

# Electron Microscopy I

## Lecture 01

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## **1. From light microscopy to electron microscopy**

- 1.1 Light and matter waves
- 1.2 Fundamentals of optical imaging: geometrical optics
- 1.3 Wave optics: Abbe's theory of imaging, Fourier optics
- 1.4 Limitation of resolution due to lens aberrations in electron optics

## **2. Practical aspects of transmission electron microscopy (TEM).**

- 2.1 Structure and function of a transmission electron microscope
- 2.2 Specimen preparation
- 2.3 Radiation damage

## **3. Electron diffraction in the solid state/kinematic diffraction theory**

- 3.1 Interaction of electrons with individual atoms
- 3.2 Interaction of electrons with crystalline objects:
  - Kinematic diffraction theory

## **4. Contrast formation and practical examples of the mapping of crystalline objects in solid state and materials research**

- 4.1 Mass thickness contrast
- 4.2 Column approach
- 4.3 Contrasts in perfect (single) crystals
- 4.4 Contrasts in crystalline samples with lattice defects, moiré effect
- 4.5 Analysis of phase mixtures
- 4.6 Diffraction patterns (convergent electron diffraction)

## **5. Dynamic electron diffraction**

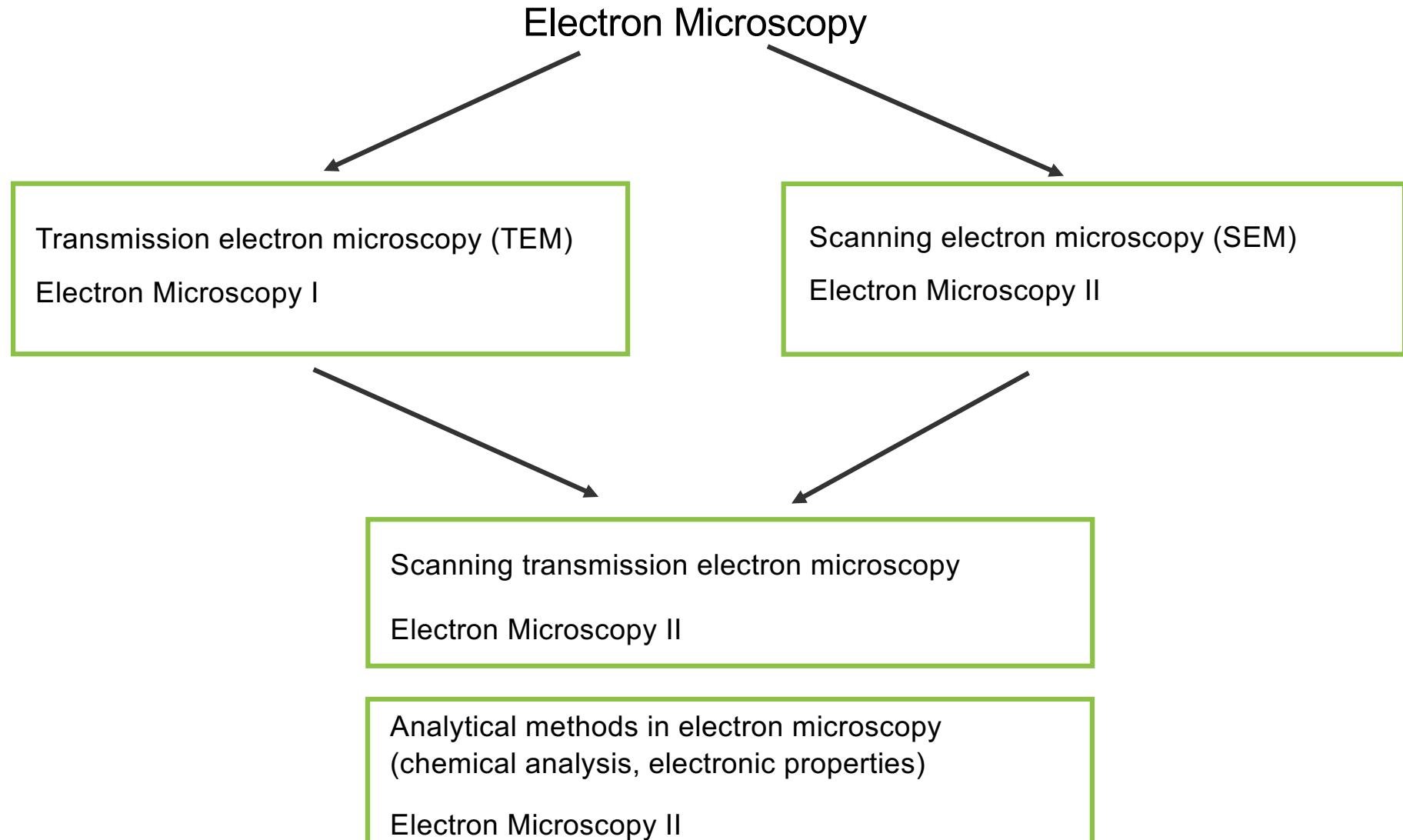
## **6. Imaging of the crystal lattice/high-resolution electron microscopy (HRTEM).**

- 6.1 Introduction and practical aspects of high-resolution transmission electron-microscopy
- 6.2 Dynamic electron diffraction in the HRTEM
- 6.3 Image formation in the HRTEM

## **7. Scanning transmission electron microscopy**

## **8. Electron holography**

## **9. Transmission electron microscopy with phase plates**



**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

**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 →



The screenshot shows a digital platform interface for a lecture course. At the top, there's a green header bar with the course code '4027011 – Elektronenmikroskopie I'. Below the header, there's a brief description of the course: 'Die Vorlesung Elektronenmikroskopie I behandelt die physikalischen Grundlagen zur Anwendung dieser Techniken in der Festkörper- und Materialforschung wie Funktionsweise von Transmissionselektronenmikroskopen und Probenpräparationen hochauflösende (S)TEM mit atomarer Auflösung, (S)TEM Kontrastentstehung'. Below the description is a navigation menu with tabs: Inhalt (selected), Info, Einstellungen, Mitglieder, Lernfortschritt, and Metadaten. Under the 'Inhalt' tab, there are four items listed: 'Elektronenmikroskopie I: Vorlesungsfolien' (with a document icon), 'Zoom Link zur Elektronenmikroskopie 1' (with a video camera icon), 'Keine Garantie für stabile Internetverbindung.', and 'Übungen zu Elektronenmikroskopie 1' (with a person icon).

## ILIAS Course: Exercises in Electron Microscopy I WS23/24

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

PERSÖNLICHER SCHREIBTISCH ▾ MAGAZIN ▾

### 4027012 – Übungen zu Elektronenmikroskopie I

Mit der Transmissionselektronenmikroskopie (TEM) können Untersuchungen der Struktur im Probeninneren durchgeführt werden. Mit konventionellen Abbildungen in Größenordnung von 1 nm auflösen. In der hochauflösenden TEM wird mit Geräten der neuesten Generation ein Auflösungsvermögen von besser als 0.1 nm erreicht. Die maximaldurchstrahlbare Probendicke liegt in der Größenordnung von 1000 nm. Die TEM kann in Kombination mit der e-Verlustspektroskopie und elektronenspezifischen Abbildungen zur Lösung folgender Fragestellungen eingesetzt werden: - Charakterisierung von Defekten (Verteilung und Dichte der Defekte - Verteilung und Größe von Ausscheidungen, Partikeln und Hohlräumen bis herab zu Größen von wenigen Nanometern - Analyse unterschiedlicher Elemente - Morphologie, Dicke und Grenzflächeneigenschaften von dünnen Schichten

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### INHALT



#### Anmeldung Übungen EM 1

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



#### Versuch 1



#### Versuch 2



#### Versuch 3



#### Versuch 4

← LINK to registration form

<http://www.lem.kit.edu/praktikumsanmeldung.php>

4 exercises,

Documents will be provided 2 weeks prior to the exercise

## 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

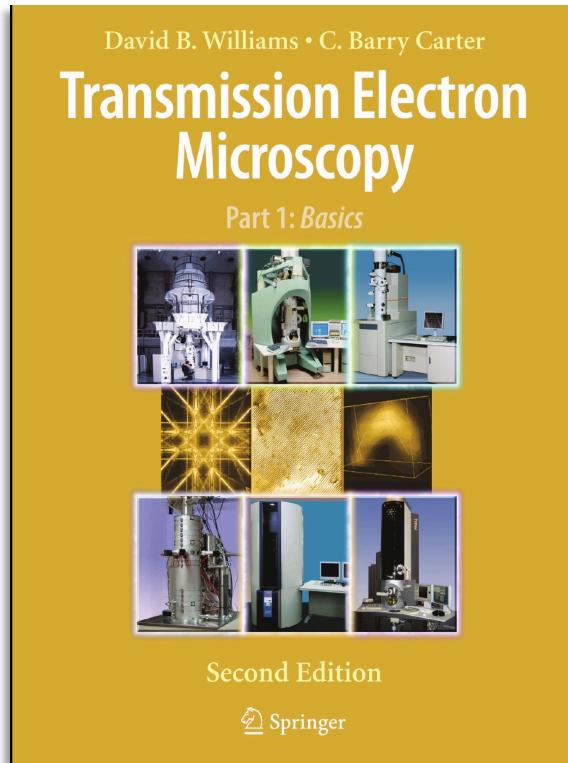


Anmeldung Übungen EM 1

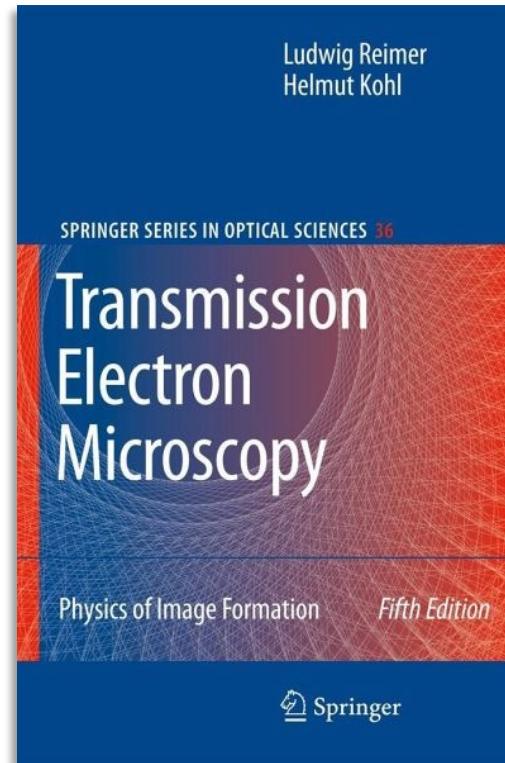
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← LINK to registration form

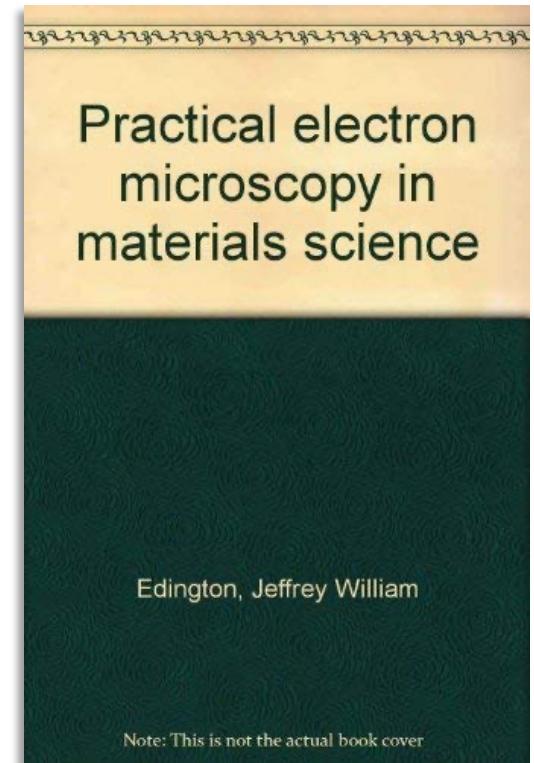
<http://www.lem.kit.edu/praktikumsanmeldung.php>



D.B. Williams, C.B. Carter,  
Transmission Electron  
Microscopy, Plenum Press  
2009.



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

## Optic

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

## Transmission electron microscopy and electron diffraction

H. Alexander, Physikalische Grundlagen der Elektronenmikroskopie  
Teubner 1997

*D.B. Williams, C.B. Carter, Transmission Electron Microscopy, Plenum Press 2009*

P.J. Goodhew, F.J. Humphreys, P. Beanland, Electron Microscopy and Analysis, 3rd edition, Taylor and Francis  
ca. 40 EU (vergriffen)

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

B. Fultz, J.M. Howe, Transmission Electron Microscopy and Diffractometry of Materials (Advanced Texts in Physics)  
Springer Verlag 3rd edition

P. Hirsch, A. Howie, R.B. Nicholson, D.W. Pashley, J. Wheelan, Electron Microscopy of Thin Crystals,  
Robert E. Krieger Publishing Company, 1977 (

M. De Graef, Introduction to Conventional Transmission Electron Microscopy, Cambridge University Press

John C. H. Spence, Experimental High-Resolution Electron Microscopy, Oxford University Press, 4<sup>th</sup> edition, 2013

E. Fuchs, H. Oppolzer, H. Rehme, Particle Beam Microanalysis, VCH Verlag 1990

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

E.J. Kirkland, Advanced Computing in Electron Microscopy, Springer 2nd edition

## **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

- 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, ...

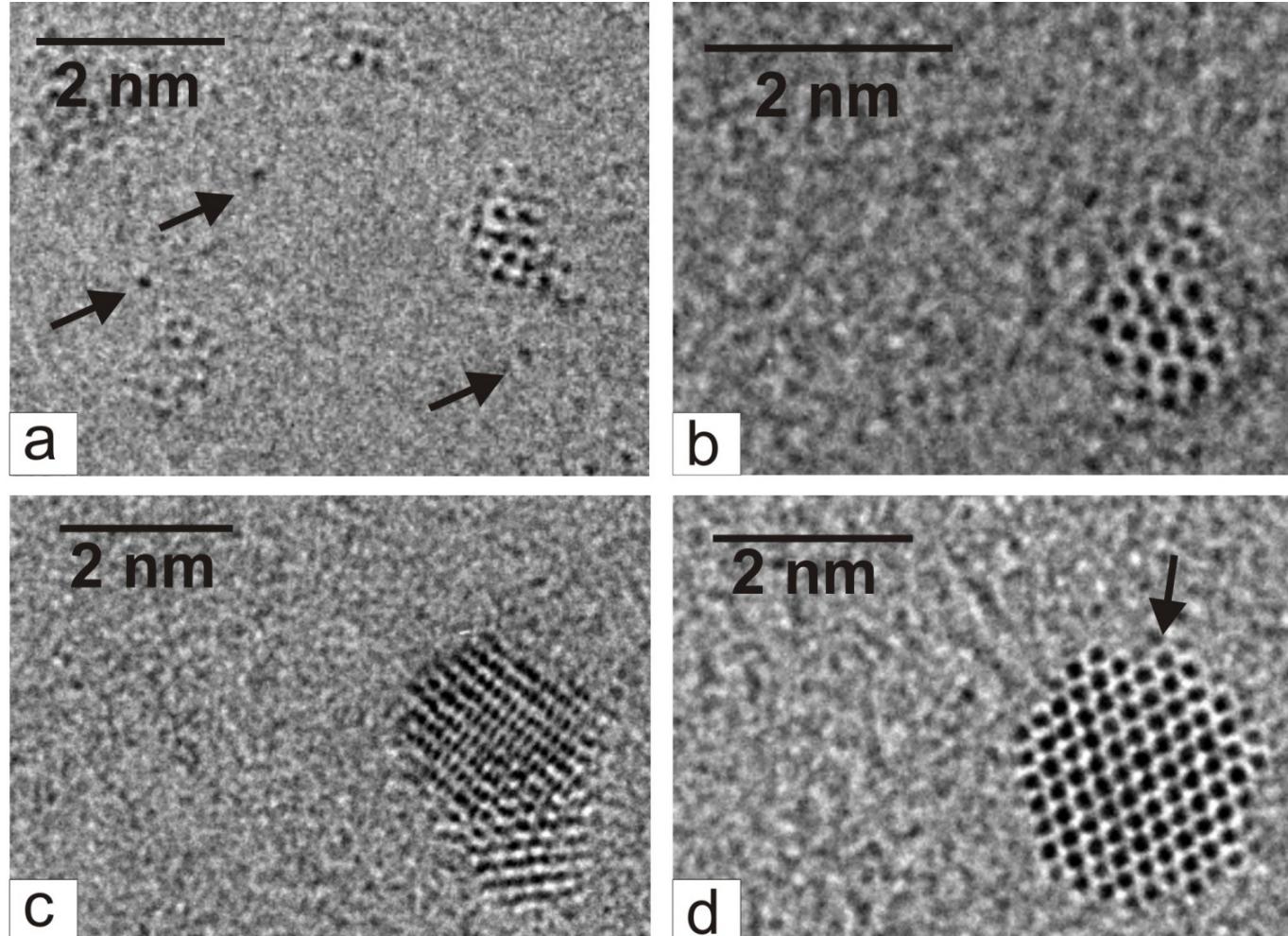
## Application in:

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

Platinum clusters and single platinum atoms on a thin carbon film



R. Schneider, Laboratory for Electron Microscopy (LEM)

# Motivation

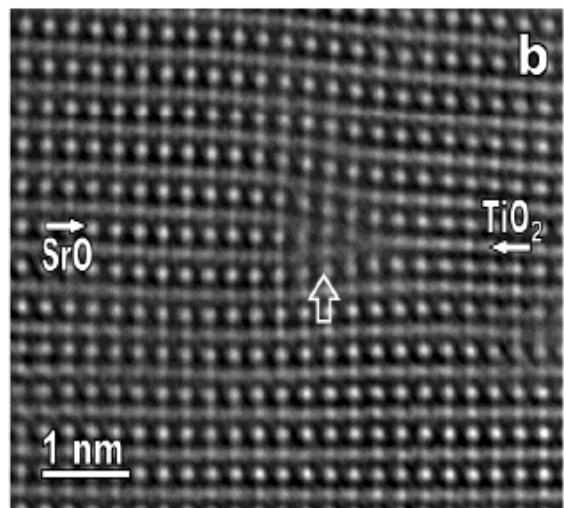
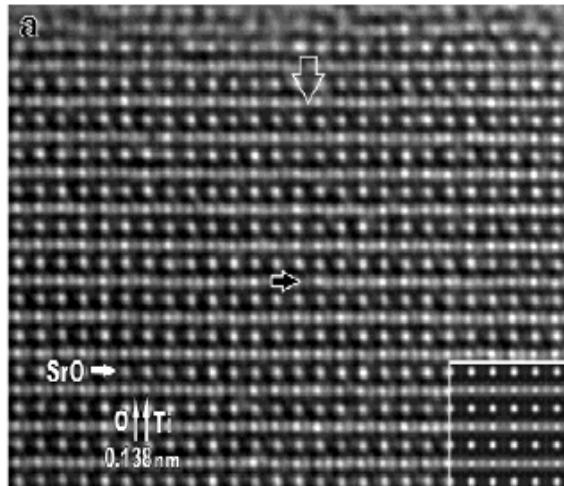


Figure 8. Experimental images of two different edge dislocations in  $\text{SrTiO}_3$  [110] with a spherical aberration of  $-40 \mu\text{m}$  and a defocus of around  $8 \text{ nm}$ .

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

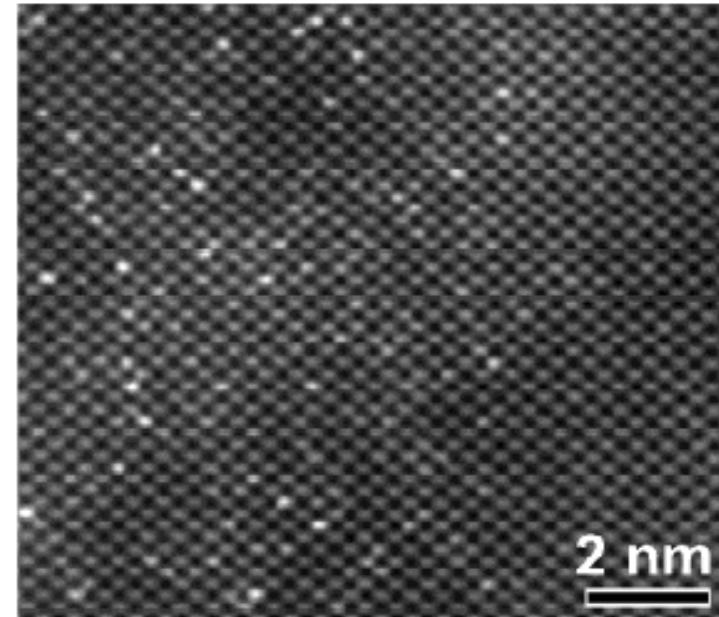


Figure 1. An atomic-resolution ADF-STEM image of a  $(110)$  projection of Si doped with Sb by low-temperature MBE showing contrast from single atoms. The right-hand side is the Si substrate, in which there is no Sb and all the atomic columns are the same intensity (atomic columns are white in this imaging 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 ( $\sim 15\%$ ) 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  $\sim 50 \text{ \AA}$  thick. The image was smoothed and background corrected.

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

Wide range of applications at medium magnifications

## Electron holography

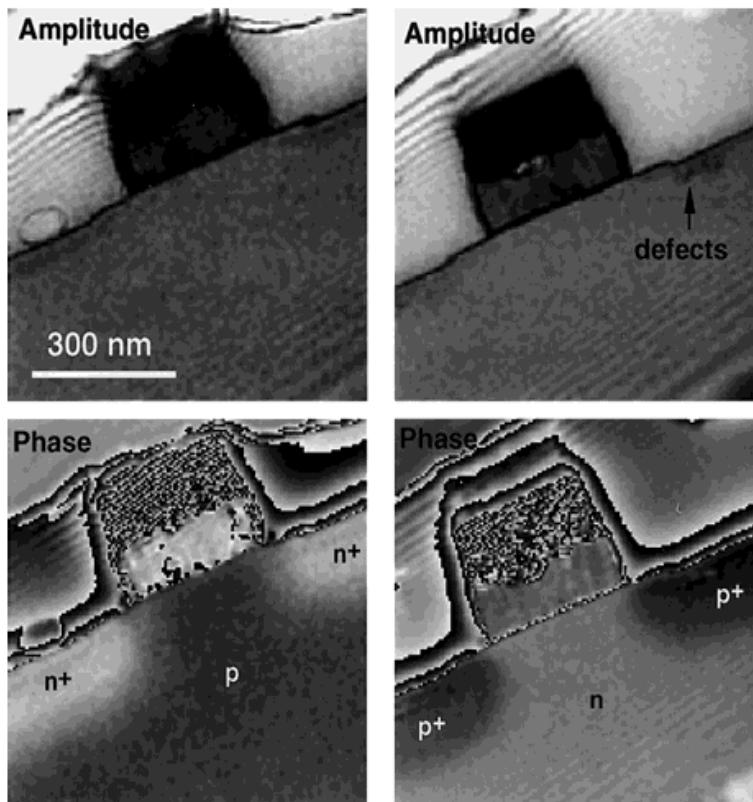
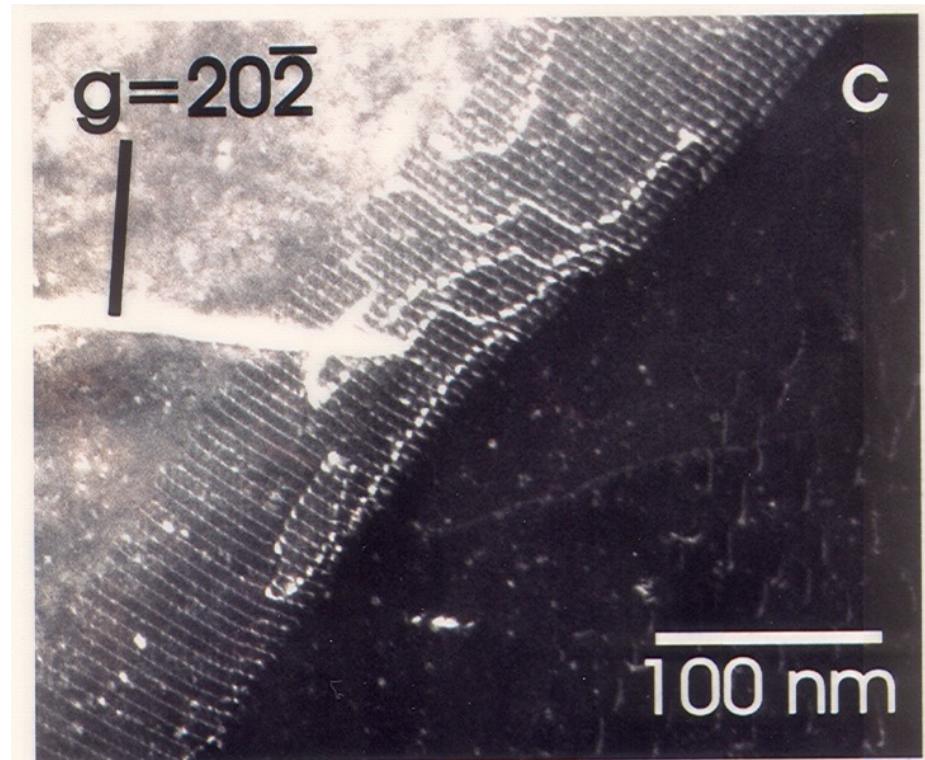


Fig. 4. Amplitude and phase image of  $0.3\text{ }\mu\text{m}$  NMOS (left) and PMOS (right) transistors. The source and drain areas are revealed in the phase images. Sharp black-white contrast lines are due to phase changes larger than  $2\pi$

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)

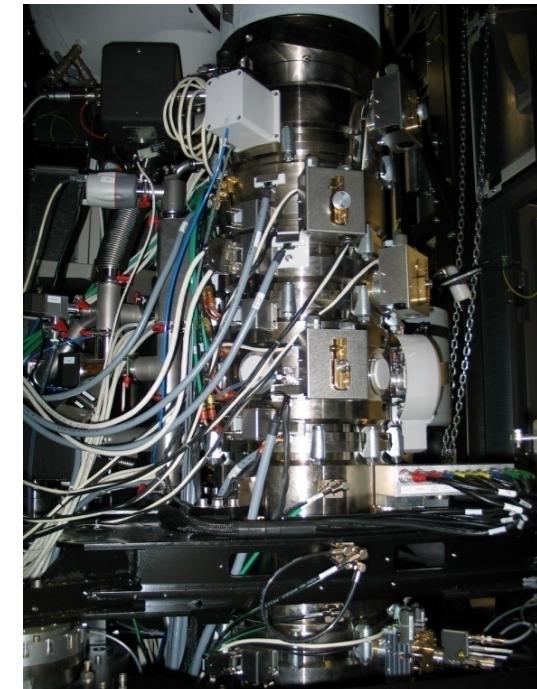
# Motivation



Philips CM200  
point resolution  
0.24 nm @200kV



FEI Titan<sup>3</sup> 80-300  
point resolution 0.07 nm @ 300kV



Upper part of the  
microscope column

# 1. From light microscopy to electron microscopy

## 1.1 Light and matter waves

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

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

$\lambda$ : Wavelength

$p$ : Impulse

$h$ : Planck's constant  $1.05 \cdot 10^{-34}$  Nms ( $6.5 \cdot 10^{-16}$  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):  $v \approx 0.5 c$   $\longrightarrow$  relativistic calculation  $p = mv$

$m_0$ : Electron rest mass  
 $c$ : Speed of light

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

# 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

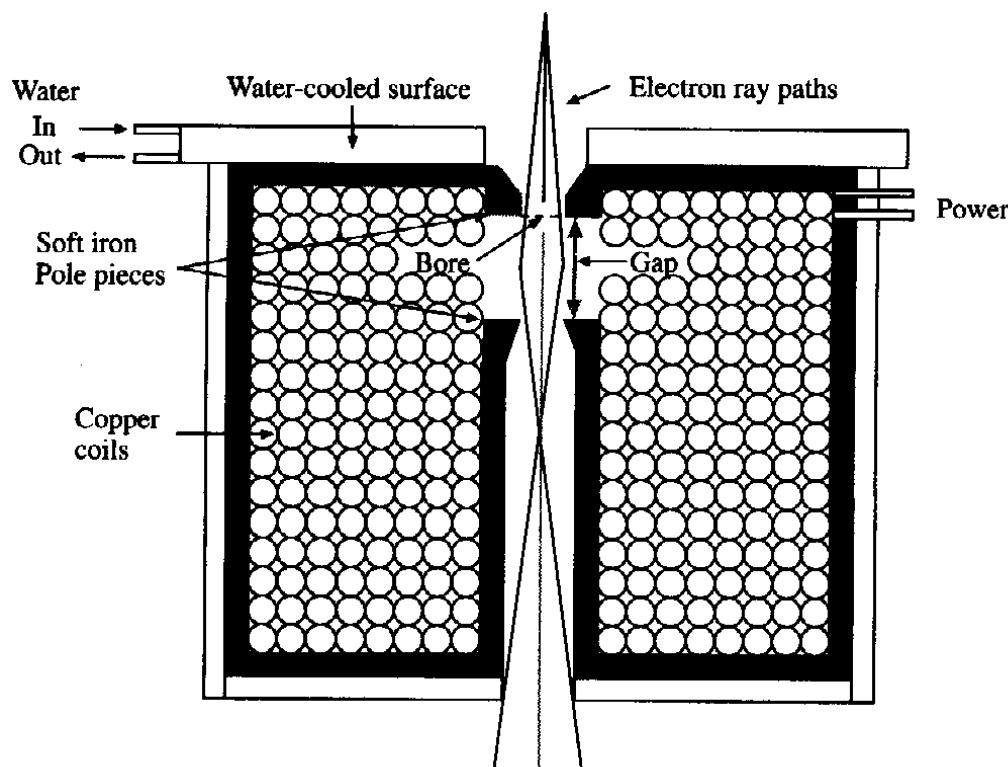
Discrepancy between best possible (50 pm) and diffraction-limited resolution due to lens aberration!

# 1.2 Fundamentals of Optical Imaging: Geometric Optics

Light optics: glass/plastic lenses

Electron optics: electrostatic or **magnetic** lenses (refraction by Lorentz force)

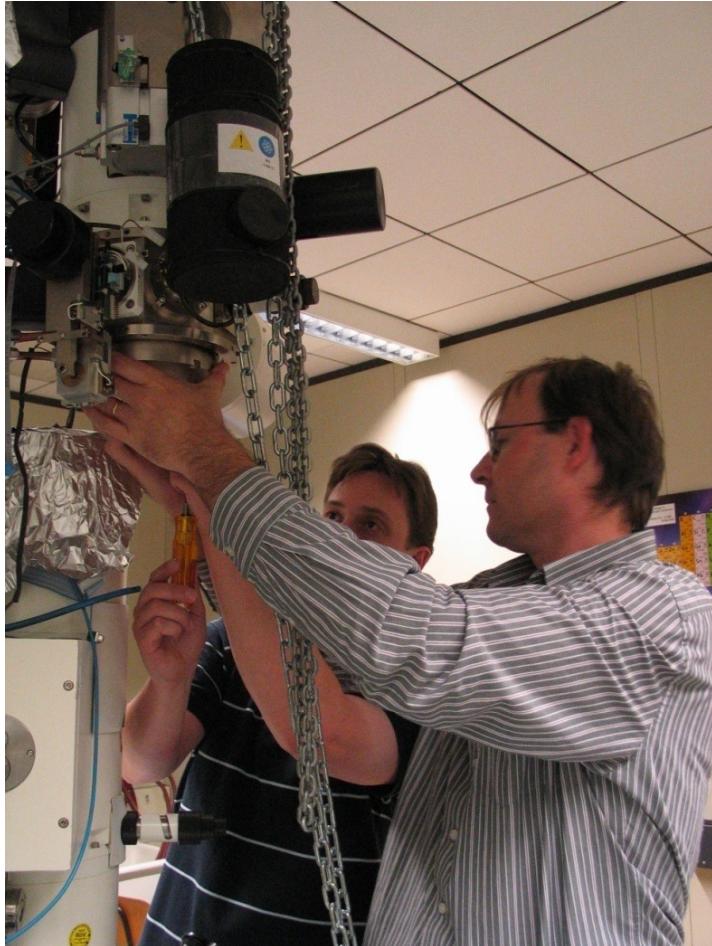
Electron magnetic lens



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

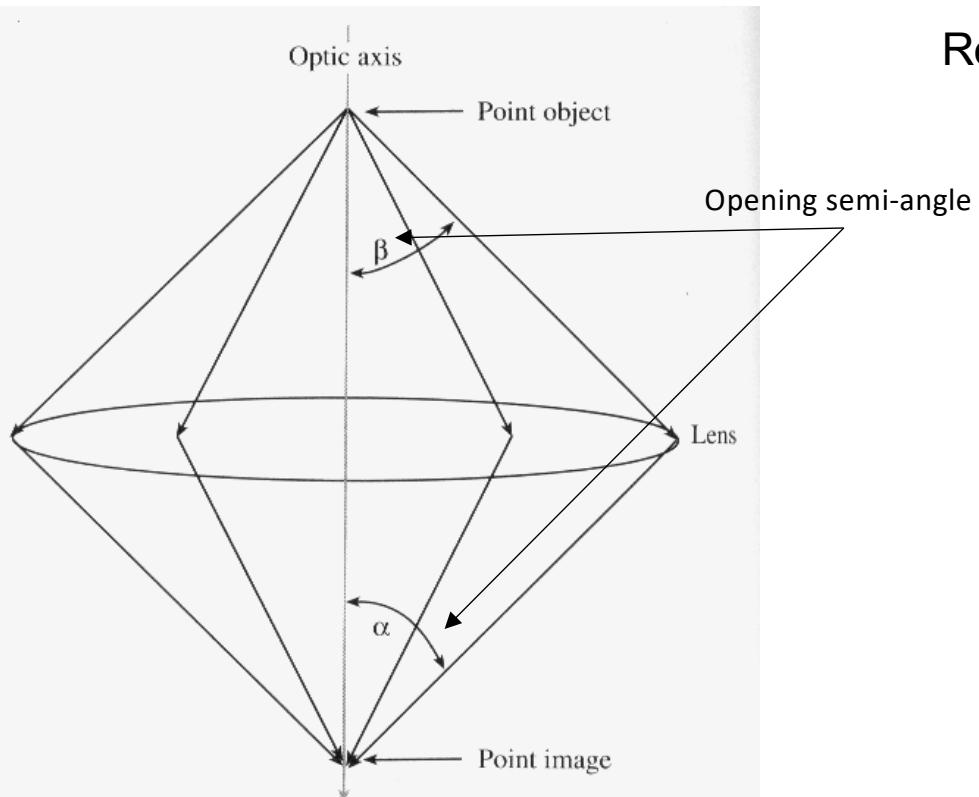
# 1.2 Fundamentals of Optical Imaging: Geometric Optics



Pictures: Levin Dieterle (LEM)

# 1.2 Fundamentals of Optical Imaging: Geometric Optics

**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 ( $\beta$ ) or the image ( $\alpha$ ).

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

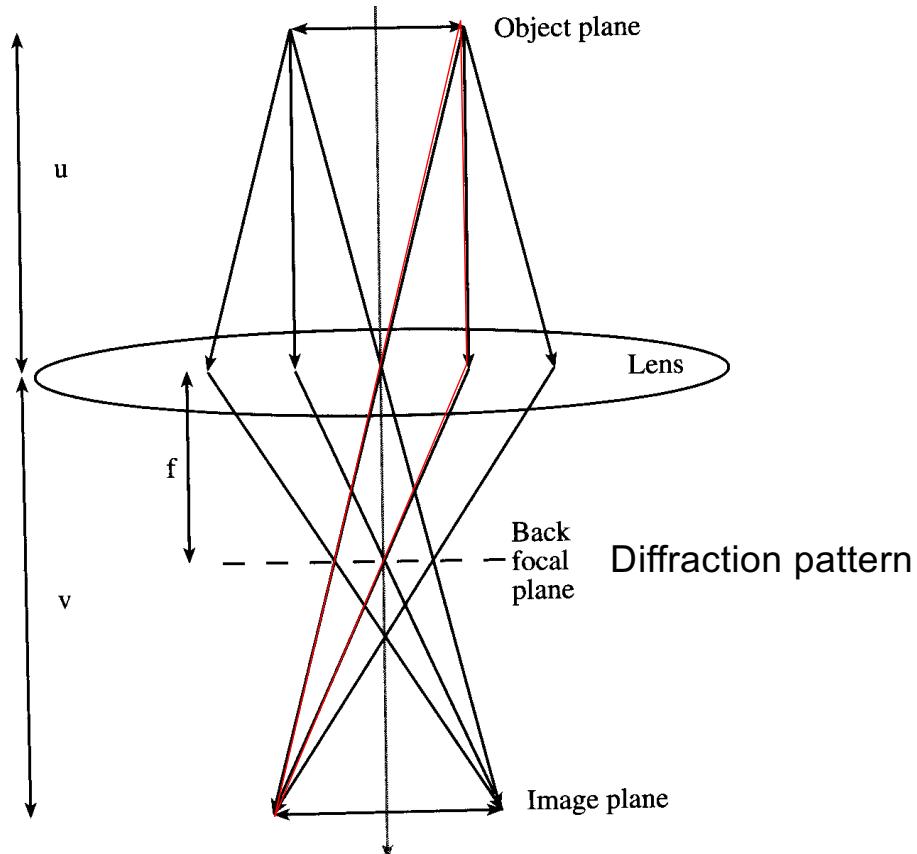
Optical axis through center of lens

Object side opening semi-angle  $\beta$   
Image side convergence semi-angle  $\alpha$

$\alpha, \beta$  in the TEM very small (few degrees)

# 1.2 Fundamentals of Optical Imaging: Geometric Optics

## 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)

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

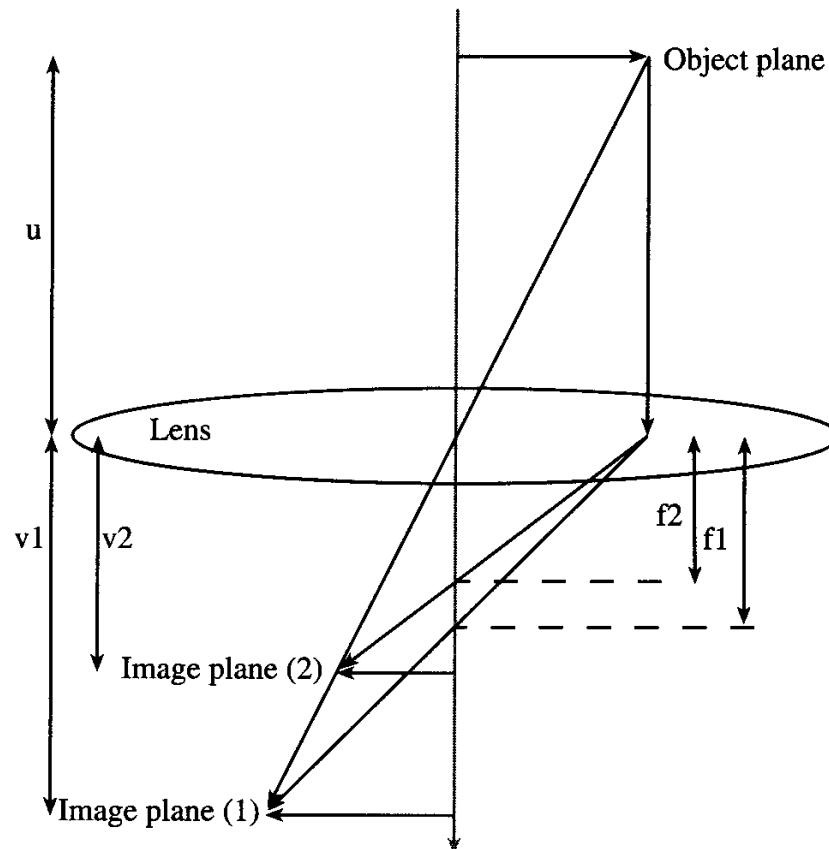
Validity shown for electron optics  
by Ernst Ruska in his Diploma thesis 1931

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

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

# 1.2 Fundamentals of Optical Imaging: Geometric Optics

## Construction of an image by imaging with a thin lens



In the TEM

- For a fixed object width  $u$ , a stronger lens has shorter focal length  $f_2$  and produces a lower magnification than a weaker lens with a longer focal length  $f_1$ .
- 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 lens

**Figure 6.4.** Strengthening the lens shortens the focal length  $f$ . So a weaker lens ( $f_1$ ) produces a higher magnification of the object than a stronger lens ( $f_2$ ) since the image distance  $v$  increases, but the object distance is unchanged.

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

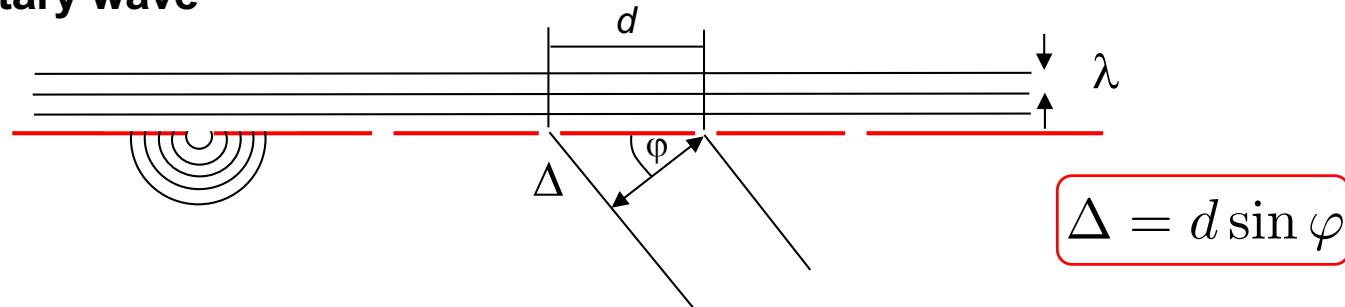
# 1.3 Wave optics: Abbe's theory of imaging

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

$$\vec{E}(\vec{r}, t) = \vec{E}_0 \exp(i(\vec{k}\vec{r} - \omega t)) \quad \text{Electric wave} \qquad |\vec{k}| = \frac{1}{\lambda}$$
$$\psi(\vec{r}, t) = \psi_0 \exp(i(\vec{k}\vec{r} - \omega t)) \quad \text{Electron wave function}$$

- 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**



Constructive interference  
Destructive interference  
 $\Delta$  path length difference

$$\Delta = d \sin \varphi = n\lambda$$
$$\Delta = d \sin \varphi = (2n + 1) \frac{\lambda}{2} \quad n = 0, \pm 1, \pm 2, \dots$$