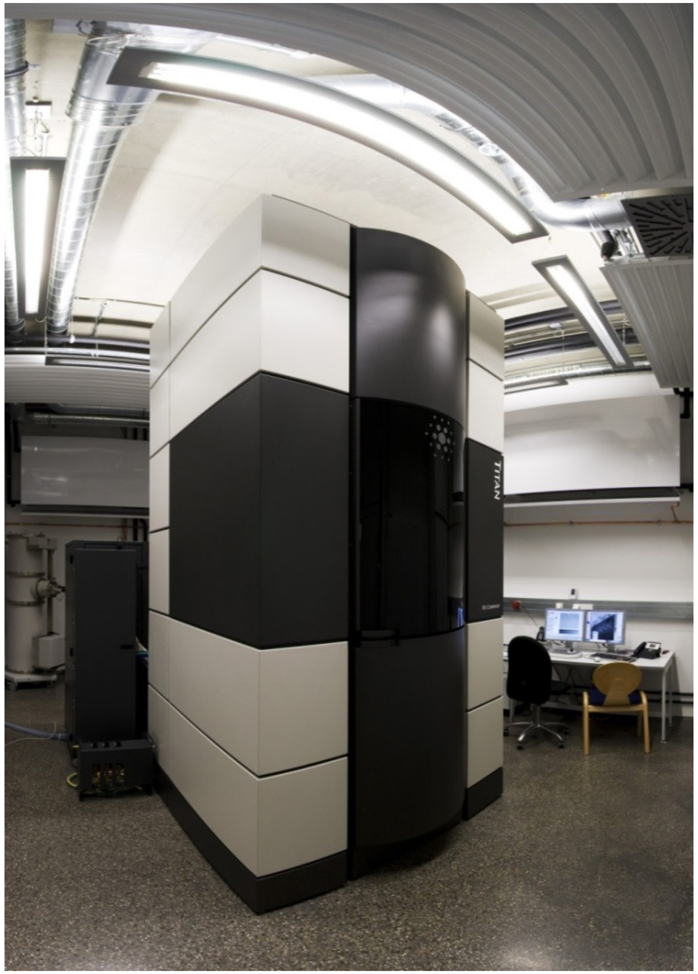
Rau et al, phys. Stat. sol. (b) 222, 213 (2000)



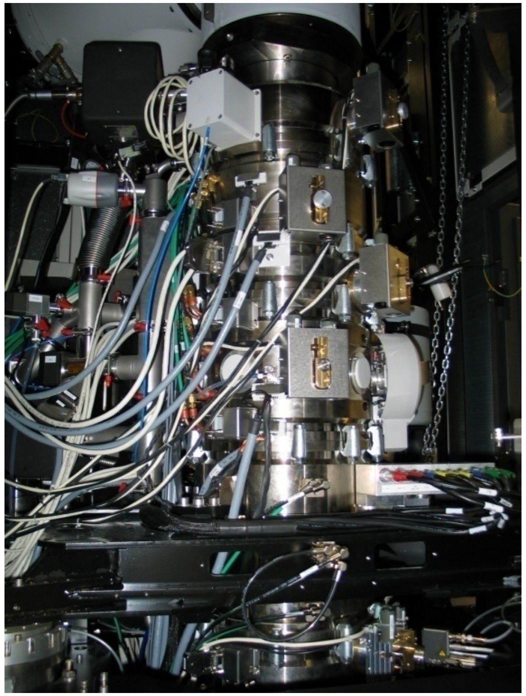
Dislocation network/small angle grain boundary in aluminum
R. Wittmann et al. (LEM)
Mat. Sci. Engn. A 266, 183 (1999)

Motivation

Philips CM200
point resolution
0.24 nm @200kV



FEI Titan³ 80-300
point resolution 0.07 nm @ 300kV



Upper part of the
microscope column

1.1 Light and matter waves

Basis of resolution improvement: wave-particle duality
(de Broglie, 1924)

$$\lambda = \frac{h}{p}$$

λ: Wavelength
p: Impulse
h: Planck's constant 1.05-10^{-34} Nms (6.5-10^{-16} eVs)

Impulse of an electron accelerated in vacuum with voltage U:

$$eU = \frac{p^2}{2m} \longrightarrow p = \sqrt{2eUm} \longrightarrow \lambda = \frac{h}{\sqrt{2eUm}}$$

For U = 100000 V (100 kV): v ≅ 0.5 c ⟶ relativistic calculation $\mathrm{p} = mv$

$$\lambda = \frac{h}{\sqrt{2m_0eU\left(1 + \frac{eU}{2m_0c^2}\right)}}$$

m_0 : Electron rest mass
c: Speed of light

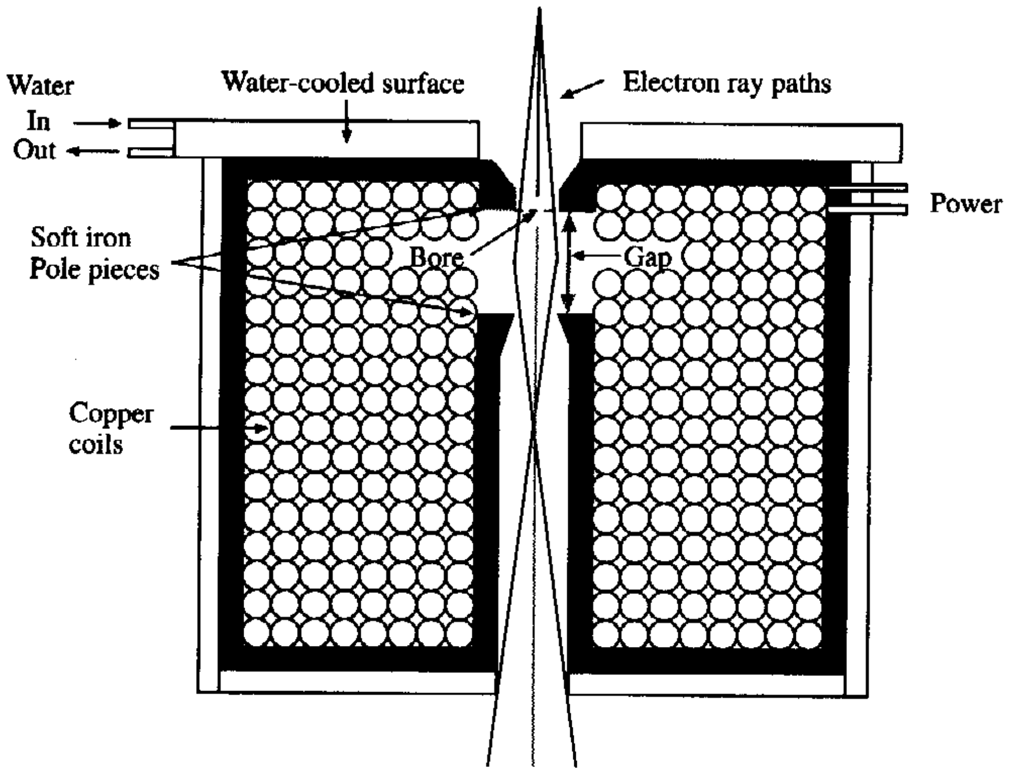
1.1 Light and matter waves

Wavelength in pm (10^{-12} m)	Electron energy in keV
3.5	100
3.348	120
2.507	200
1.968	300
1.643	400
0.8715	1000

Discrepancy between best possible (50 pm) and diffraction-limited resolution due to lens aberration!

Light optics: glass/plastic lenses
Electron optics: electrostatic or **magnetic** lenses (refraction by Lorentz force)

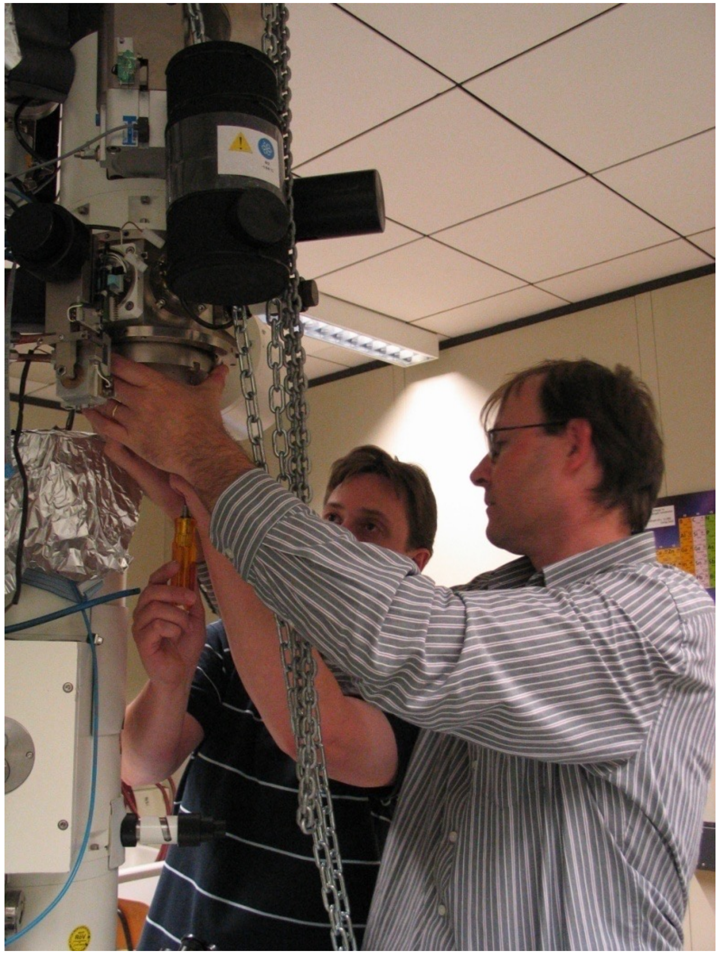
Electron magnetic lens



Variable focal length through change of the coil current and the magnetic field strength

D.B. Williams, C.B. Carter, Transmission Electron Microscopy, Fig. 6.6

1.2 Fundamentals of Optical Imaging: Geometric Optics



Pictures: Levin Dieterle (LEM)

1.2 Fundamentals of Optical Imaging: Geometric Optics

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Construction of an image through ray diagrams comparable to light optics
Rays: Trajectories of electrons

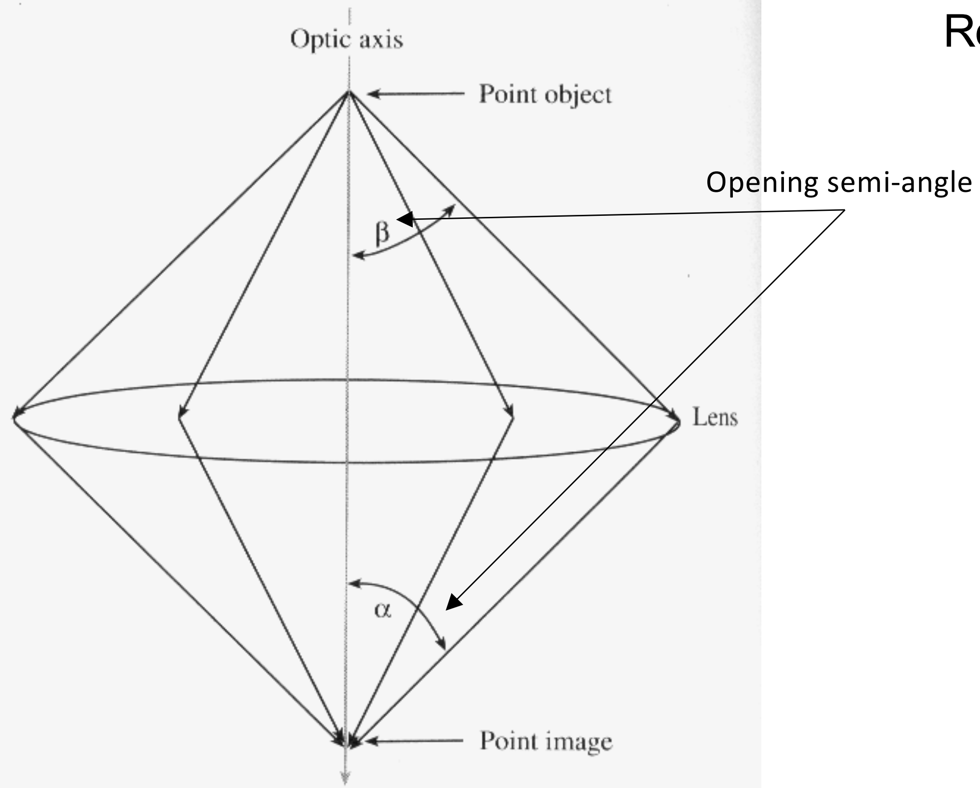


Figure 6.1. Image formation by a convex lens. A point object is imaged as a point and the collection semiangle of the lens is defined relative to the object (β) or the image (α).

D.B. Williams, C.B. Carter, Transmission Electron Microscopy, Fig.6.1

Recording of the image on a photographic plate or CCD (charge-coupled device) camera

↓

Real image, convex lens necessary

Optical axis through center of lens

Object side opening semi-angle β
Image side convergence semi-angle α

α, β in the TEM very small (few degrees)

Construction of an image through ray diagrams comparable to light optics

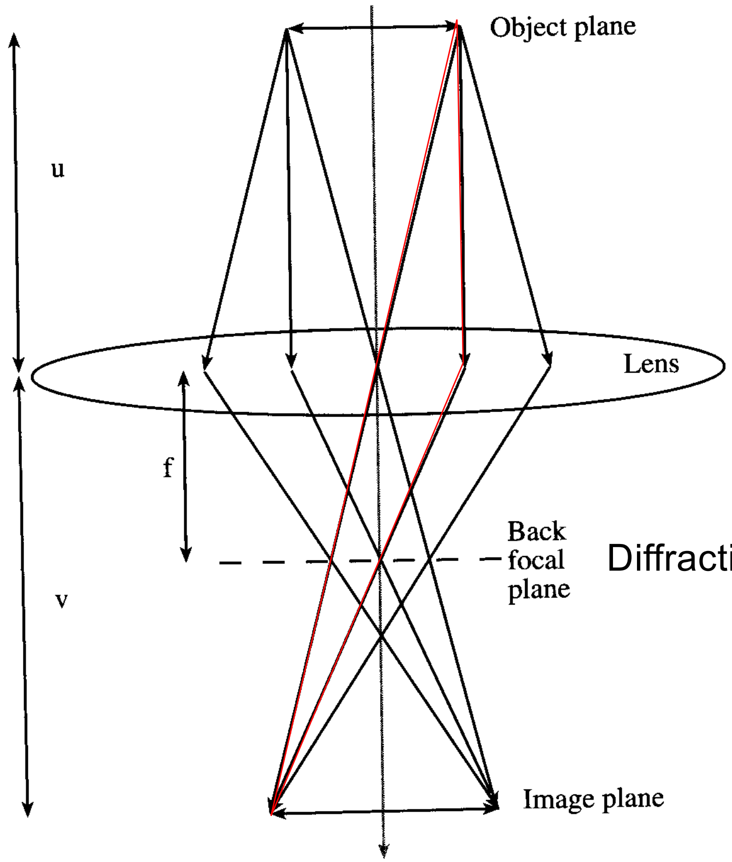


Figure 6.3. A complete ray diagram for a finite object, symmetrically positioned around the optic axis. All rays emerging from a point in the object (distance u from the lens) that are gathered by the lens converge to a point in the image (distance v from the lens) and all parallel rays are focused in the focal plane (distance f from the lens).

D.B. Williams, C.B. Carter, Transmission Electron Microscopy, Fig.6.3

Gaussian lens equation (thin lenses)

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

Validity shown for electron optics
by Ernst Ruska in his Diploma thesis 1931

$$M = \frac{v}{u} = \frac{I}{O}$$

I: Image size
O: Object size
M: Magnification
u: Object width
v: Image width
f: Focal length

Construction of an image by imaging with a thin lens

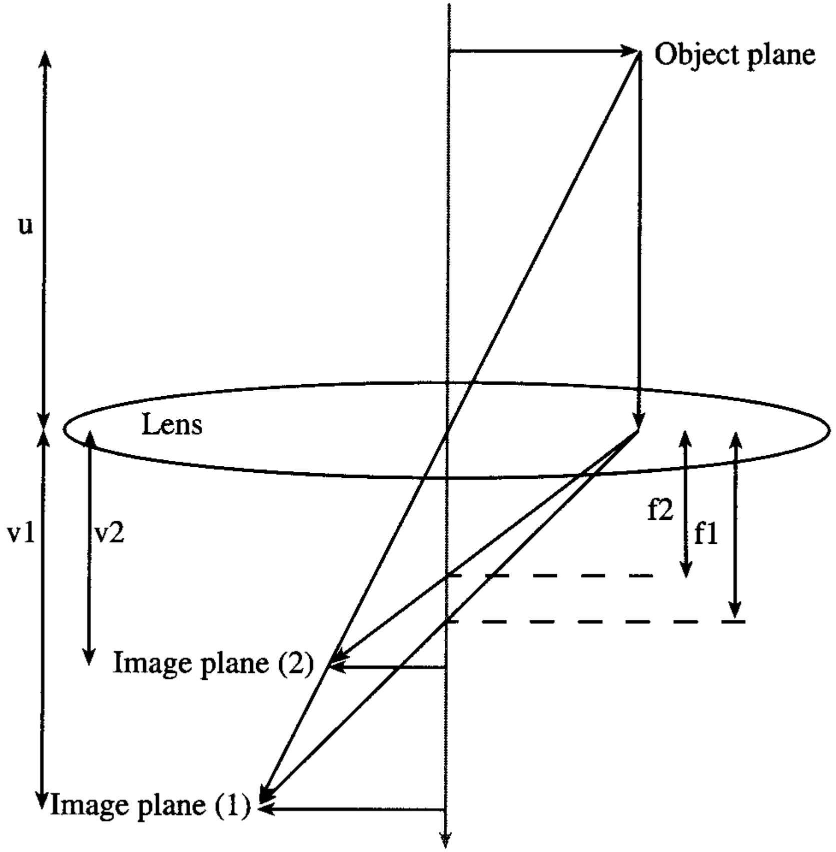


Figure 6.4. Strengthening the lens shortens the focal length *f*. So a weaker lens (*f1*) produces a higher magnification of the object than a stronger lens (*f2*) since the image distance *v* increases, but the object distance is unchanged.

D.B. Williams, C.B. Carter, Transmission Electron Microscopy, Fig.6.4

In the TEM

- For a fixed object width ***u***, a stronger lens has shorter focal length ***f2*** and produces a lower magnification than a weaker lense with a longer focal length ***f1***.
- 4 to 6-stage lens systems, in order to reach magnifications of up to 1 million
- Total magnification: product of the magnifications of every single lense

1.3 Wave optics: Abbe's theory of imaging

General description of a wave by location and time dependent amplitude with wavenumber vector $\vec{k}$, wavelength λ and frequency ω

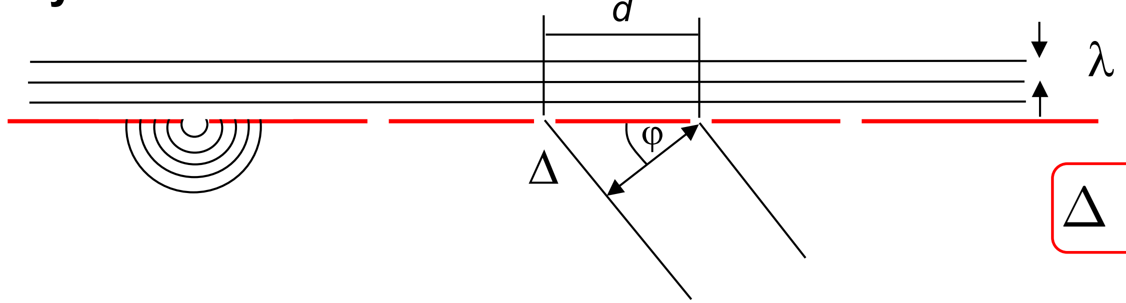
$$\vec{E}(\vec{r},t) = \vec{E_0}\exp\left(i(\vec{k}\vec{r} - \omega t)\right)$$ Electric wave

$$\psi(\vec{r},t) = \psi_0 \exp\left(i(\vec{k}\vec{r} - \omega t)\right)$$ Electron wave function

$$|\vec{k}| = \frac{1}{\lambda}$$

- Model object slit grid, illumination by monochromatic, coherent light
  Slit width << wavelength (corresponds to situation in TEM)
  In TEM: atomic nuclei 10^{-15} m vs. wavelength 10^{-12} m
- TEM: Crystal as three-dimensional lattice with "infinitely" large "number of slits" (atoms)
- TEM: steady state $\rightarrow$ no time dependence

Huygens-Fresnel principle: each point of a wave front is starting point of an elementary wave



$$\Delta = d\sin\varphi$$

Constructive interference $\quad \Delta = d\sin\varphi = n\lambda$

Destructive interference $\quad \Delta = d\sin\varphi = (2n+1)\frac{\lambda}{2} \qquad n = 0, \pm1, \pm2, \ldots$

Δ: path length difference