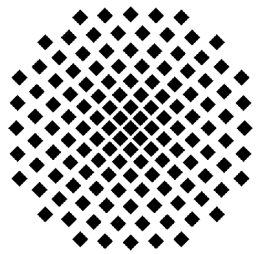
Structural analyis of nanostructures by electron microscopy

IHFG Seminar: Nanooptics and Nanophotonics

Nicolai Lang

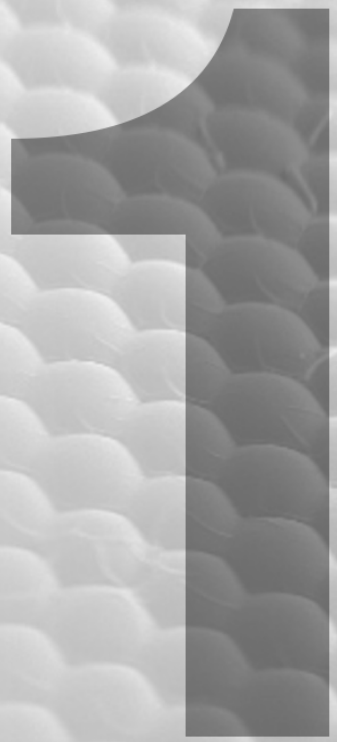
University of Stuttgart

May 3, 2012



Overview

Overview: Introduction



Analysing Microscopic Structures

Analysing Microscopic Structures

Optical microscopy ($\gtrsim 100\,\mathrm{nm}$)

- Bright/Dark field m.
- Phase contrast m.
- Fluorescence m.
- Confocal m.
- Ultraviolet m.
- Infrared m.
- Laser m.

Analysing Microscopic Structures

Optical microscopy ($\gtrsim 100\,\mathrm{nm}$)

- Bright/Dark field m.
- Phase contrast m.
- Fluorescence m.
- Confocal m.
- Ultraviolet m.
- Infrared m.
- Laser m.

Scanning probe microscopy ($\gtrsim 0.01\,\mathrm{nm}$)

- Atomic force m. (AFM)
- Scanning tunneling m. (STM)

Analysing Microscopic Structures

Optical microscopy ($\gtrsim 100\,\mathrm{nm}$)

- Bright/Dark field m.
- Phase contrast m.
- Fluorescence m.
- Confocal m.
- Ultraviolet m.
- Infrared m.
- Laser m.

Scanning probe microscopy ($\gtrsim 0.01\,\mathrm{nm}$)

- Atomic force m. (AFM)
- Scanning tunneling m. (STM)

Electron microscopy ($\gtrsim 0.05\,\mathrm{nm}$)

- Scanning electron m. (SEM)
- Transmission electron m. (TEM)

Analysing Microscopic Structures

Optical microscopy ($\gtrsim 100\,\mathrm{nm}$)

- Bright/Dark field m.
- Phase contrast m.
- Fluorescence m.
- Confocal m.
- Ultraviolet m.
- Infrared m.
- Laser m.

Scanning probe microscopy ($\gtrsim 0.01\,\mathrm{nm}$)

- Atomic force m. (AFM)
- Scanning tunneling m. (STM)

Electron microscopy ($\gtrsim 0.05\,\mathrm{nm}$)

- Scanning electron m. (SEM)
- Transmission electron m. (TEM)

Analysing Microscopic Structures

Optical microscopy ($\gtrsim 100\,\mathrm{nm}$)

- Bright/Dark field m.
- Phase contrast m.
- Fluorescence m.
- Confocal m.
- Ultraviolet m.
- Infrared m.
- Laser m.

Scanning probe microscopy ($\gtrsim 0.01\,\mathrm{nm}$)

- Atomic force m. (AFM)
- Scanning tunneling m. (STM)

Electron microscopy ($\gtrsim 0.05\,\mathrm{nm}$)

- Scanning electron m. (SEM)
- Transmission electron m. (TEM)

Analysing Microscopic Structures

Optical microscopy ($\gtrsim 100\,\mathrm{nm}$)

- Bright/Dark field m.
- Phase contrast m.
- Fluorescence m.
- Confocal m.
- Ultraviolet m.
- Infrared m.
- Laser m.

Scanning probe microscopy ($\gtrsim 0.01\,\mathrm{nm}$)

- Atomic force m. (AFM)
- Scanning tunneling m. (STM)

Electron microscopy ($\gtrsim 0.05\,\mathrm{nm}$)

- Scanning electron m. (SEM)
- Transmission electron m. (TEM)

Why Electrons?

- Diffraction limited optical imaging:

$$d = \frac{0.61 \cdot \lambda}{n \cdot \sin \alpha} \approx \frac{\lambda}{2 \cdot \mathrm{NA}} \geq \frac{\lambda}{2}$$

- Holds for any wave-based imaging technique
- New paradigm: Particle-wave duality

$$\lambda_e = \frac{h}{p_e} = \frac{h}{v \cdot m_e}$$

- TEM: $U_a \sim 50\,\mathrm{keV} \Rightarrow \lambda_e \sim 0.005\,\mathrm{nm}$
  (cf. visible light: $\lambda \sim 500\,\mathrm{nm}$)
- Theoretical/Practical improvement: $100,000/1,000$
  $\Rightarrow$ Electron microscopes are **not** diffraction limited.

Why Electrons?

- Diffraction limited optical imaging:

$$d = \frac{0.61 \cdot \lambda}{n \cdot \sin \alpha} \approx \frac{\lambda}{2 \cdot \mathrm{NA}} \geq \frac{\lambda}{2}$$

- Holds for any wave-based imaging technique
- New paradigm: Particle-wave duality

$$\lambda_e = \frac{h}{p_e} = \frac{h}{v \cdot m_e}$$

- TEM: $U_a \sim 50\,\mathrm{keV} \Rightarrow \lambda_e \sim 0.005\,\mathrm{nm}$
  (cf. visible light: $\lambda \sim 500\,\mathrm{nm}$)
- Theoretical/Practical improvement: $100,000/1,000$
  $\Rightarrow$ Electron microscopes are **not** diffraction limited.

Why Electrons?

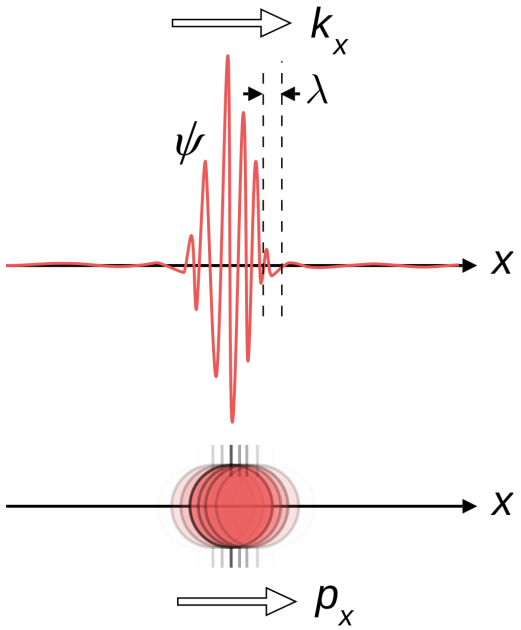
- Diffraction limited optical imaging:

$$d = \frac{0.61 \cdot \lambda}{n \cdot \sin \alpha} \approx \frac{\lambda}{2 \cdot \mathrm{NA}} \geq \frac{\lambda}{2}$$

- Holds for any wave-based imaging technique
- New paradigm: Particle-wave duality

$$\lambda_e = \frac{h}{p_e} = \frac{h}{v \cdot m_e}$$

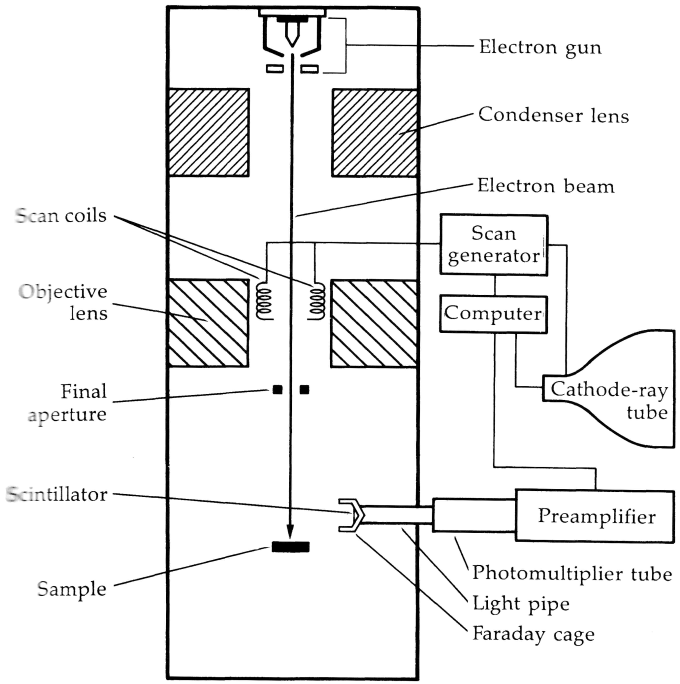
- TEM: $U_a \sim 50\,\mathrm{keV} \Rightarrow \lambda_e \sim 0.005\,\mathrm{nm}$
  (cf. visible light: $\lambda \sim 500\,\mathrm{nm}$)
- Theoretical/Practical improvement: $100,000/1,000$
  $\Rightarrow$ Electron microscopes are **not** diffraction limited.



Source: http://en.wikipedia.org/wiki/Particle-wave_duality

Scanning Electron Microscopy (SEM)

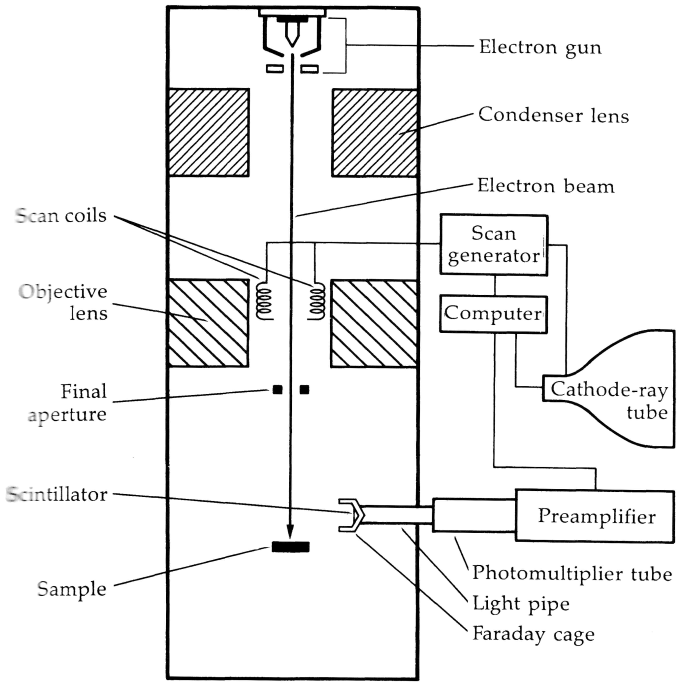
- General use: Analysis of surface morphology via interaction with beam of high-speed electrons
- Sample: No thin samples required; must be conductive
- Best resolution: $3 - 6\,\mathrm{nm}$ ($\rightarrow$ Beam thickness)
- Magnification range: $20 - 150,000\times$
- Depth of field: $0.003 - 1\,\mathrm{mm}$
- Various information channels: Secondary electrons, Backscattered electrons, EBIC, X-Rays, Cathodoluminescence, ...



Source: [Flegler et al., 1993]

Scanning Electron Microscopy (SEM)

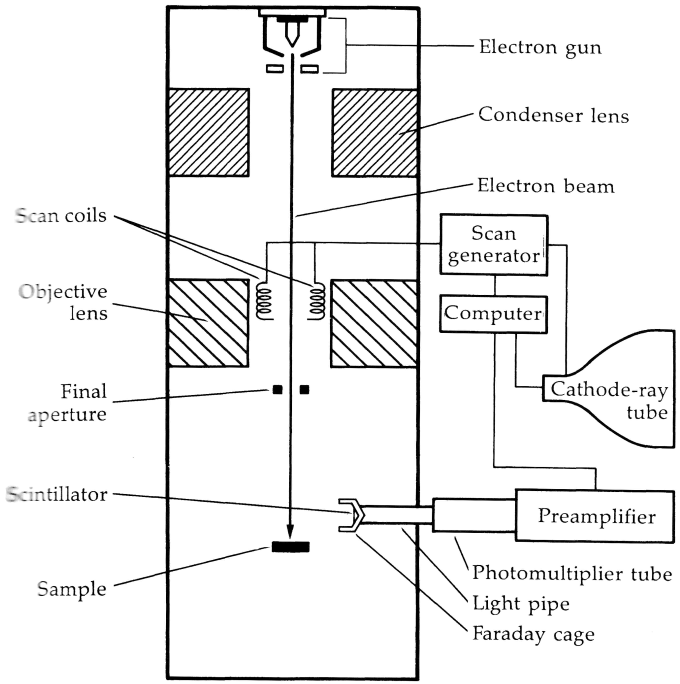
- General use: Analysis of surface morphology via interaction with beam of high-speed electrons
- Sample: No thin samples required; must be conductive
- Best resolution: $3 - 6\,\mathrm{nm}$ ($\rightarrow$ Beam thickness)
- Magnification range: $20 - 150,000\times$
- Depth of field: $0.003 - 1\,\mathrm{mm}$
- Various information channels: Secondary electrons, Backscattered electrons, EBIC, X-Rays, Cathodoluminescence, ...



Source: [Flegler et al., 1993]

Scanning Electron Microscopy (SEM)

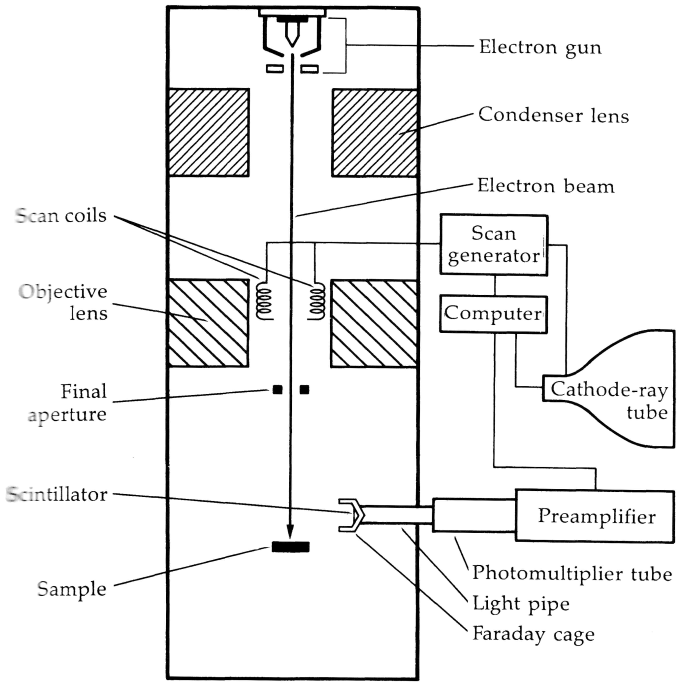
- General use: Analysis of surface morphology via interaction with beam of high-speed electrons
- Sample: No thin samples required; must be conductive
- Best resolution: $3 - 6\,\mathrm{nm}$ ($\rightarrow$ Beam thickness)
- Magnification range: $20 - 150,000\times$
- Depth of field: $0.003 - 1\,\mathrm{mm}$
- Various information channels: Secondary electrons, Backscattered electrons, EBIC, X-Rays, Cathodoluminescence, ...



Source: [Flegler et al., 1993]

Scanning Electron Microscopy (SEM)

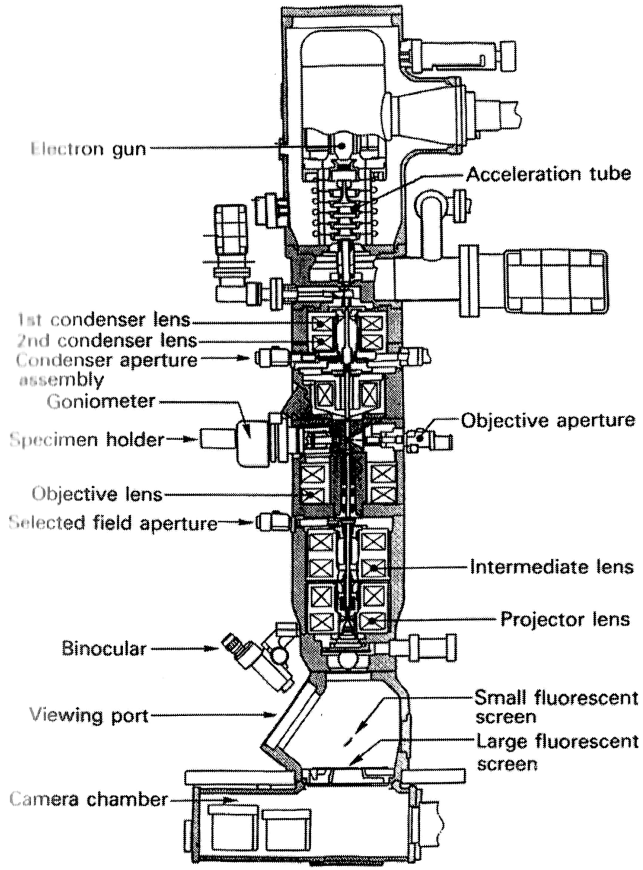
- General use: Analysis of surface morphology via interaction with beam of high-speed electrons
- Sample: No thin samples required; must be conductive
- Best resolution: $3 - 6\,\mathrm{nm}$ ($\rightarrow$ Beam thickness)
- Magnification range: $20 - 150,000\times$
- Depth of field: $0.003 - 1\,\mathrm{mm}$
- Various information channels: Secondary electrons, Backscattered electrons, EBIC, X-Rays, Cathodoluminescence, ...



Source: [Flegler et al., 1993]

Transmission Electron Microscopy (TEM)

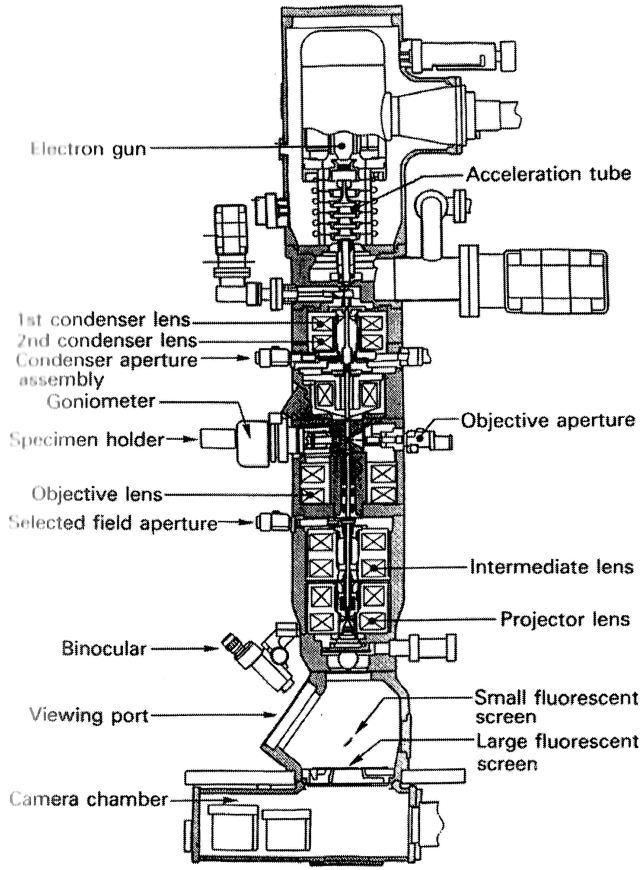
- General use: Analysis of sections via transmission of high-speed electrons
- Sample: Thin samples required ($40 - 150\,\mathrm{nm}$); intricate sample preparation procedures
- Best resolution: $0.05\,\mathrm{nm}$ ($\rightarrow$ Electron optics)
- Magnification range: $500 - 500,000\times$
- Depth of field: $0.004 - 0.006\,\mathrm{mm}$ (cf. sample thickness)
- Various imaging techniques: Dark field, Bright field, HRTEM, SAD, EELS, ...



Source: [Fultz and Howe, 2002]

Transmission Electron Microscopy (TEM)

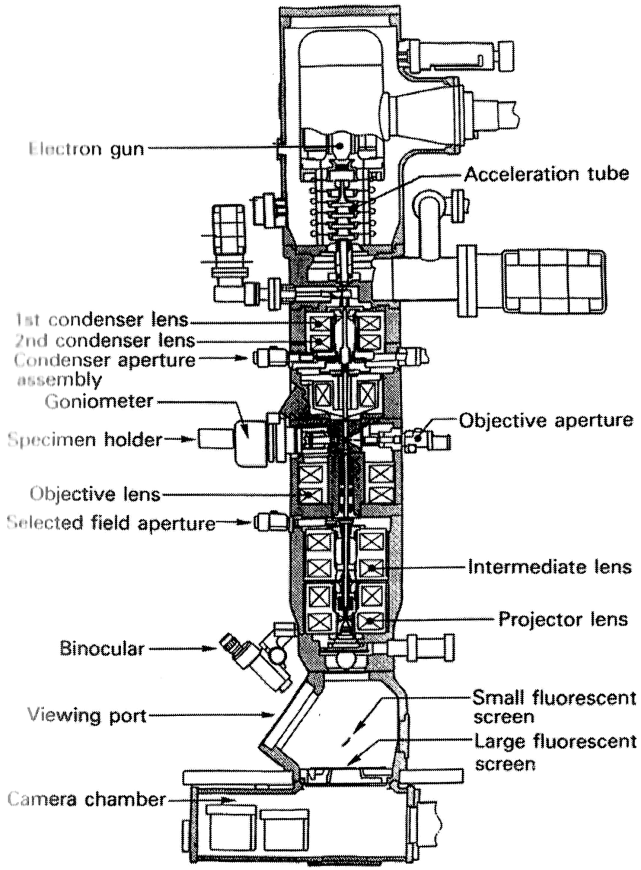
- General use: Analysis of sections via transmission of high-speed electrons
- Sample: Thin samples required ($40 - 150\,\mathrm{nm}$); intricate sample preparation procedures
- Best resolution: $0.05\,\mathrm{nm}$ ($\rightarrow$ Electron optics)
- Magnification range: $500 - 500,000\times$
- Depth of field: $0.004 - 0.006\,\mathrm{mm}$ (cf. sample thickness)
- Various imaging techniques: Dark field, Bright field, HRTEM, SAD, EELS, ...



Source: [Fultz and Howe, 2002]

Transmission Electron Microscopy (TEM)

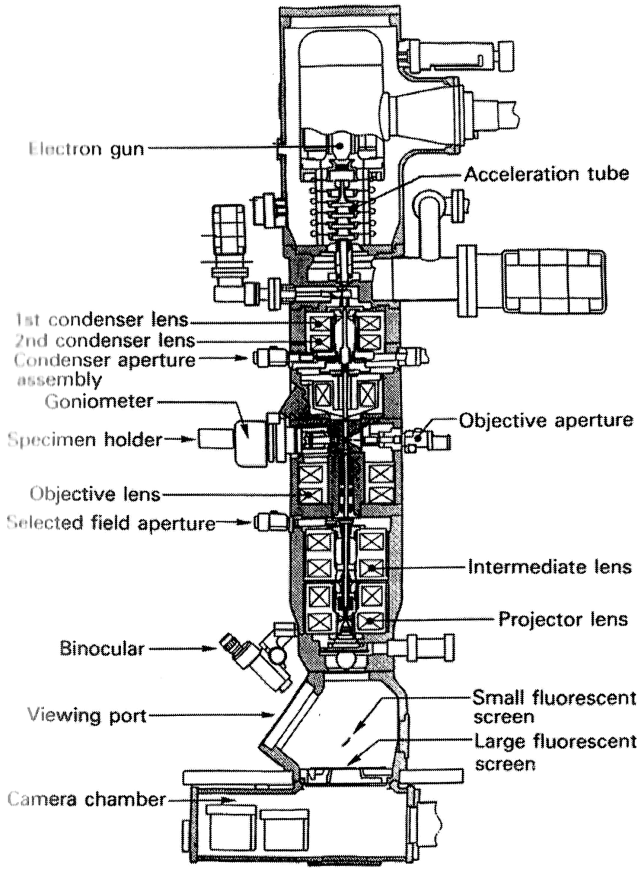
- General use: Analysis of sections via transmission of high-speed electrons
- Sample: Thin samples required ($40 - 150\,\mathrm{nm}$); intricate sample preparation procedures
- Best resolution: $0.05\,\mathrm{nm}$ ($\rightarrow$ Electron optics)
- Magnification range: $500 - 500,000\times$
- Depth of field: $0.004 - 0.006\,\mathrm{mm}$ (cf. sample thickness)
- Various imaging techniques: Dark field, Bright field, HRTEM, SAD, EELS, ...



Source: [Fultz and Howe, 2002]

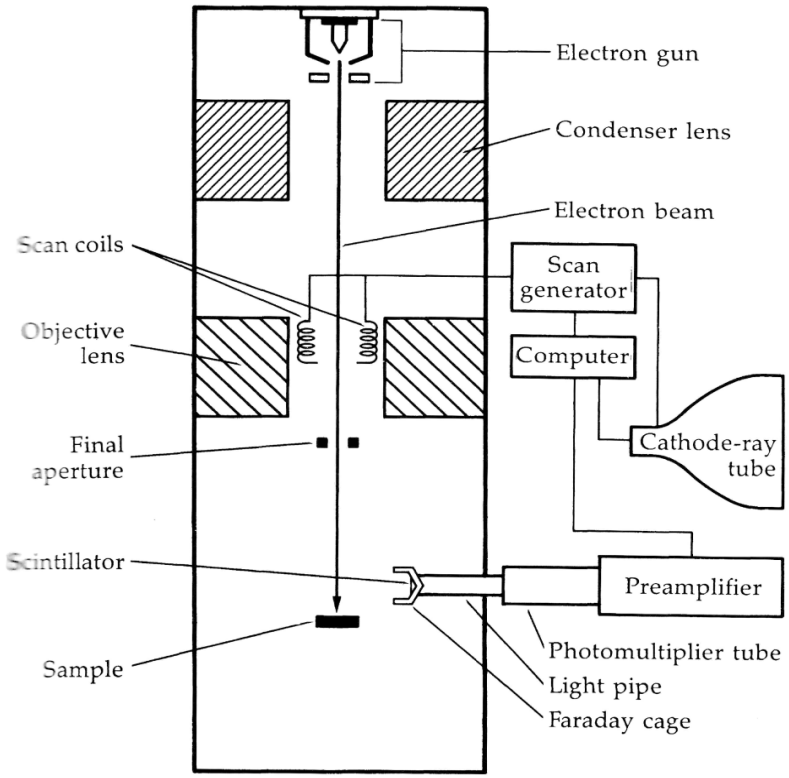
Transmission Electron Microscopy (TEM)

- General use: Analysis of sections via transmission of high-speed electrons
- Sample: Thin samples required ($40 - 150\,\mathrm{nm}$); intricate sample preparation procedures
- Best resolution: $0.05\,\mathrm{nm}$ ($\rightarrow$ Electron optics)
- Magnification range: $500 - 500,000\times$
- Depth of field: $0.004 - 0.006\,\mathrm{mm}$ (cf. sample thickness)
- Various imaging techniques: Dark field, Bright field, HRTEM, SAD, EELS, ...

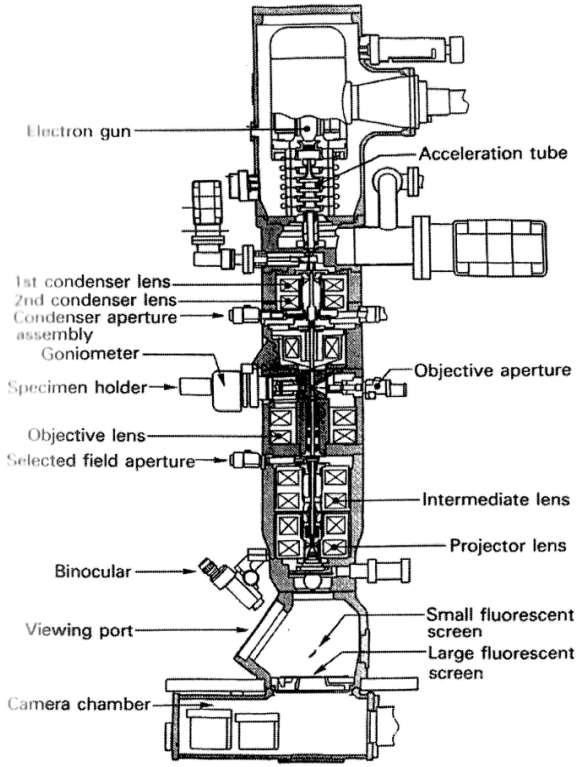


Source: [Fultz and Howe, 2002]

SEM & TEM : Technical similarities

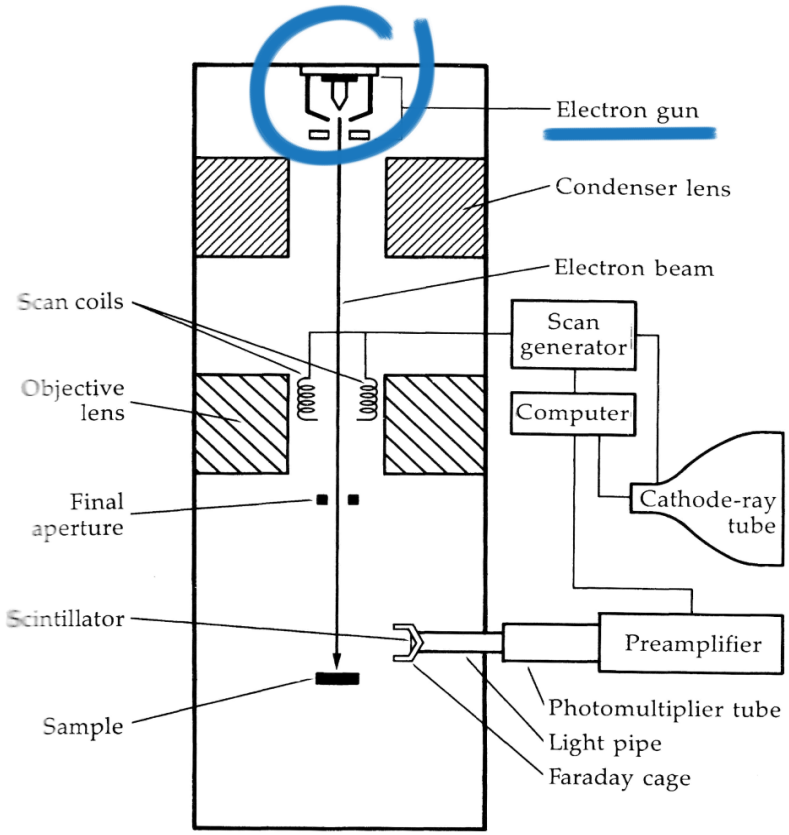


SEM

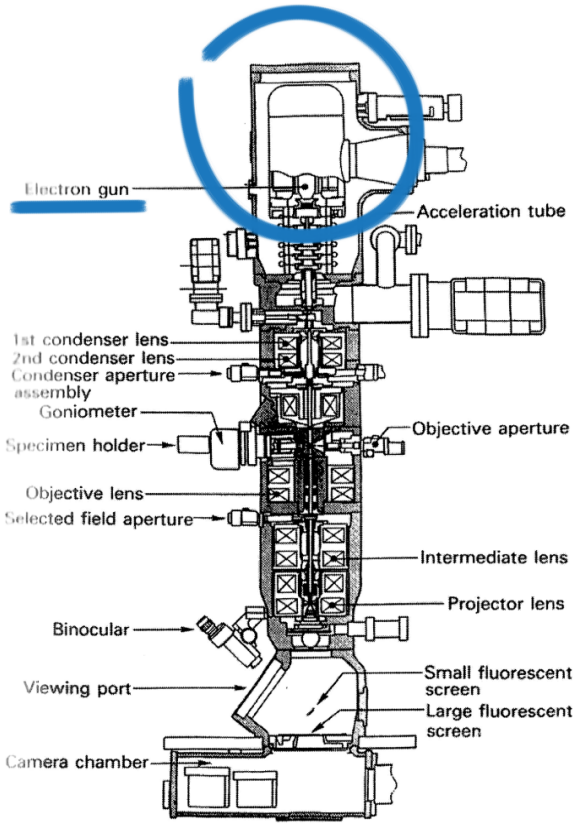


TEM

SEM & TEM : Technical similarities

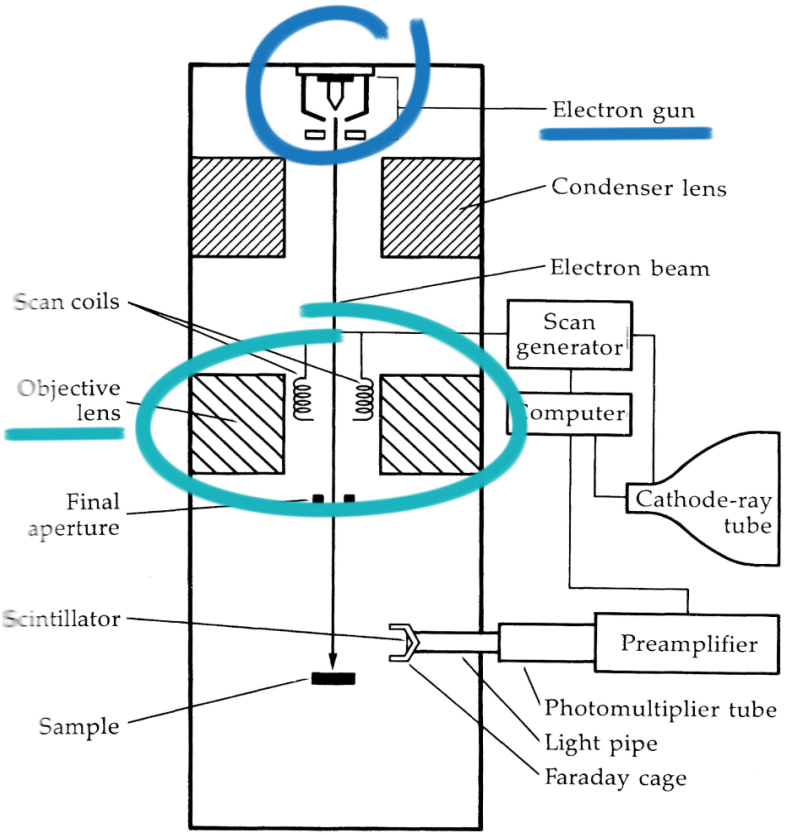


SEM

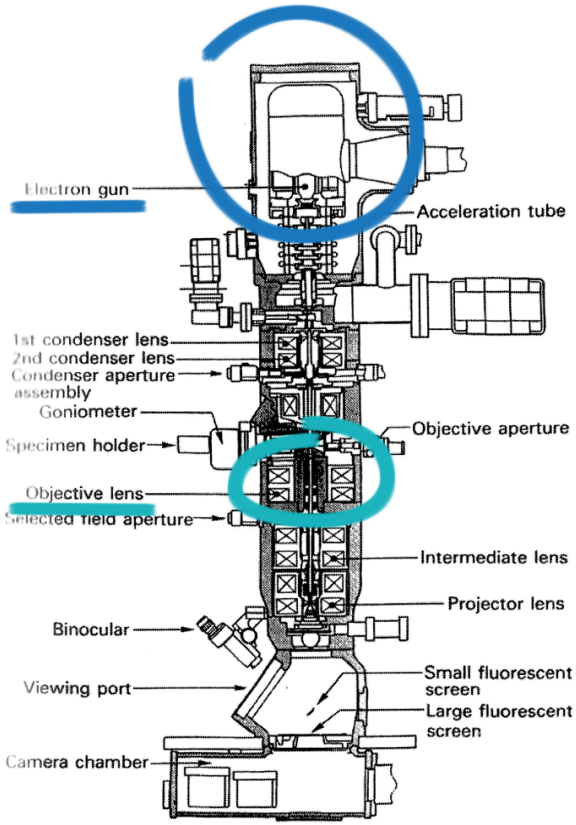


TEM

SEM & TEM : Technical similarities

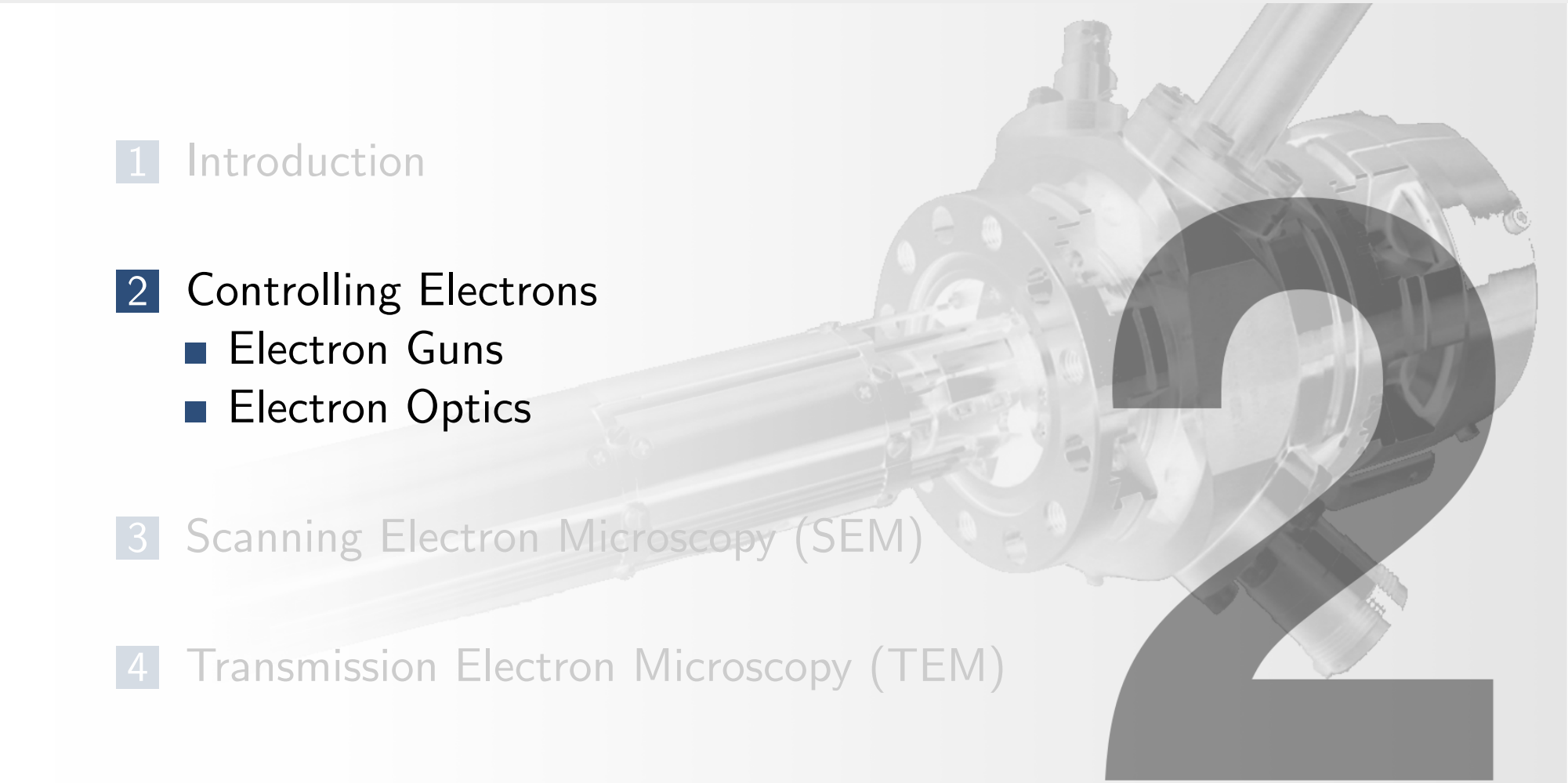


SEM



TEM

Overview: Controlling Electrons



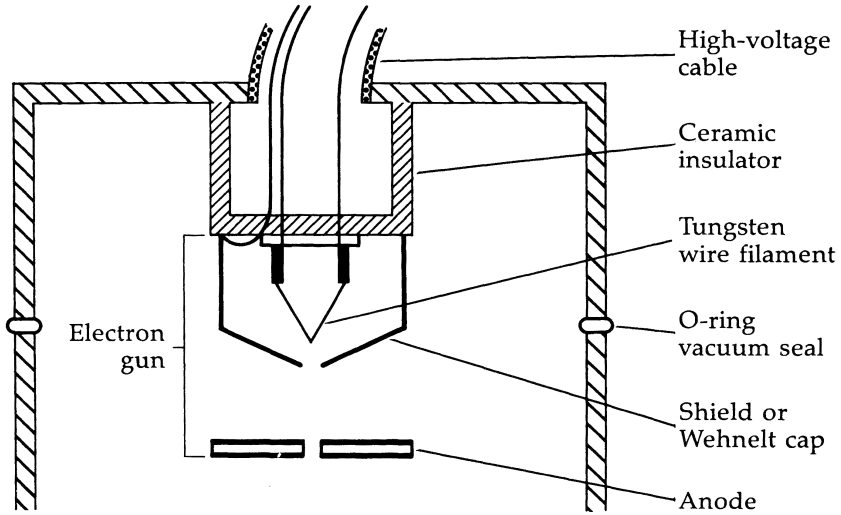
Overview: Electron Guns

2 Controlling Electrons

- Electron Guns
  - Thermionic Electron Gun : Tungsten-Hairpin design
  - Field Emission Gun (FEG)
- Electron Optics

Thermionic Electron Gun : Tungsten-Hairpin design

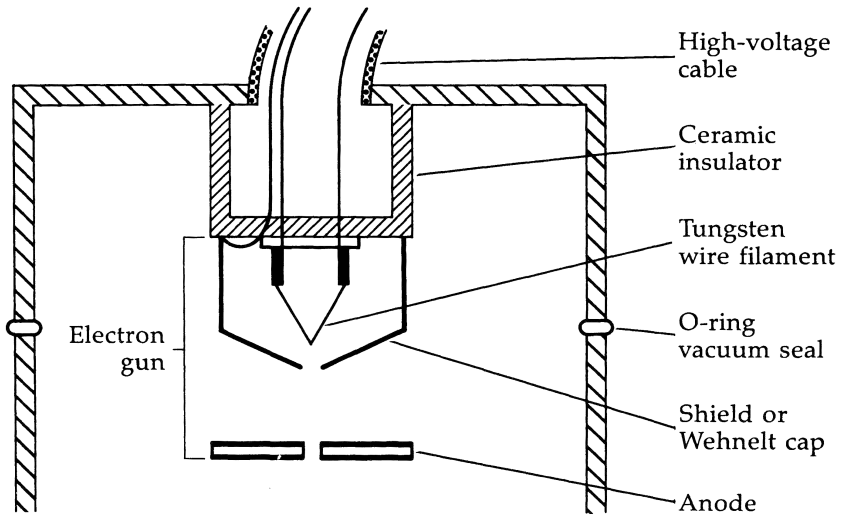
- Electron source:
  Heated loop of tungsten
- Emission mechanism:
  Thermionic emission
- Usage:
  Most common design
- Advantages:
  - Relatively stable source of electrons
  - Inexpensive
  - No ultrahigh vacuum required



Source: [Flegler et al., 1993]

Thermionic Electron Gun : Tungsten-Hairpin design

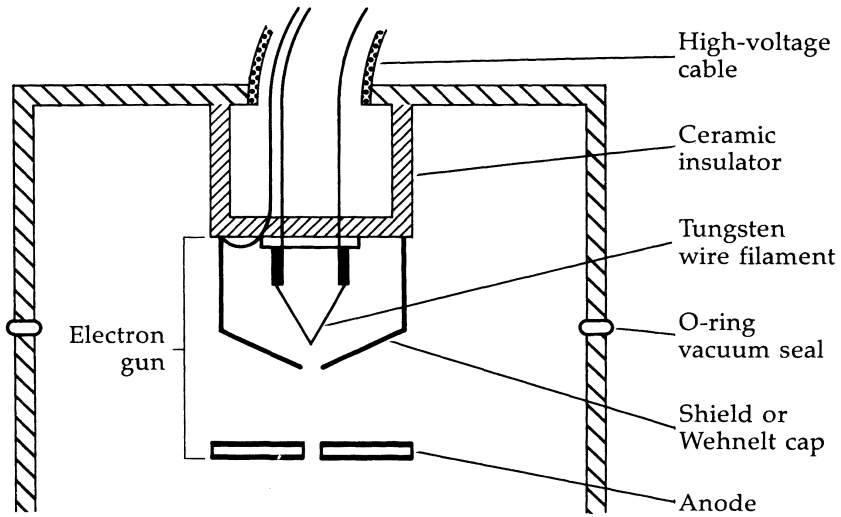
- Electron source:
  Heated loop of tungsten
- Emission mechanism:
  Thermionic emission
- Usage:
  Most common design
- Advantages:
  - Relatively stable source of electrons
  - Inexpensive
  - No ultrahigh vacuum required



Source: [Flegler et al., 1993]

Thermionic Electron Gun : Tungsten-Hairpin design

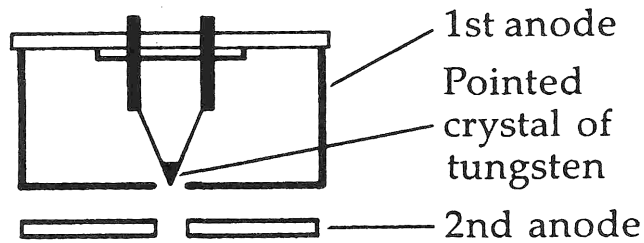
- Electron source:
  Heated loop of tungsten
- Emission mechanism:
  Thermionic emission
- Usage:
  Most common design
- Advantages:
  - Relatively stable source of electrons
  - Inexpensive
  - No ultrahigh vacuum required



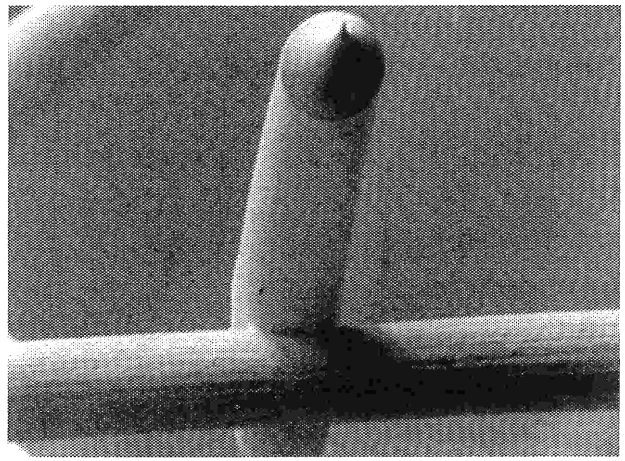
Source: [Flegler et al., 1993]

Field Emission Gun (FEG)

- Electron source:
  Cold tungsten tip
- Emission mechanism:
  Field emission
- Usage:
  Progressively replacing the W-gun



A

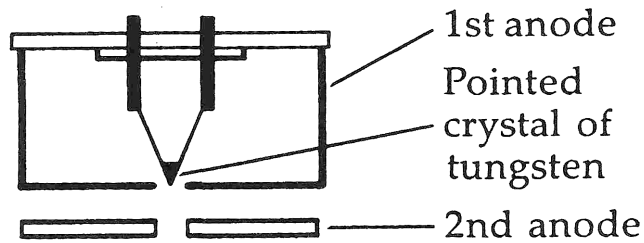


B

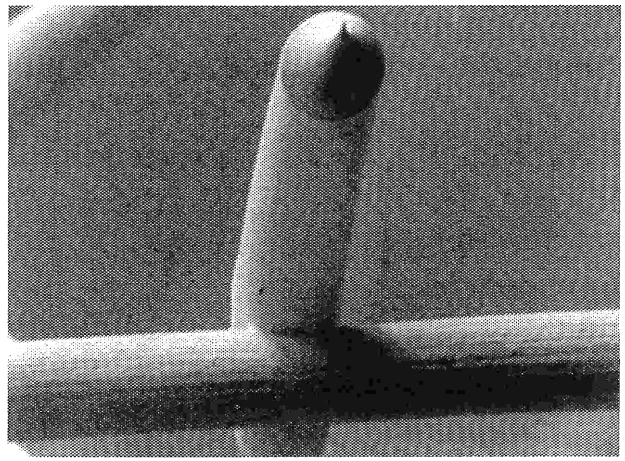
Source: [Flegler et al., 1993]

Field Emission Gun (FEG)

- Electron source:
  Cold tungsten tip
- Emission mechanism:
  Field emission
- Usage:
  Progressively replacing the W-gun



A

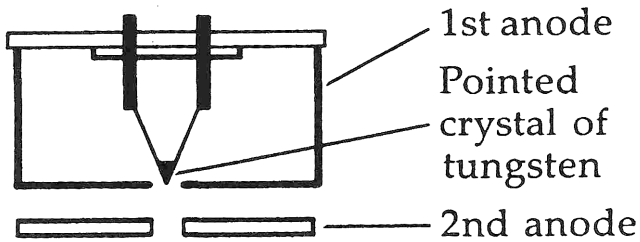


B

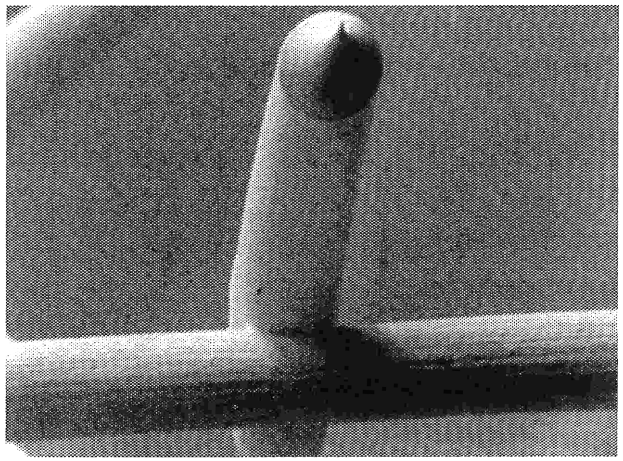
Source: [Flegler et al., 1993]

Field Emission Gun (FEG)

- Advantages:
  - Beam current up to 1000 ×
  - Smaller area of emission
  - Energy spread is about 1/10
  - **Duration of life** 100 ×
- Disadvantages:
  - Dedicated design of microscope necessary
  - Unstable intensity



A

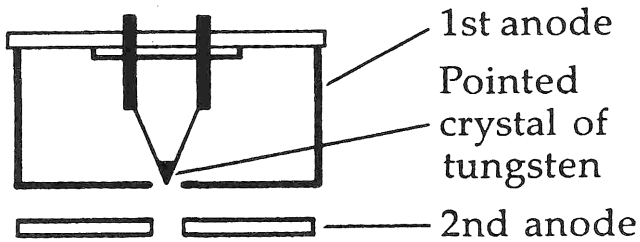


B

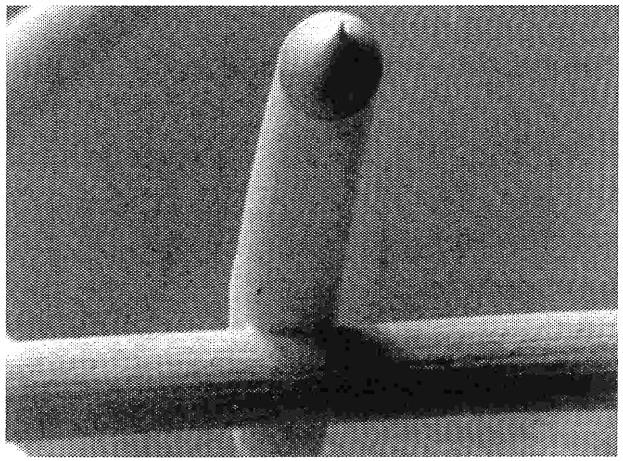
Source: [Flegler et al., 1993]

Field Emission Gun (FEG)

- Advantages:
  - Beam current up to 1000 $\times$
  - Smaller area of emission
  - Energy spread is about 1/10
  - **Duration of life** 100 $\times$
- Disadvantages:
  - Dedicated design of microscope necessary
  - Unstable intensity



A



B

Source: [Flegler et al., 1993]

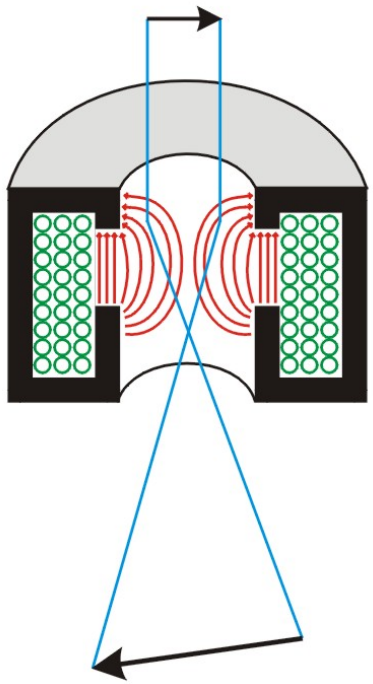
Overview: Electron Optics

Magnetic Lenses: Main Principle

- Formerly: electrostatic lenses
  Today: magnetic lenses
- Design ("pole-piece lens"):
  - Coil around hollow core
  - Covered with soft iron ("shroud")
  - Narrow gap without covering
- Focusing due to the Lorentz force

$$\mathbf{F} = -e \cdot \mathbf{v} \times \mathbf{B}$$

- Focal length depends on
  - **Coil current**
  - Radial distance ($\rightarrow$ spherical a.)
  - Velocity ($\rightarrow$ chromatic a.)



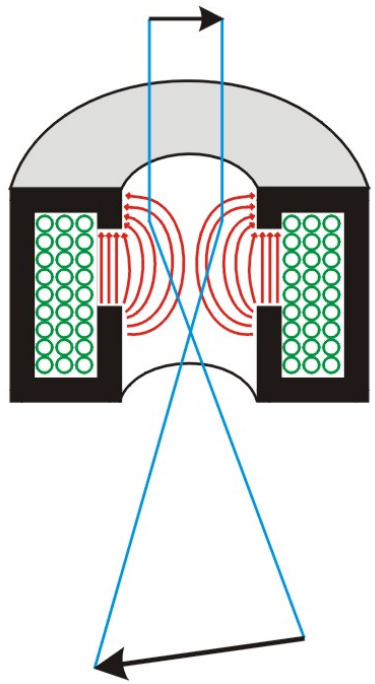
Source: http://www.microscopy.ethz.ch/lens.htm

Magnetic Lenses: Main Principle

- Formerly: electrostatic lenses
  Today: magnetic lenses
- Design ("pole-piece lens"):
  - Coil around hollow core
  - Covered with soft iron ("shroud")
  - Narrow gap without covering
- Focusing due to the Lorentz force

$$\mathbf{F} = -e \cdot \mathbf{v} \times \mathbf{B}$$

- Focal length depends on
  - **Coil current**
  - Radial distance ($\rightarrow$ spherical a.)
  - Velocity ($\rightarrow$ chromatic a.)



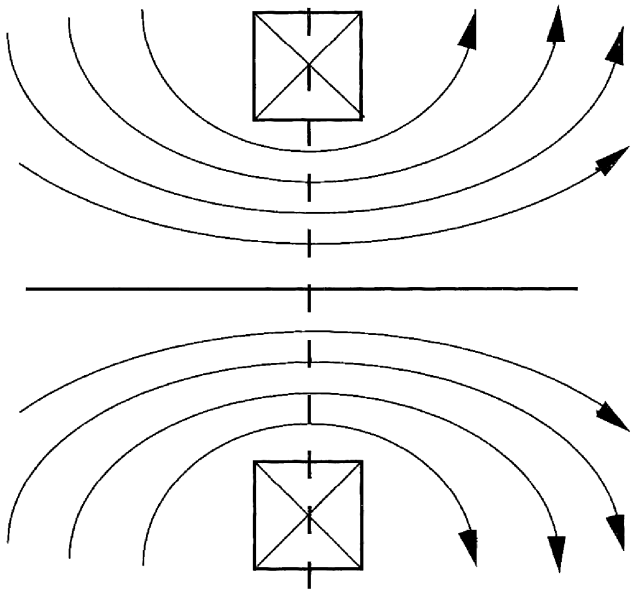
Source: http://www.microscopy.ethz.ch/lens.htm

Magnetic Lenses: Main Principle

- Formerly: electrostatic lenses
  Today: magnetic lenses
- Design ("pole-piece lens"):
  - Coil around hollow core
  - Covered with soft iron ("shroud")
  - Narrow gap without covering
- Focusing due to the Lorentz force

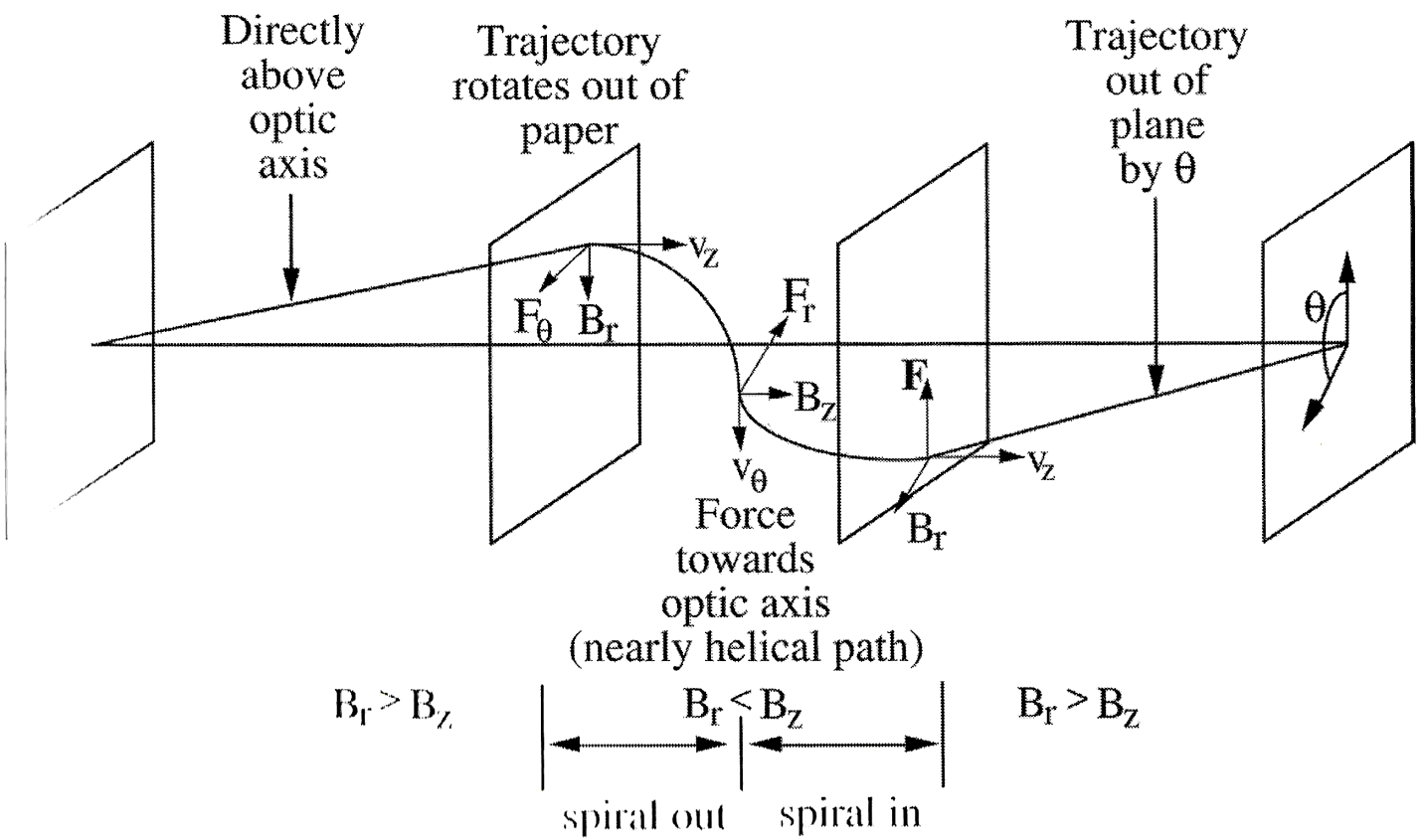
$$\mathbf{F} = -e \cdot \mathbf{v} \times \mathbf{B}$$

- Focal length depends on
  - **Coil current**
  - Radial distance ($\rightarrow$ spherical a.)
  - Velocity ($\rightarrow$ chromatic a.)



Source: [Fultz and Howe, 2002]

Magnetic Lenses: Electron Trajectory



Source: [Fultz and Howe, 2002]

Magnetic Lenses: Adjusting the Focus

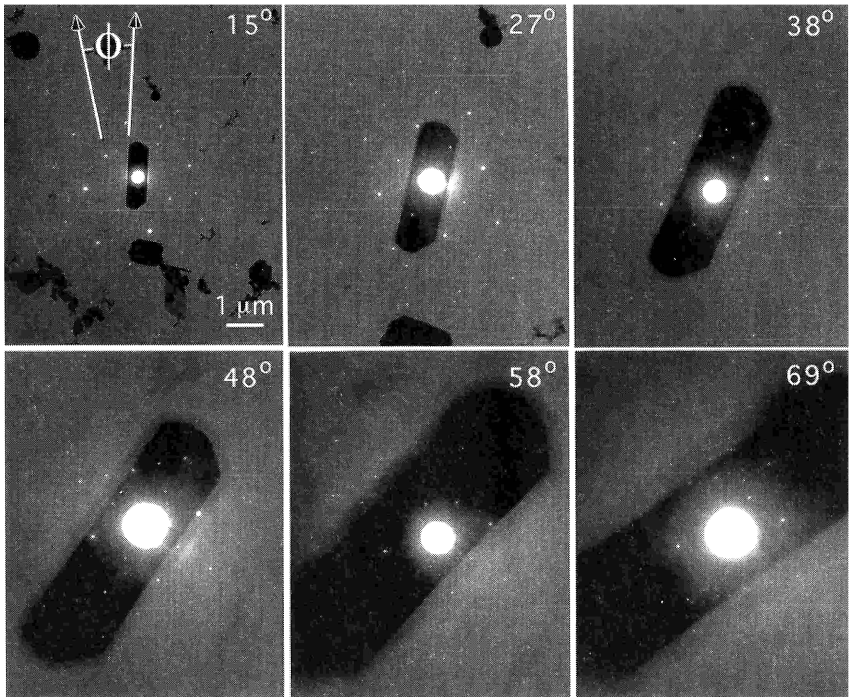
- Adjusting the focus / magnification:
  variation of the coil current,
  i.e. the **B**-Field
- Helical path "shrinks" or "expands"
- θ varies $\Rightarrow$ **Image rotates!**
- Important for TEM:
  Comparability of images
  and/or diffraction patterns

Magnetic Lenses: Adjusting the Focus

- Adjusting the focus / magnification:
  variation of the coil current,
  i.e. the **B**-Field
- Helical path "shrinks" or "expands"
- θ varies $\Rightarrow$ **Image rotates!**
- Important for TEM:
  Comparability of images
  and/or diffraction patterns

Magnetic Lenses: Adjusting the Focus

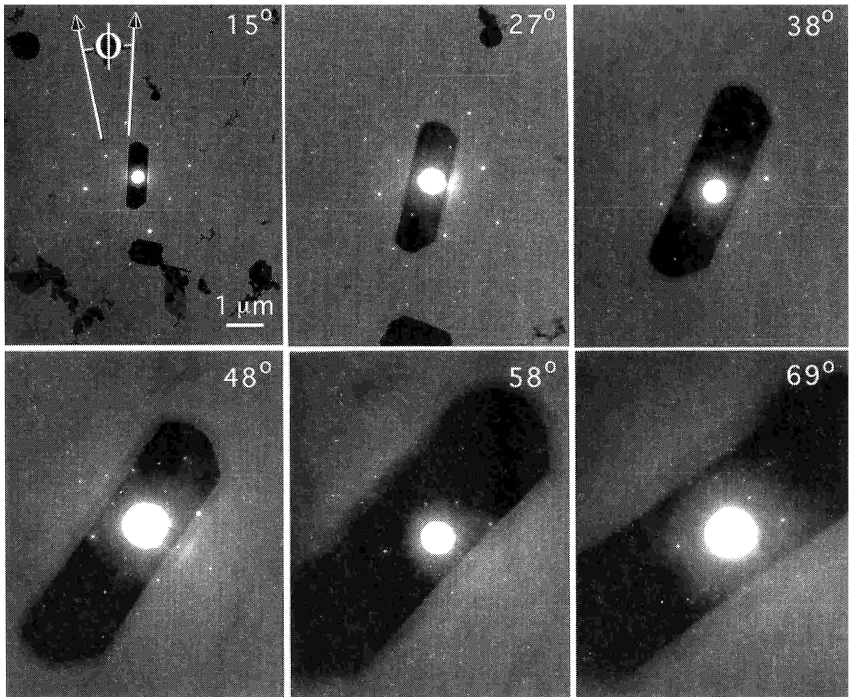
- Adjusting the focus / magnification:
  variation of the coil current, i.e. the **B**-Field
- Helical path "shrinks" or "expands"
- θ varies $\Rightarrow$ **Image rotates!**
- Important for TEM:
  Comparability of images and/or diffraction patterns



Source: [Fultz and Howe, 2002]

Magnetic Lenses: Adjusting the Focus

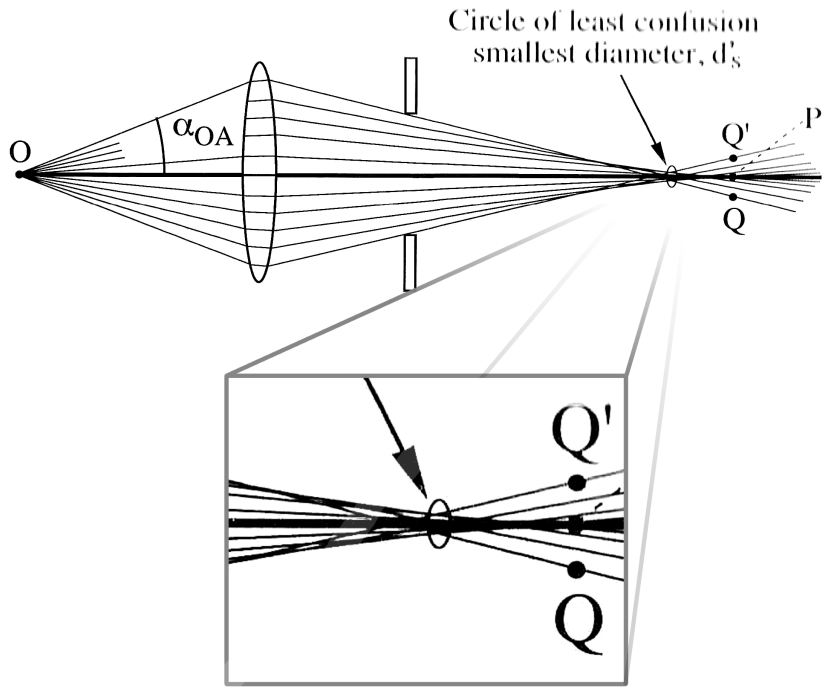
- Adjusting the focus / magnification:
  variation of the coil current, i.e. the **B**-Field
- Helical path "shrinks" or "expands"
- θ varies $\Rightarrow$ **Image rotates!**
- Important for TEM:
  Comparability of images and/or diffraction patterns



Source: [Fultz and Howe, 2002]

Aberrations

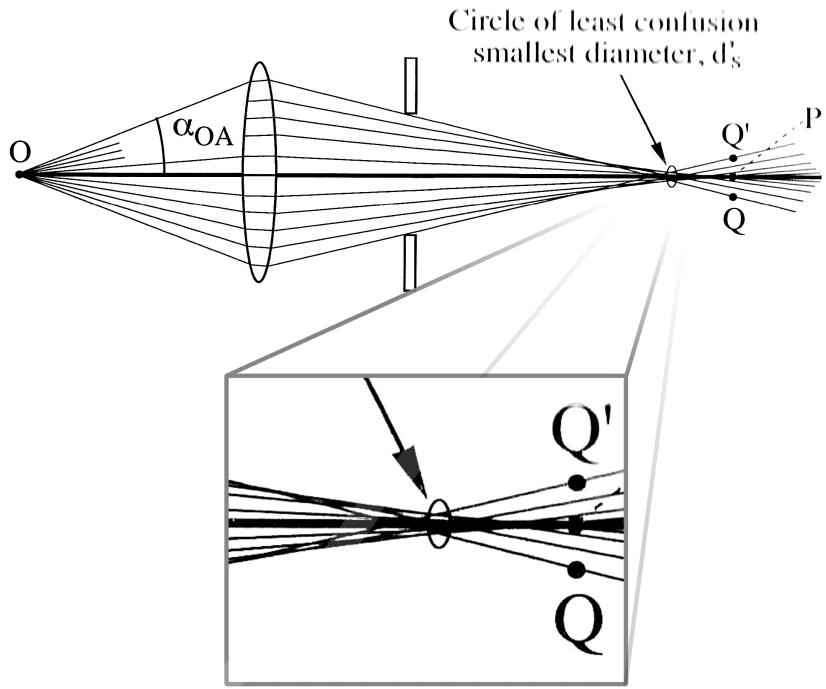
- Lense aberrations: **Limiting factor!**
  (cf. theoretical vs. practical improvement: $100,000 \leftrightarrow 1,000$)
- Types:
  - Spherical aberration
  - Chromatic aberration
  - Astigmatism
  - Diffraction
- Astigmatism:
  Correctable by astigmation
  ($\rightarrow$ multipole lenses)



Source: [Fultz and Howe, 2002]

Aberrations

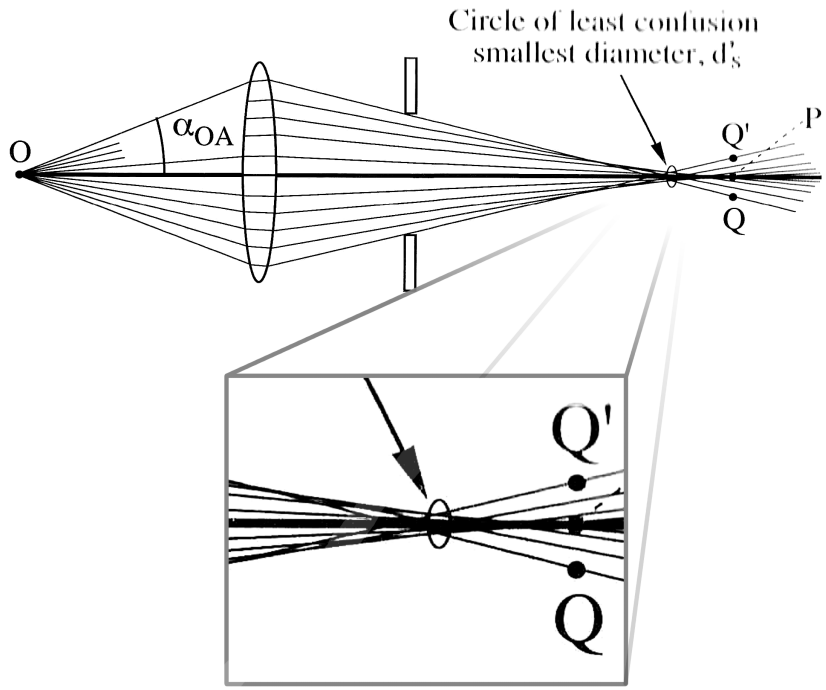
- Lense aberrations: **Limiting factor!**
  (cf. theoretical vs. practical improvement: $100,000 \leftrightarrow 1,000$)
- Types:
  - Spherical aberration
  - Chromatic aberration
  - Astigmatism
  - Diffraction
- Astigmatism:
  Correctable by astigmation
  ($\rightarrow$ multipole lenses)



Source: [Fultz and Howe, 2002]

Aberrations

- Lense aberrations: **Limiting factor!**
  (cf. theoretical vs. practical improvement: $100,000 \leftrightarrow 1,000$)
- Types:
  - Spherical aberration
  - Chromatic aberration
  - Astigmatism
  - Diffraction
- Astigmatism:
  Correctable by astigmation
  ($\rightarrow$ multipole lenses)

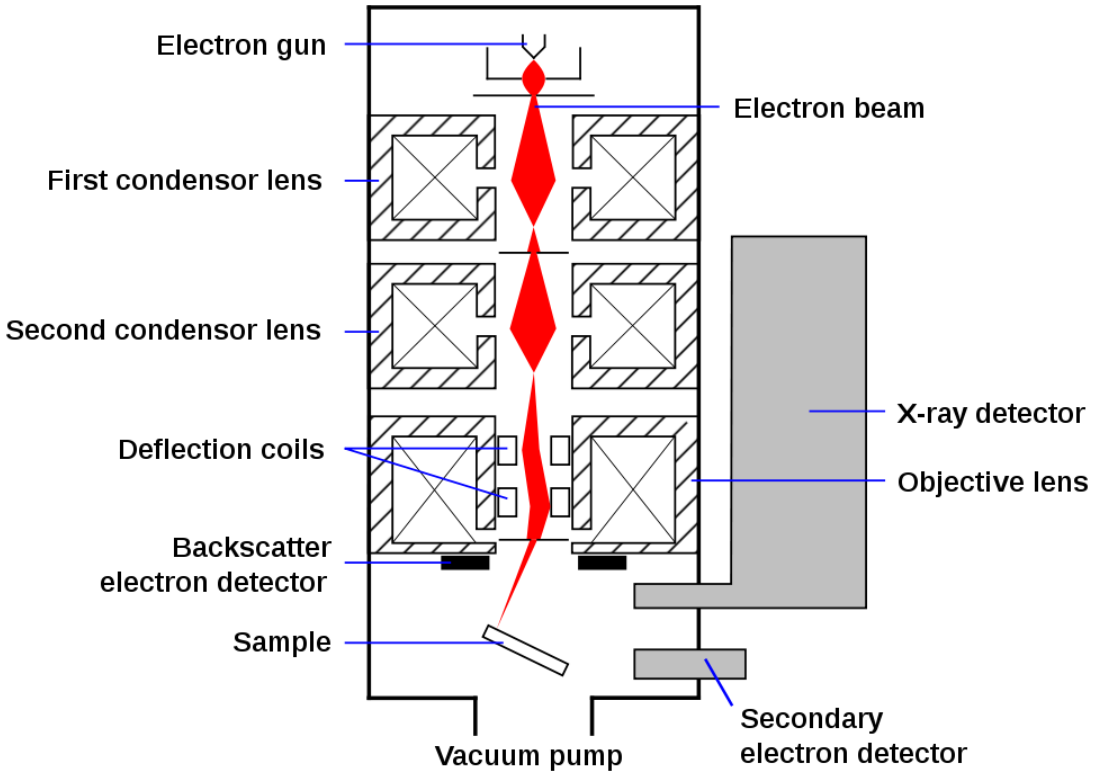


Source: [Fultz and Howe, 2002]

Overview: Scanning Electron Microscopy (SEM)

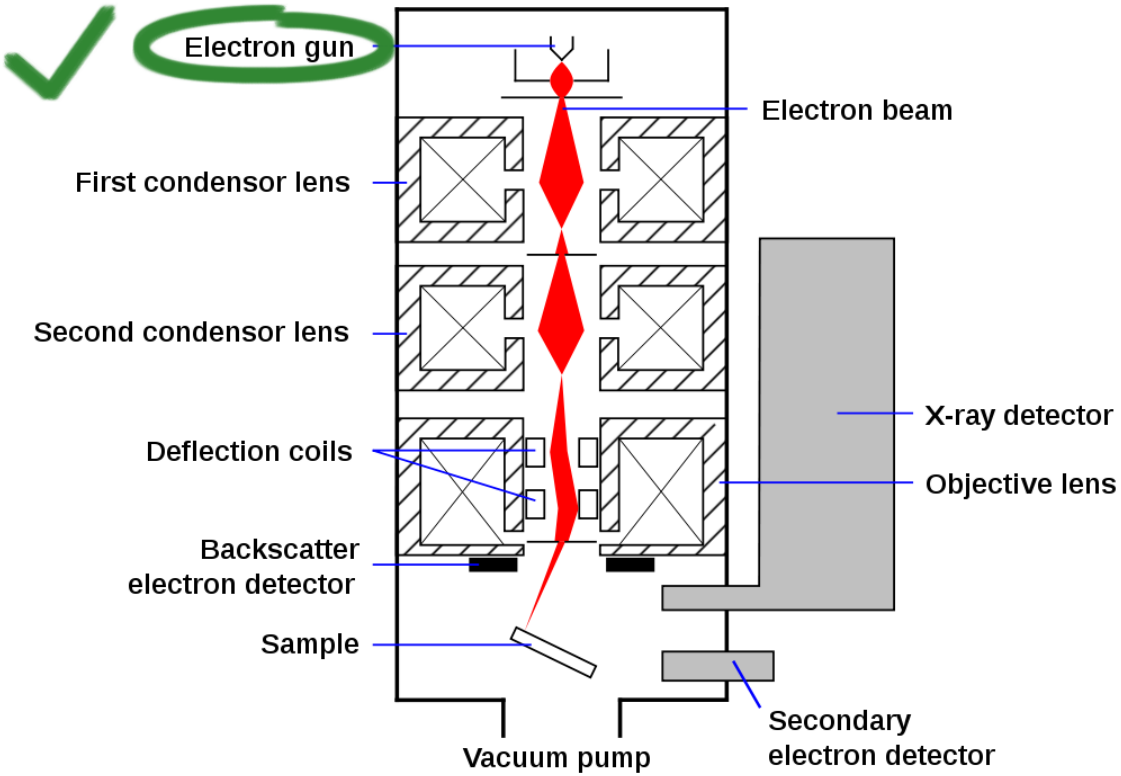
Overview: Technical Issues

Layout



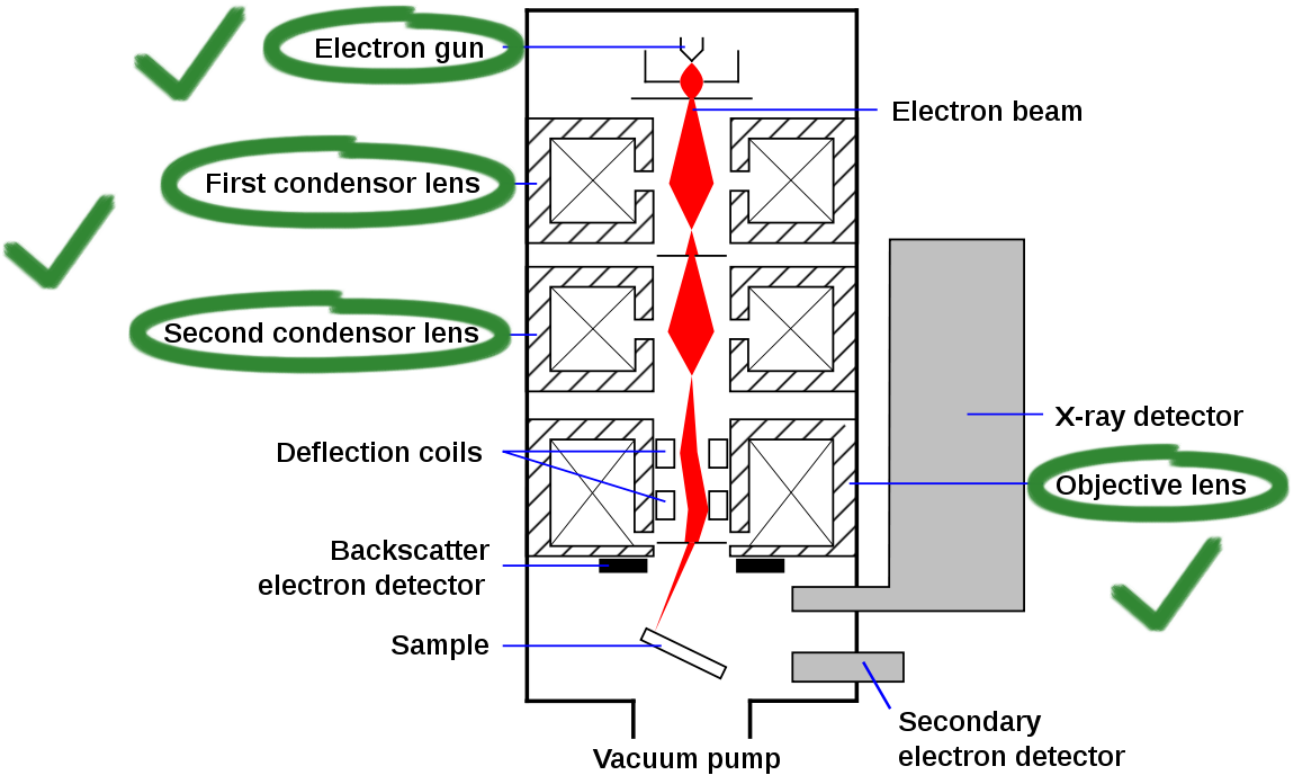
Source: http://en.wikipedia.org/wiki/Scanning_electron_microscopy

Layout



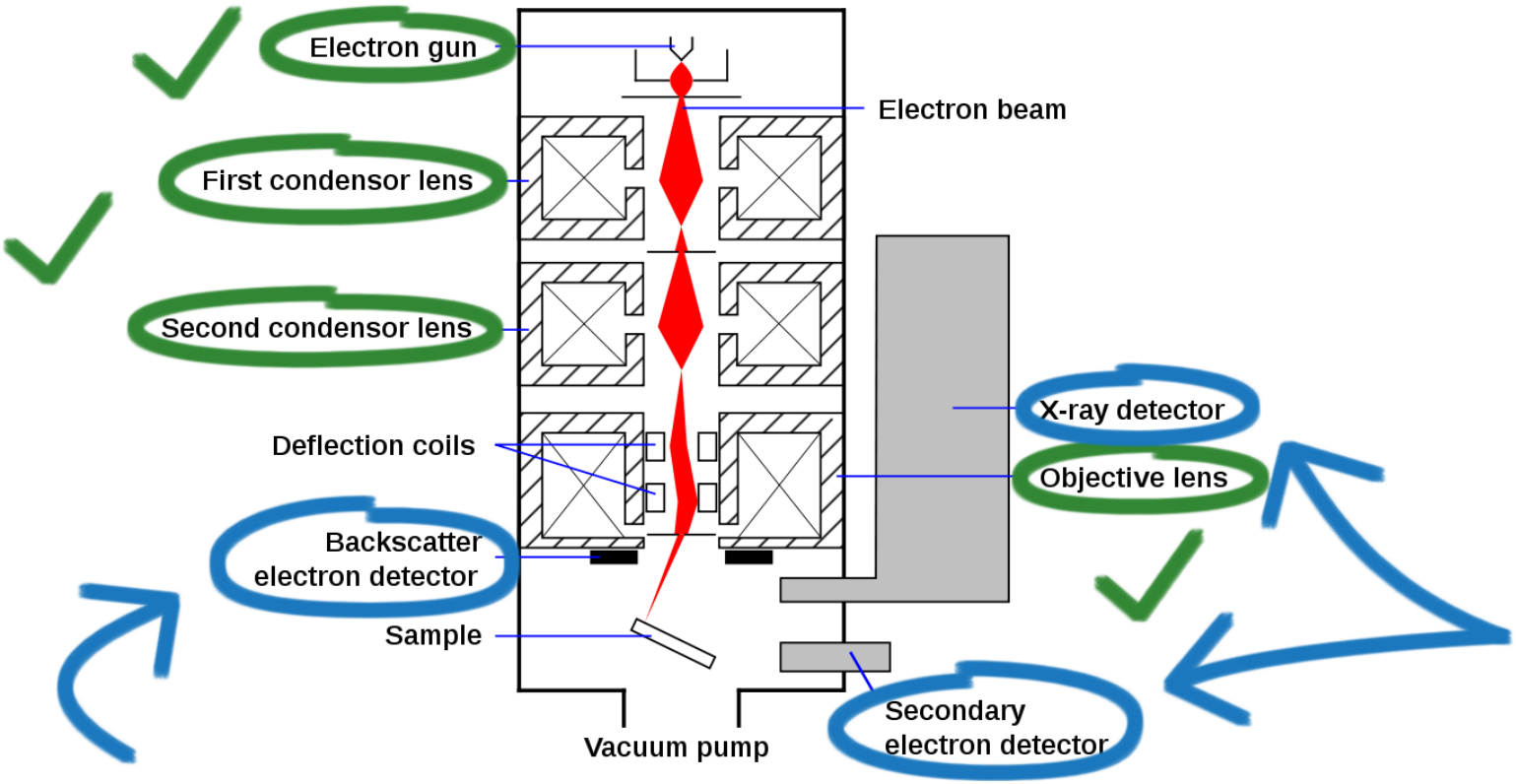
Source: http://en.wikipedia.org/wiki/Scanning_electron_microscopy

Layout



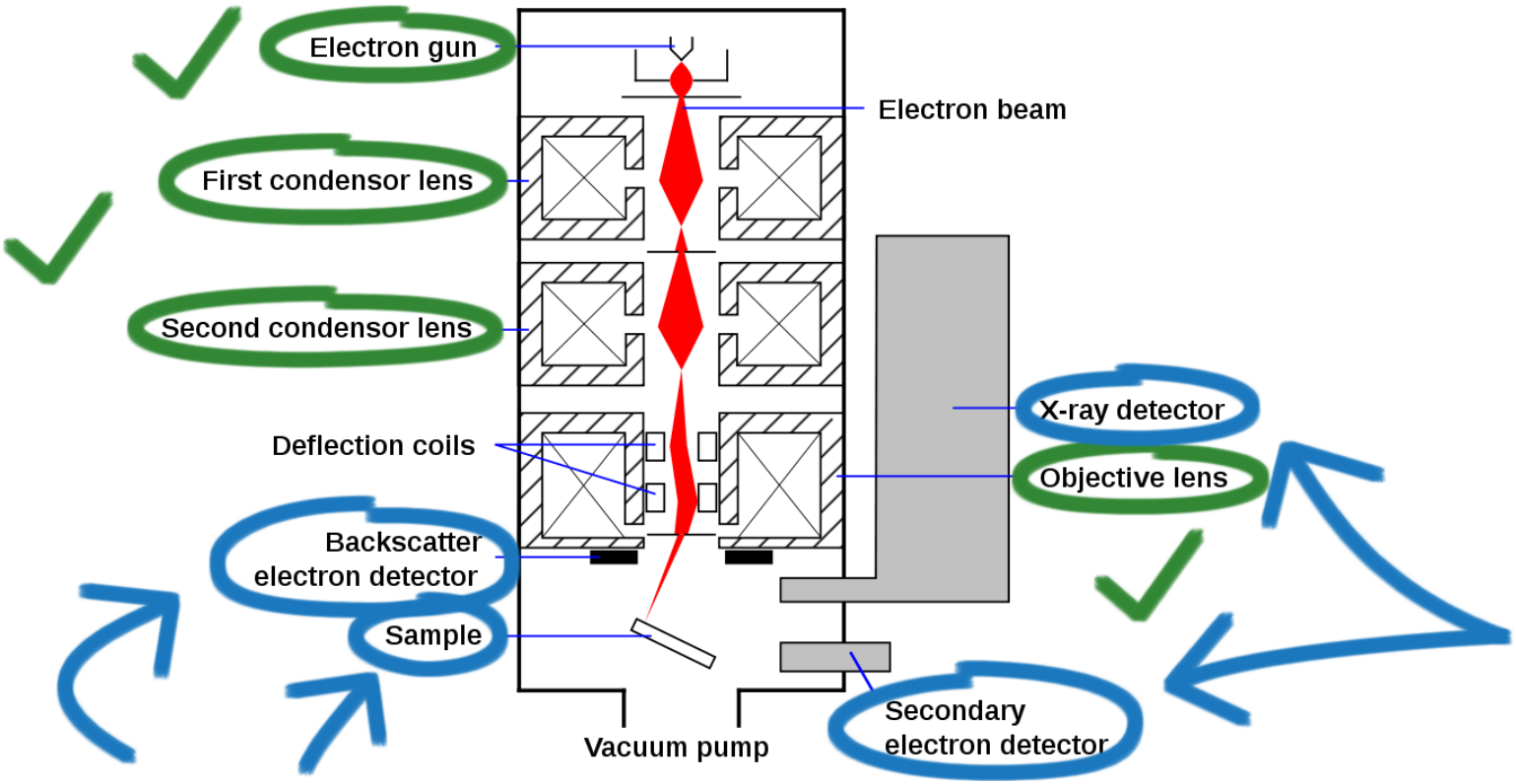
Source: http://en.wikipedia.org/wiki/Scanning_electron_microscopy

Layout



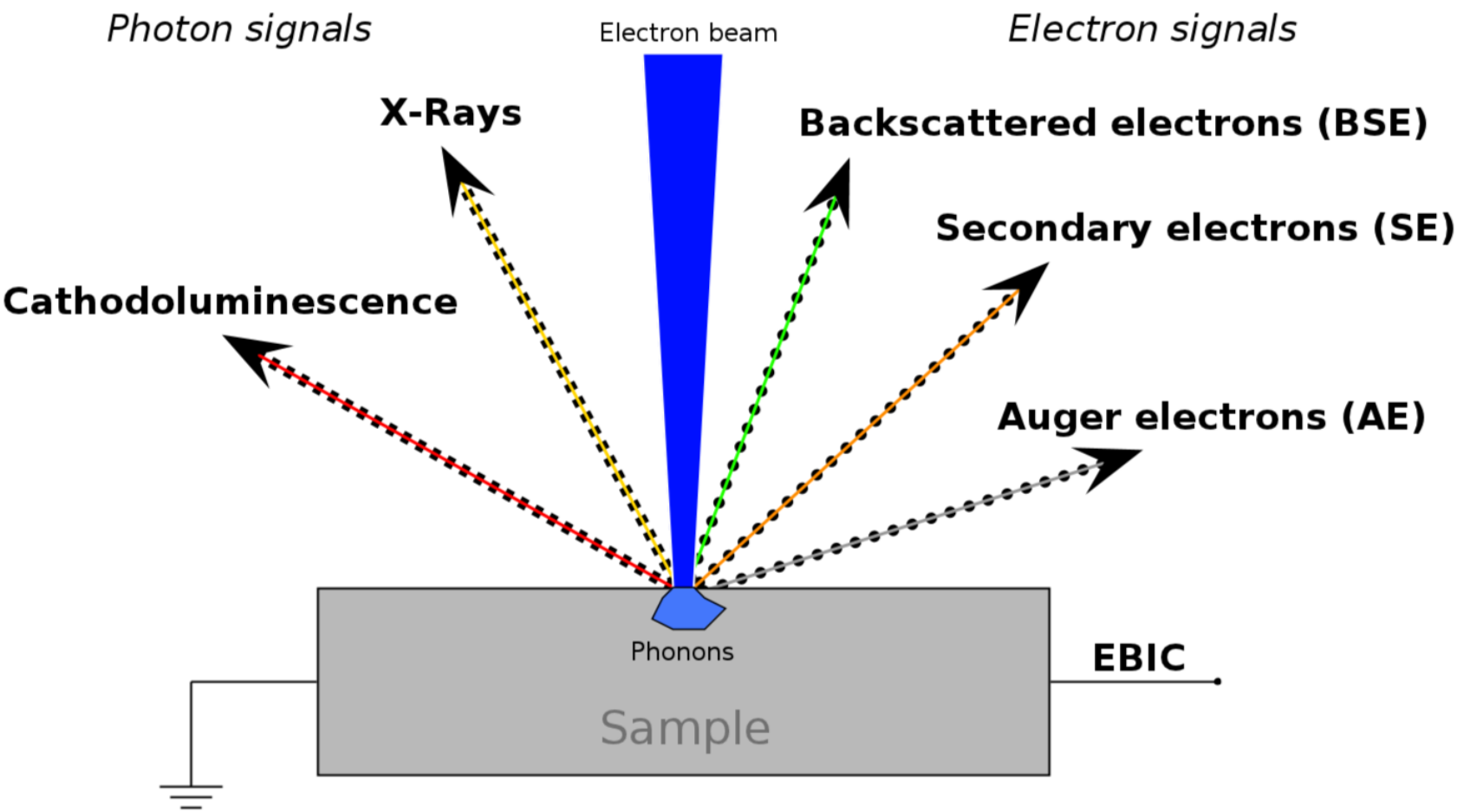
Source: http://en.wikipedia.org/wiki/Scanning_electron_microscopy

Layout



Source: http://en.wikipedia.org/wiki/Scanning_electron_microscopy

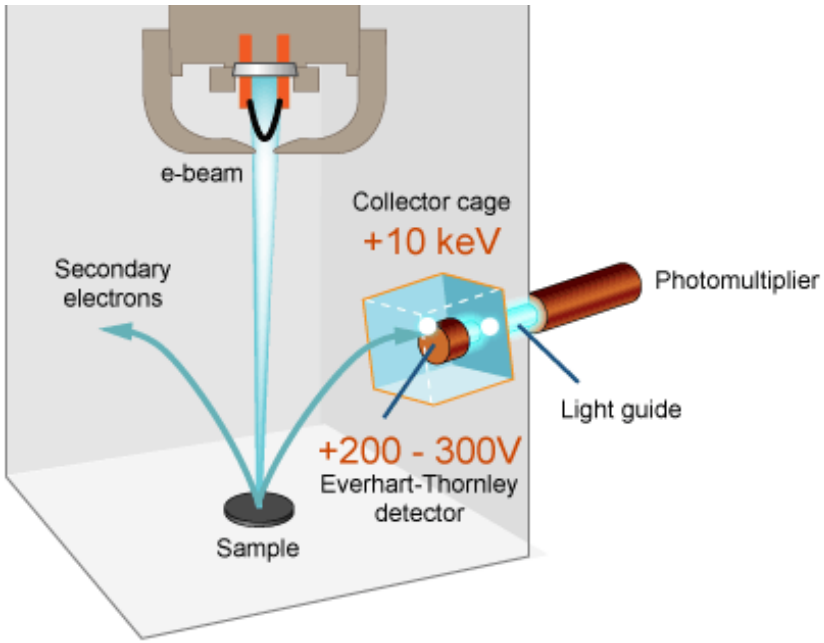
Available Signals



Detecting Electrons

Detecting Electrons

Secondary electron detector



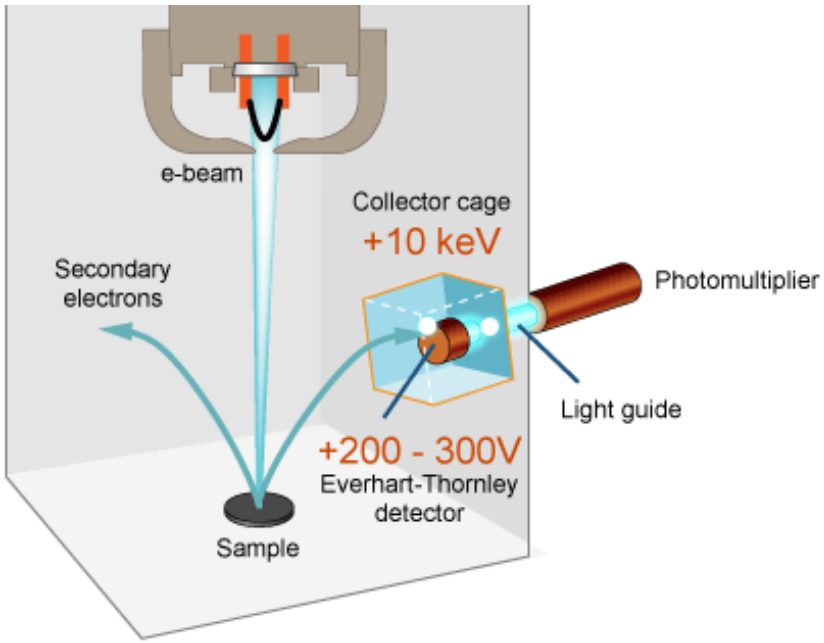
Source: http://www.ammrf.org.au/myscope/sem/

Typ. Energy: $\sim 2 - 50\,\mathrm{eV}$

Setup: Everhart-Thornley Detector

Detecting Electrons

Secondary electron detector

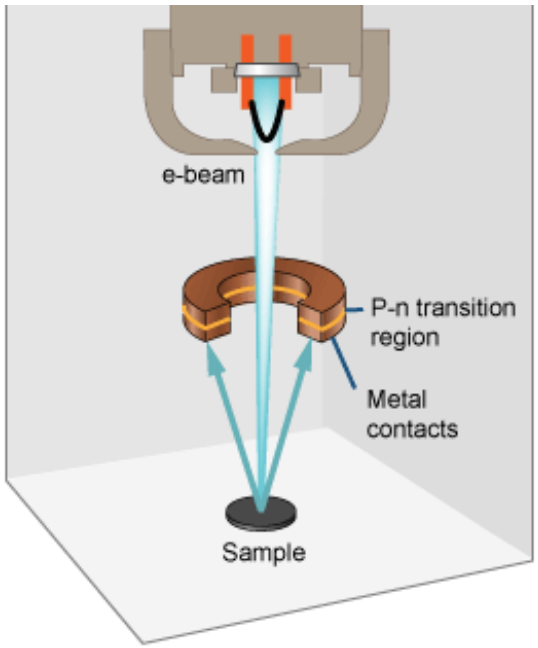


Source: http://www.ammrf.org.au/myscope/sem/

Typ. Energy: $\sim 2 - 50\,\mathrm{eV}$

Setup: Everhart-Thornley Detector

Backscattered electron detector



Source: http://www.ammrf.org.au/myscope/sem/

Typ. Energy: $\sim 20\,\mathrm{keV}$

Setup: Solid state diode detector

Detecting Photons

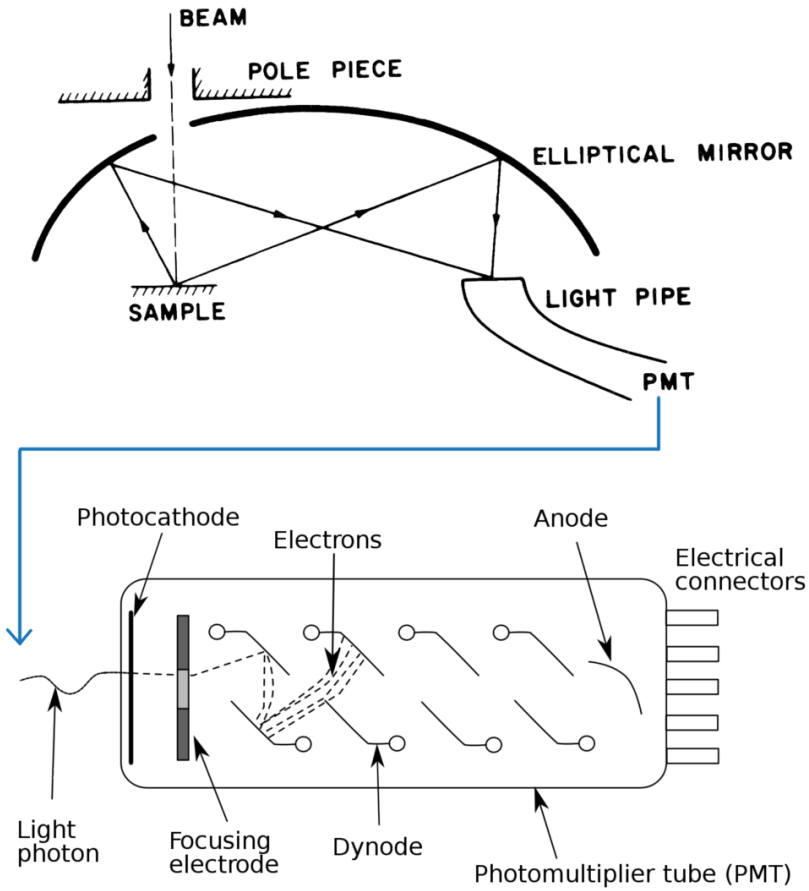
- Problem:
  Small number
  of emitted photons
- Solution:
  Sample is placed at one focus
  of an **elliptical mirror**
- Setup:
  Light pipe carries photons
  from second focus to a
  photomultiplier tube (PMT)
- Spectral analysis:
  Possible; dispersive element
  (prism- or FT-spectrometer) in
  front of PMT

Detecting Photons

- Problem:
  Small number
  of emitted photons
- Solution:
  Sample is placed at one focus
  of an **elliptical mirror**
- Setup:
  Light pipe carries photons
  from second focus to a
  photomultiplier tube (PMT)
- Spectral analysis:
  Possible; dispersive element
  (prism- or FT-spectrometer) in
  front of PMT

Detecting Photons

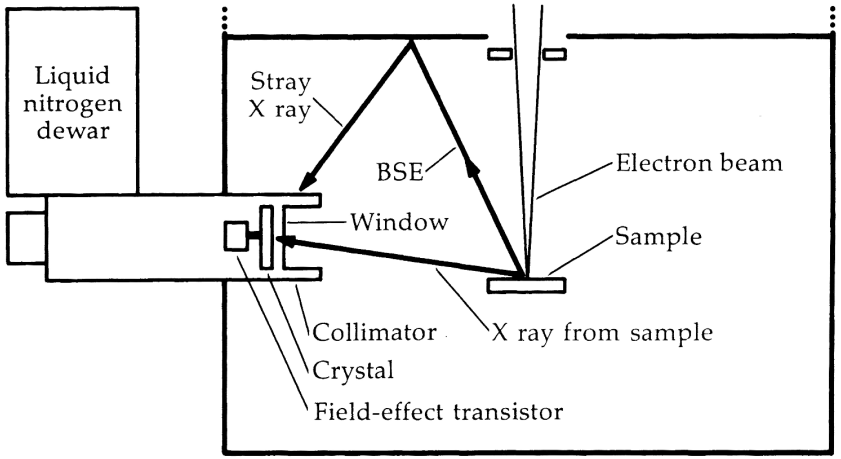
- Problem:
  Small number
  of emitted photons
- Solution:
  Sample is placed at one focus
  of an **elliptical mirror**
- Setup:
  Light pipe carries photons
  from second focus to a
  photomultiplier tube (PMT)
- Spectral analysis:
  Possible; dispersive element
  (prism- or FT-spectrometer) in
  front of PMT



Source: [Newbury, 1986]
Source: http://en.wikipedia.org/wiki/Photomultiplier

Detecting X-Rays

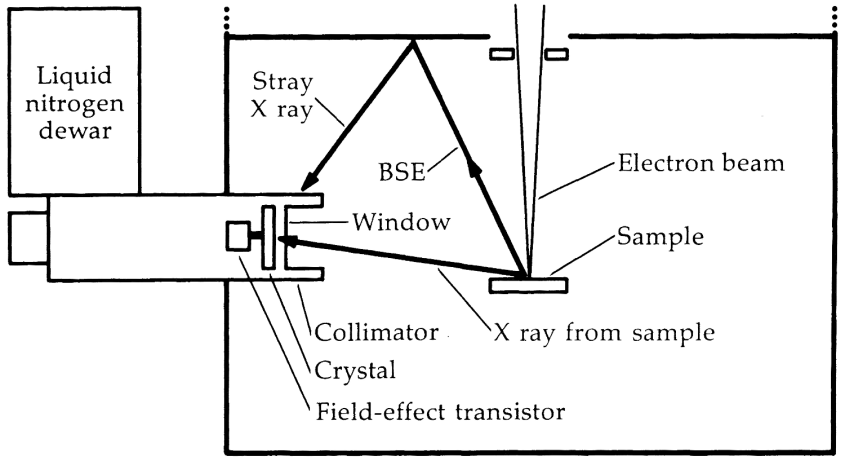
- Method: **EDS** ("EDX")
- Energy-Dispersive Spectroscopy (EDS):
  1. Si(Li)-crystal absorbs X-rays
  2. Creation of electron-hole pairs (number proportional to energy)
  3. Extraction of charge by applied voltage
- Energy of X-rays measured
- Wide scan range: Short measuring times for complete scan



Source: [Flegler et al., 1993]

Detecting X-Rays

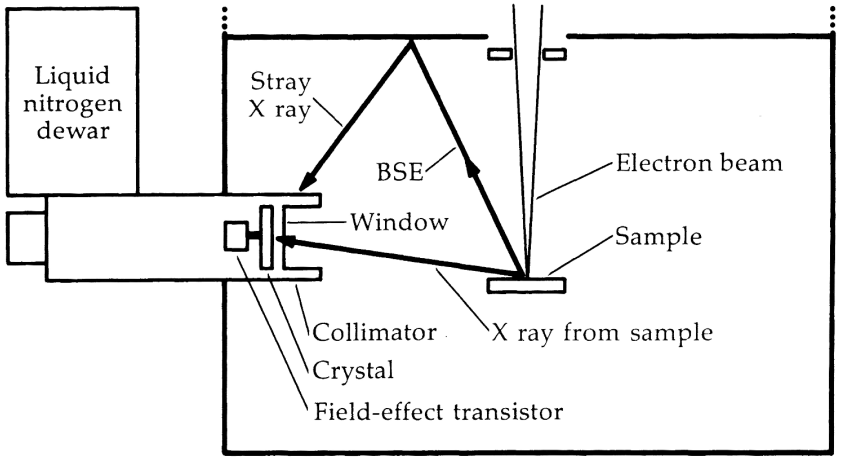
- Method: **EDS** ("EDX")
- Energy-Dispersive Spectroscopy (EDS):
  1. Si(Li)-crystal absorbs X-rays
  2. Creation of electron-hole pairs (number proportional to energy)
  3. Extraction of charge by applied voltage
- Energy of X-rays measured
- Wide scan range: Short measuring times for complete scan



Source: [Flegler et al., 1993]

Detecting X-Rays

- Method: **EDS** ("EDX")
- Energy-Dispersive Spectroscopy (EDS):
  1. Si(Li)-crystal absorbs X-rays
  2. Creation of electron-hole pairs (number proportional to energy)
  3. Extraction of charge by applied voltage
- Energy of X-rays measured
- Wide scan range:
  Short measuring times for complete scan



Source: [Flegler et al., 1993]

Sample Preparation

- Whole samples can be imaged; no sectioning required (cf. TEM)
- Requirements: Samples must be ...
  - devoid of volatile materials (e.g. water).
  - firmly mounted ($\rightarrow$ stubs).
  - electrically conductive.
- Biological samples: extensive prepartion (fixation, coating, mounting)
- Plastic/Ceramics: less extensive preparation (coating, mounting)
- Metals/Semiconductors: **simple preparation** (mounting)

Source: http://en.wikipedia.org/wiki/Scanning_electron_microscope

Sample Preparation

- Whole samples can be imaged; no sectioning required (cf. TEM)
- Requirements: Samples must be ...
  - devoid of volatile materials (e.g. water).
  - firmly mounted ($\rightarrow$ stubs).
  - electrically conductive.
- Biological samples: extensive prepartion (fixation, coating, mounting)
- Plastic/Ceramics: less extensive preparation (coating, mounting)
- Metals/Semiconductors: **simple preparation** (mounting)

Source: http://en.wikipedia.org/wiki/Scanning_electron_microscope

Sample Preparation

- Whole samples can be imaged; no sectioning required (cf. TEM)
- Requirements: Samples must be ...
  - devoid of volatile materials (e.g. water).
  - firmly mounted ($\rightarrow$ stubs).
  - electrically conductive.
- Biological samples: extensive prepartion (fixation, coating, mounting)
- Plastic/Ceramics: less extensive preparation (coating, mounting)
- Metals/Semiconductors: **simple preparation** (mounting)

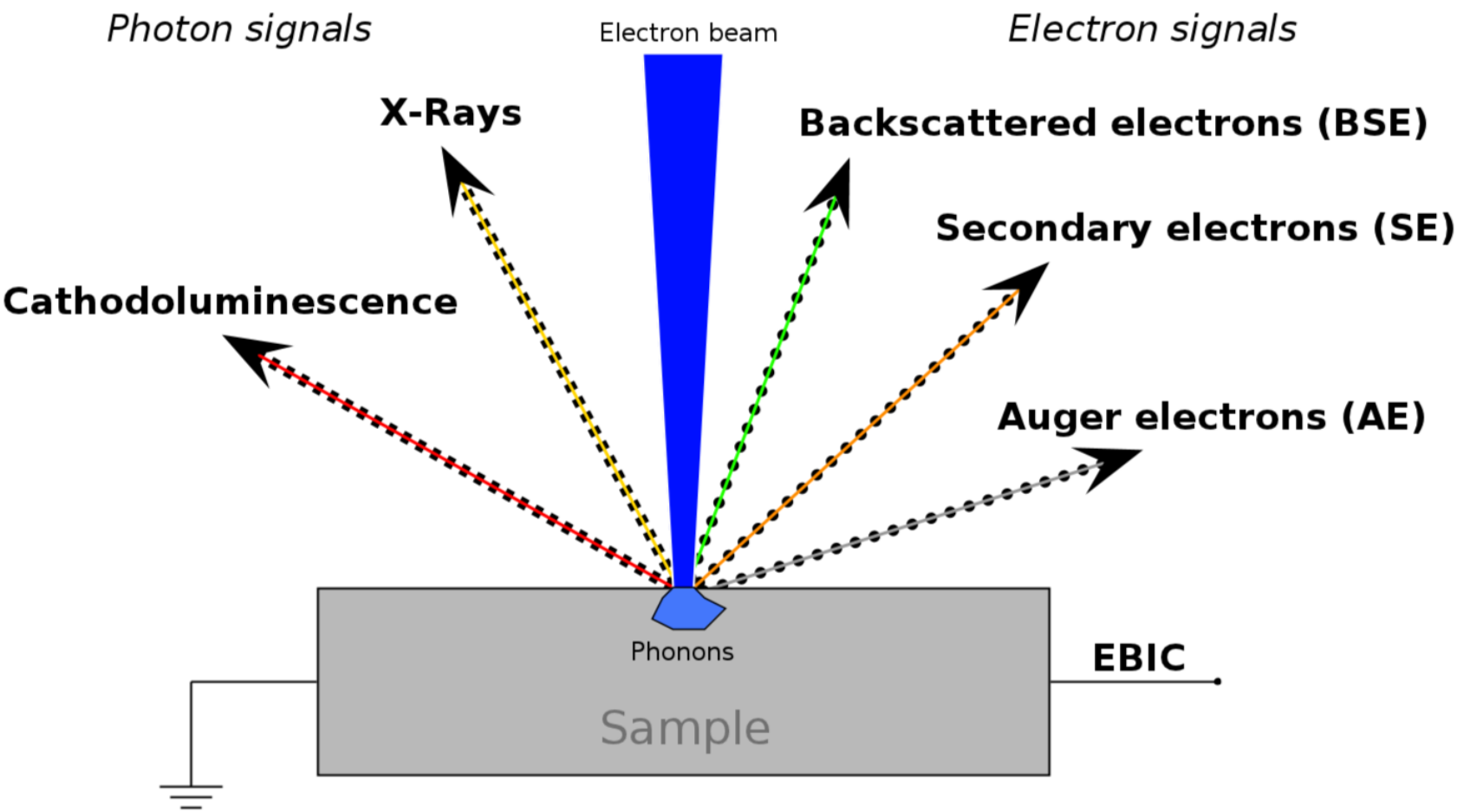
Source: http://en.wikipedia.org/wiki/Scanning_electron_microscope

Overview: Operation Modes and Contrast Mechanisms

3 Scanning Electron Microscopy (SEM)

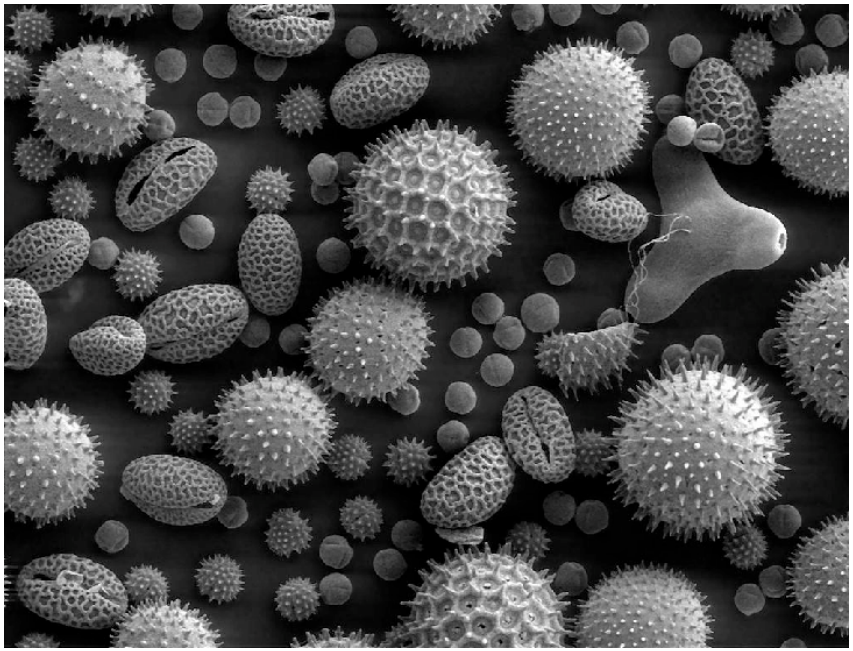
- Technical Issues
- Operation Modes and Contrast Mechanisms
  - Secondary Electrons (SE)
  - Backscattered Electrons (BSE)
  - Electron Beam Induced Current (EBIC)
  - Cathodoluminescence (CL)
  - X-Ray Fluorescence (EDX)

Various Information Channels



Secondary Electrons (SE)

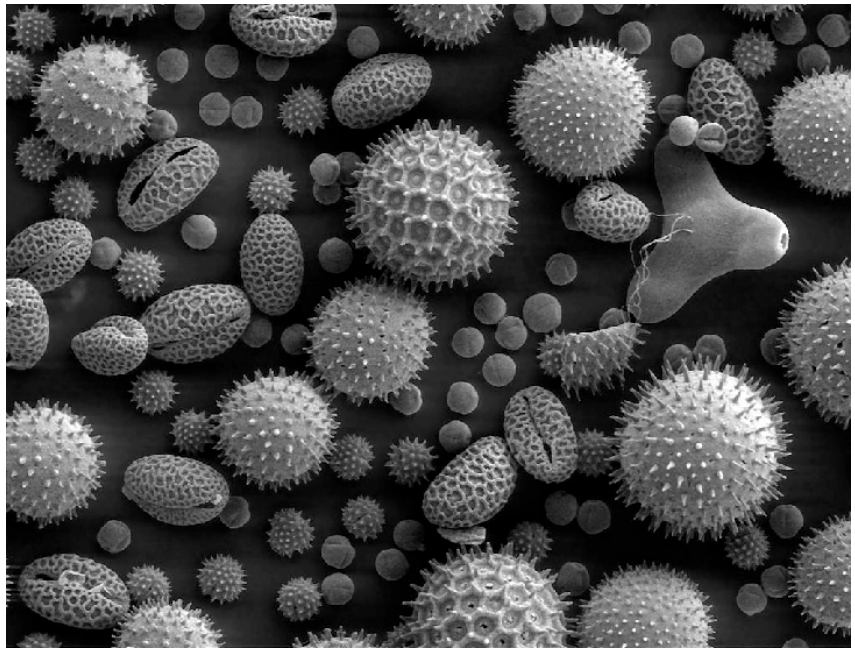
- Signal: Secondary electrons ($\rightarrow$ Everhart-Thornley det.)
- Usage: Standard SEM image
- Contrast mechanisms:
  - Surface tilt contrast
  - Shadowing contrast
  - Edge contrast
  - Voltage contrast
- Results: Topography of the sample
- Resolution: $\gtrsim 0.5\,\mathrm{nm}$ (highest SEM resolution)



Source: http://en.wikipedia.org/wiki/Scanning_electron_microscopy

Secondary Electrons (SE)

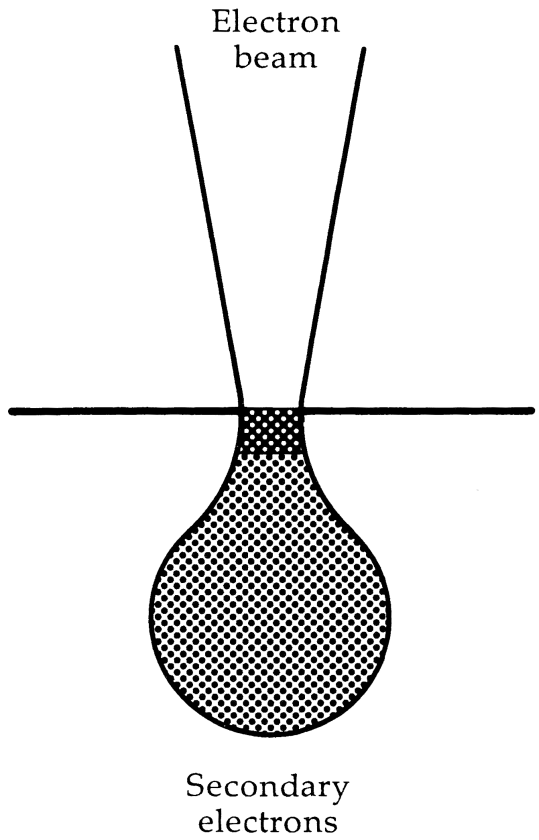
- Signal: Secondary electrons ($\rightarrow$ Everhart-Thornley det.)
- Usage: Standard SEM image
- Contrast mechanisms:
  - Surface tilt contrast
  - Shadowing contrast
  - Edge contrast
  - Voltage contrast
- Results: Topography of the sample
- Resolution: $\gtrsim 0.5\,\mathrm{nm}$ (highest SEM resolution)



Source: http://en.wikipedia.org/wiki/Scanning_electron_microscopy

Secondary Electrons (SE)

- Signal: Secondary electrons ($\rightarrow$ Everhart-Thornley det.)
- Usage: Standard SEM image
- Contrast mechanisms:
  - Surface tilt contrast
  - Shadowing contrast
  - Edge contrast
  - Voltage contrast
- Results: Topography of the sample
- Resolution: $\gtrsim 0.5\,\mathrm{nm}$ (highest SEM resolution)



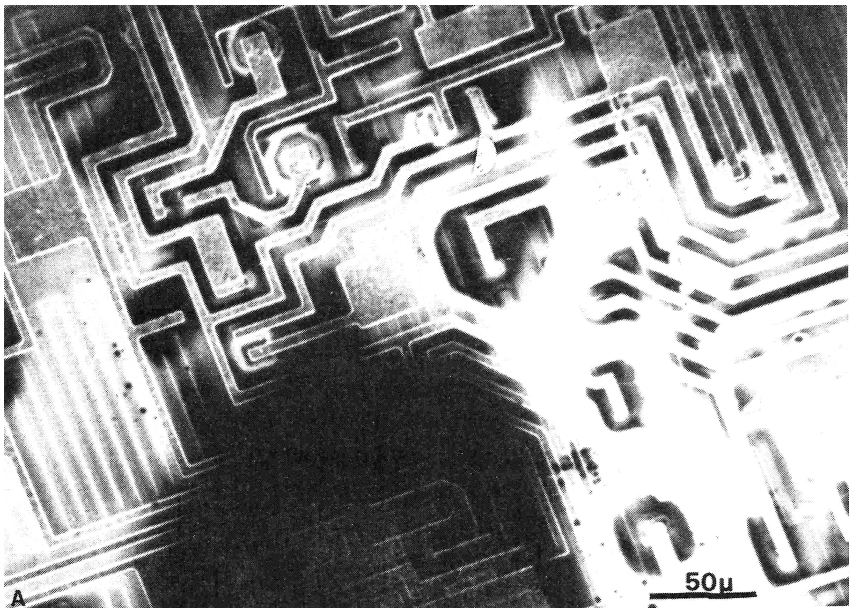
Source: [Flegler et al., 1993]

Secondary Electrons (SE): Voltage Contrast

Secondary electron image of a chip ...

Secondary Electrons (SE): Voltage Contrast

Secondary electron image of a chip ...

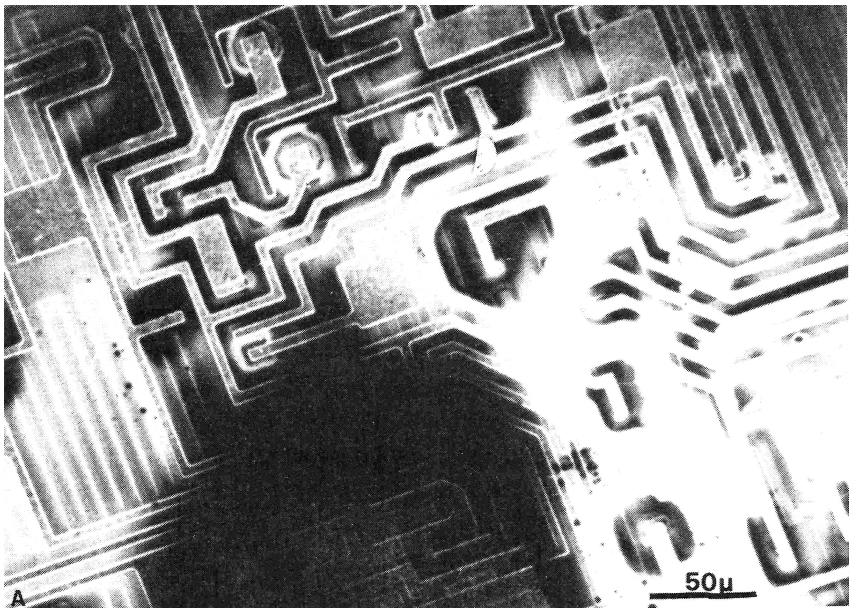


Source: [Newbury, 1986]

... without potentials.

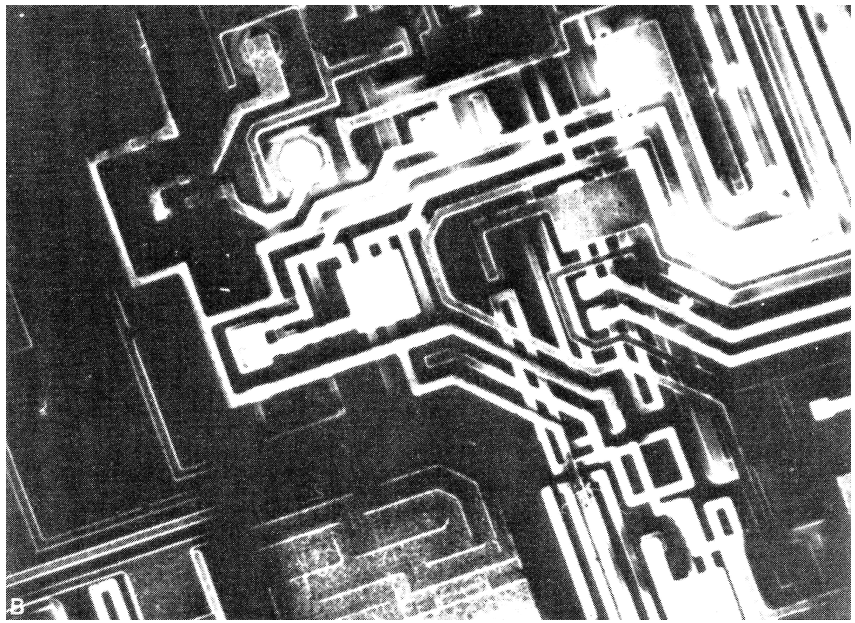
Secondary Electrons (SE): Voltage Contrast

Secondary electron image of a chip ...



Source: [Newbury, 1986]

... without potentials.

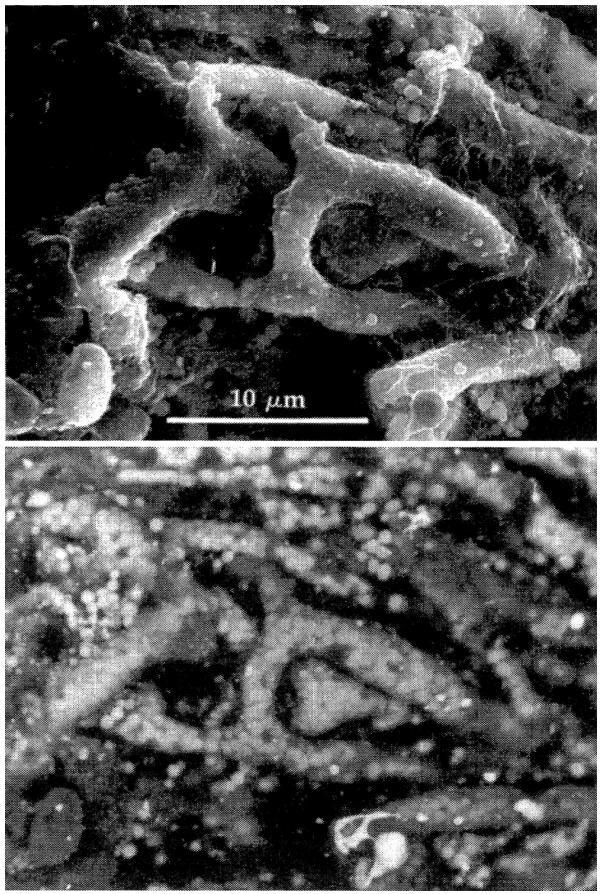


Source: [Newbury, 1986]

... with potentials.

Backscattered Electrons (BSE)

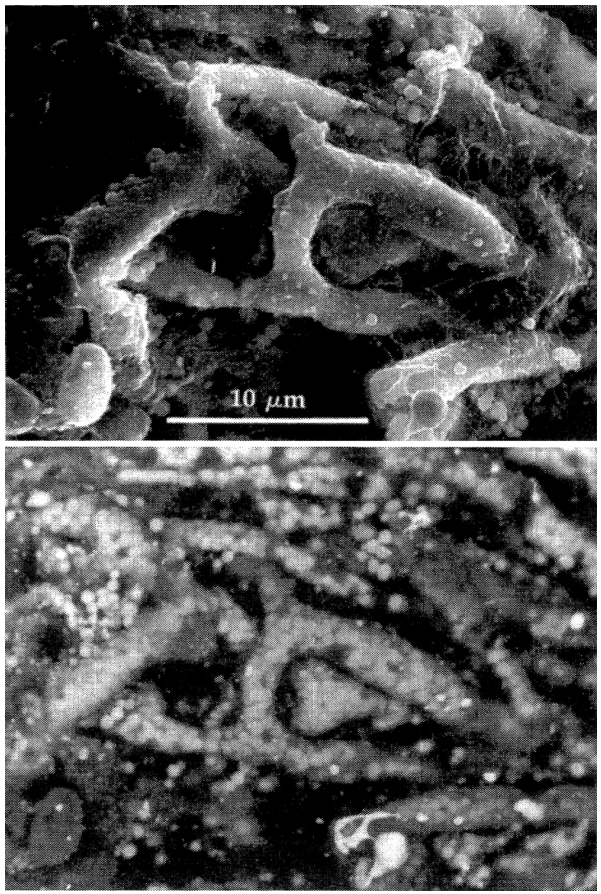
- Signal: Backscattered electrons ($\rightarrow$ Solid state diode det.)
- Usage: Widely-used imaging technique
- Contrast mechanisms:
  - **Material contrast** (Z-contrast)
  - *(Surface tilt contrast)*
  - *(Shadowing contrast)*
  - *(Voltage contrast)*
- Results: Spatial distribution of the average atomic number Z
- Resolution: $\sim 1\,\mu\mathrm{m}$ (depends on U_a)



Source: [Flegler et al., 1993]

Backscattered Electrons (BSE)

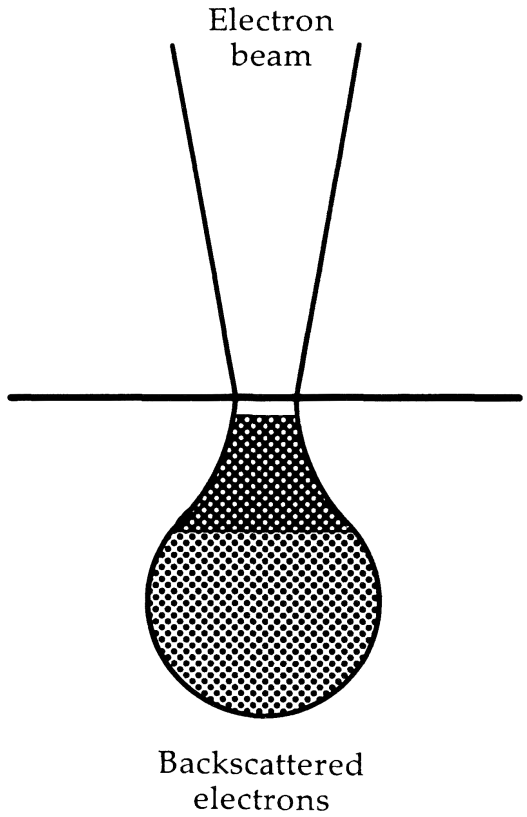
- Signal: Backscattered electrons
  ($\rightarrow$ Solid state diode det.)
- Usage:
  Widely-used imaging technique
- Contrast mechanisms:
  - **Material contrast**
    (Z-contrast)
  - *(Surface tilt contrast)*
  - *(Shadowing contrast)*
  - *(Voltage contrast)*
- Results:
  Spatial distribution of the
  average atomic number Z
- Resolution: $\sim 1\,\mu\mathrm{m}$
  (depends on U_a)



Source: [Flegler et al., 1993]

Backscattered Electrons (BSE)

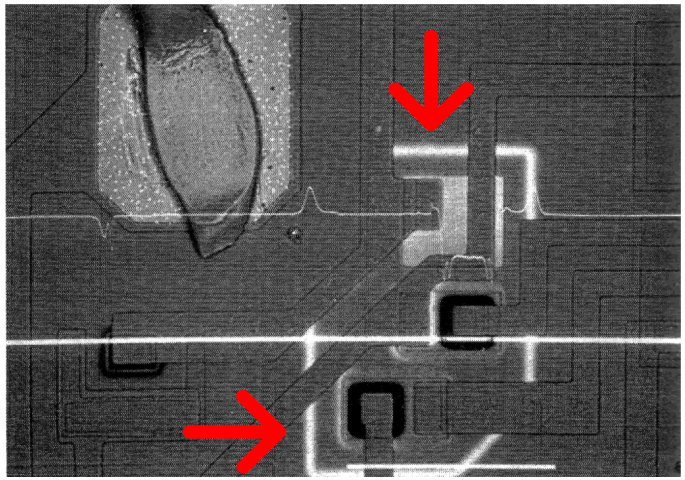
- Signal: Backscattered electrons
  ($\rightarrow$ Solid state diode det.)
- Usage:
  Widely-used imaging technique
- Contrast mechanisms:
  - **Material contrast**
    (Z-contrast)
  - *(Surface tilt contrast)*
  - *(Shadowing contrast)*
  - *(Voltage contrast)*
- Results:
  Spatial distribution of the
  average atomic number Z
- Resolution: $\sim 1\,\mu\mathrm{m}$
  (depends on U_a)



Source: [Flegler et al., 1993]

Electron Beam Induced Current (EBIC)

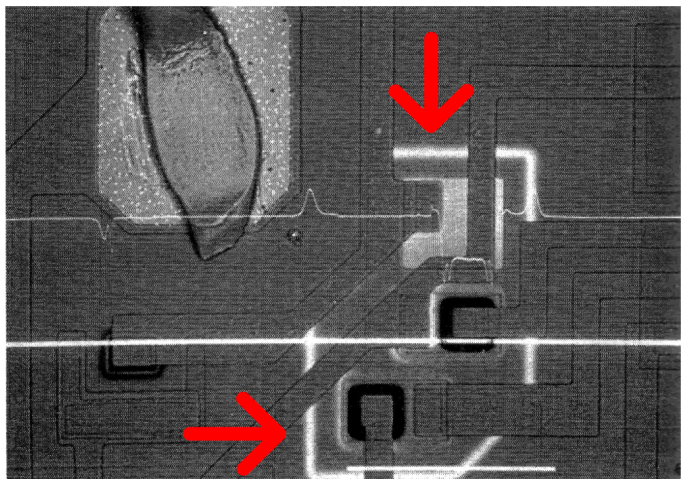
- Signal: Electric current through sample ($\rightarrow$ Picoammeter)
- Usage: Study of semiconductors
- Contrast mechanism:
  - **Depletion** ($\rightarrow$ p-n junctions appear bright)
  - Minority carrier diffusion length L
- Results: Location of depletion regions (p-n junctions)
- Resolution: $\lesssim 1\,\mu\mathrm{m}$ (depends on L)



Source: [Flegler et al., 1993]

Electron Beam Induced Current (EBIC)

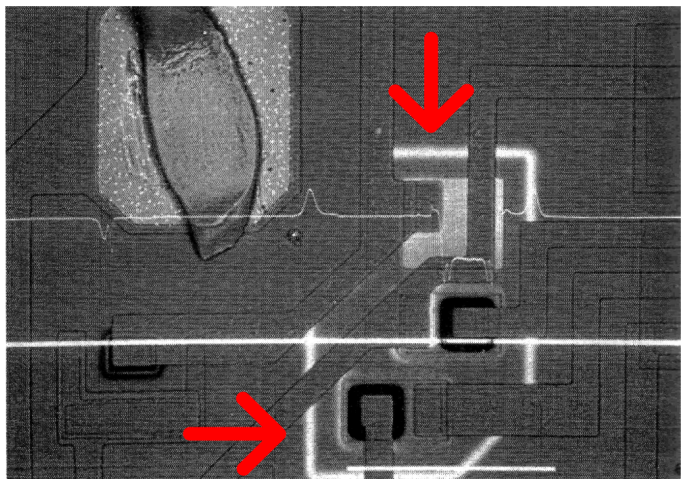
- Signal: Electric current through sample ($\rightarrow$ Picoammeter)
- Usage: Study of semiconductors
- Contrast mechanism:
  - **Depletion** ($\rightarrow$ p-n junctions appear bright)
  - Minority carrier diffusion length L
- Results: Location of depletion regions (p-n junctions)
- Resolution: $\lesssim 1\,\mu\mathrm{m}$ (depends on L)



Source: [Flegler et al., 1993]

Electron Beam Induced Current (EBIC)

- Signal: Electric current through sample ($\rightarrow$ Picoammeter)
- Usage: Study of semiconductors
- Contrast mechanism:
  - **Depletion**
    ($\rightarrow$ p-n junctions appear bright)
  - Minority carrier diffusion length L
- Results:
  Location of depletion regions
  (p-n junctions)
- Resolution: $\lesssim 1\,\mu\mathrm{m}$
  (depends on L)

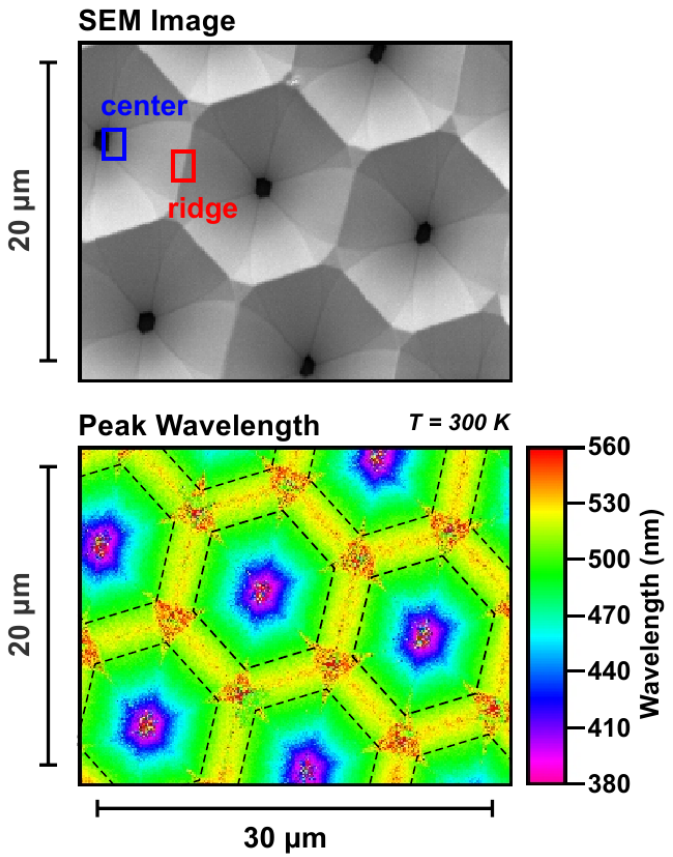


Source: [Flegler et al., 1993]

Cathodoluminescence (CL)

- Signal: Light photons
  ($\rightarrow$ elliptical mirror & PMT)
- Usage: Study composition/growth of semiconductors, minerals and ceramics
- Contrast mechanism:
  - Recombination rate
  - Photon energy

  $\Rightarrow$ **Depends on material**
- Results: Image of **heterogeneities**/defects; laterally resolved **band gap** measurements
- Resolution: $\gtrsim 1\,\mathrm{nm}$

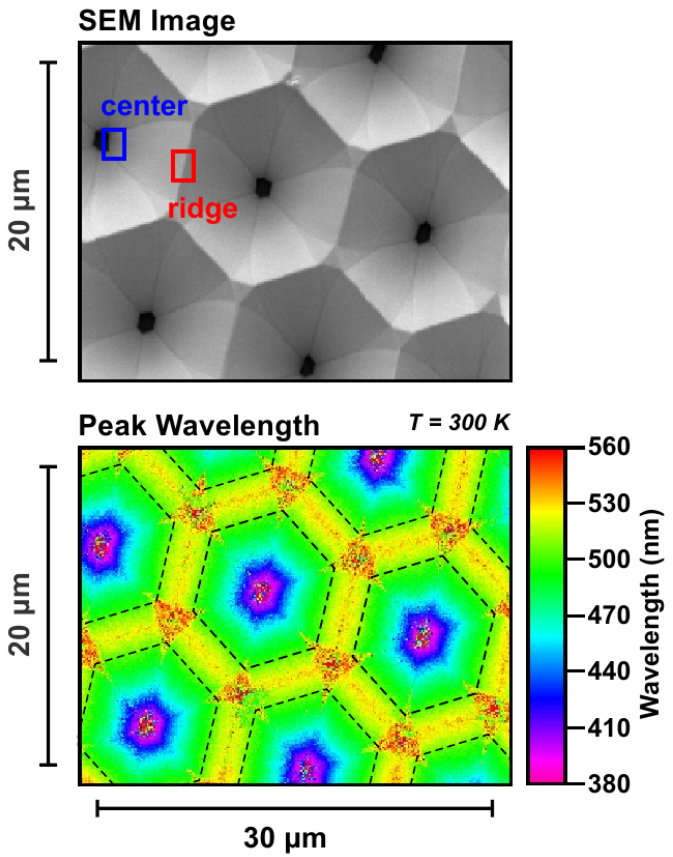


Source: [Metzner, 200X]

Cathodoluminescence (CL)

- Signal: Light photons
  ($\rightarrow$ elliptical mirror & PMT)
- Usage: Study composition/growth of semiconductors, minerals and ceramics
- Contrast mechanism:
  - Recombination rate
  - Photon energy

  $\Rightarrow$ **Depends on material**
- Results: Image of **heterogeneities**/defects; laterally resolved **band gap** measurements
- Resolution: $\gtrsim 1\,\mathrm{nm}$

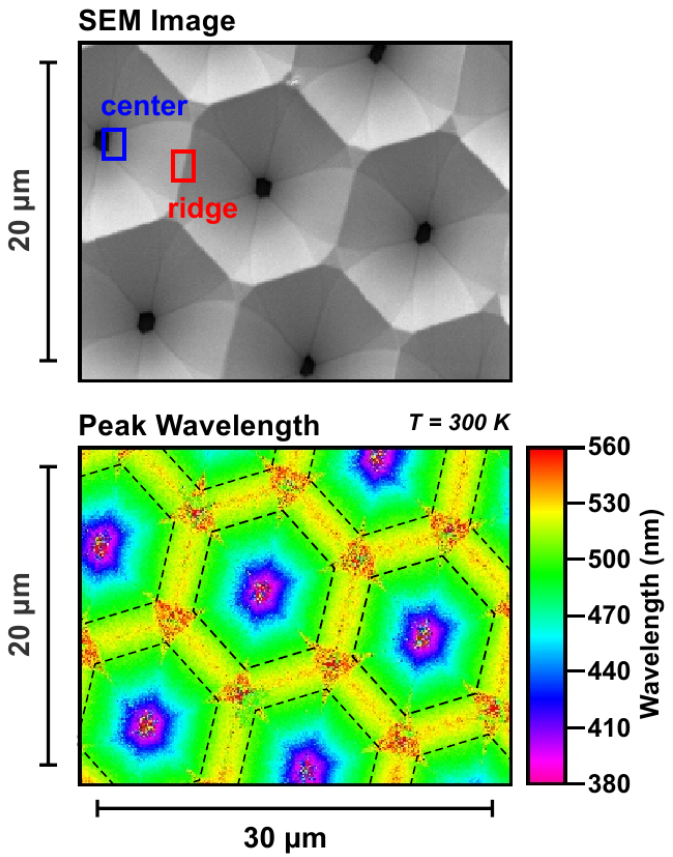


Source: [Metzner, 200X]

Cathodoluminescence (CL)

- Signal: Light photons
  ($\rightarrow$ elliptical mirror & PMT)
- Usage: Study composition/growth of semiconductors, minerals and ceramics
- Contrast mechanism:
  - Recombination rate
  - Photon energy

  $\Rightarrow$ **Depends on material**
- Results: Image of **heterogeneities**/defects; laterally resolved **band gap** measurements
- Resolution: $\gtrsim 1\,\mathrm{nm}$

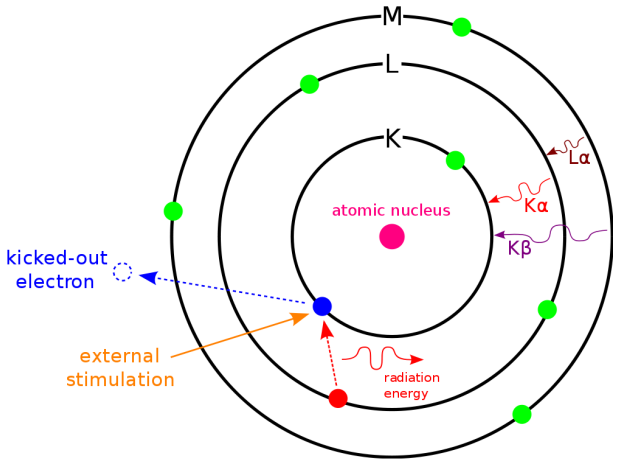


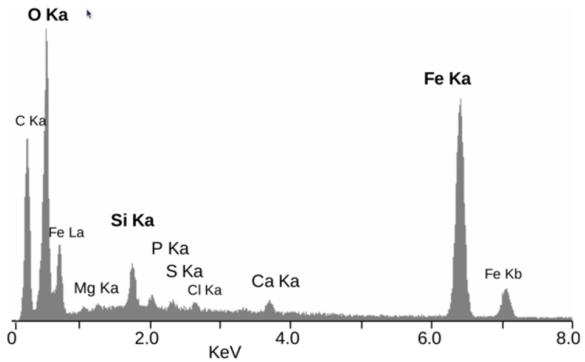
Source: [Metzner, 200X]

X-Ray Fluorescence (EDX)

- Signal: X-ray photons ($\rightarrow$ EDS)
- Usage: Wide range of applications; Study local composition of samples
- Contrast mechanism:
  - Emission rate
  - Photon energy

  $\Rightarrow$ **Depends on material**
- Results: **Spacial distribution** of elements ($\rightarrow$ dot map)
- Resolution: $\sim 5 - 30\,\mu\mathrm{m}$ (depends on material)



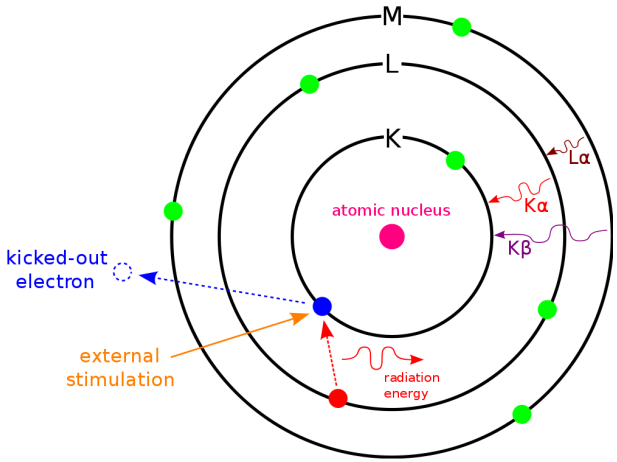


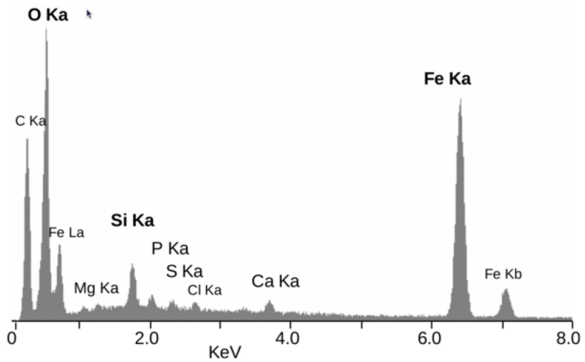
Source: http://en.wikipedia.org/wiki/Energy-dispersive_X-ray_spectroscopy

X-Ray Fluorescence (EDX)

- Signal: X-ray photons ($\rightarrow$ EDS)
- Usage: Wide range of applications; Study local composition of samples
- Contrast mechanism:
  - Emission rate
  - Photon energy

  $\Rightarrow$ **Depends on material**
- Results: **Spacial distribution** of elements ($\rightarrow$ dot map)
- Resolution: $\sim 5 - 30\,\mu\mathrm{m}$ (depends on material)



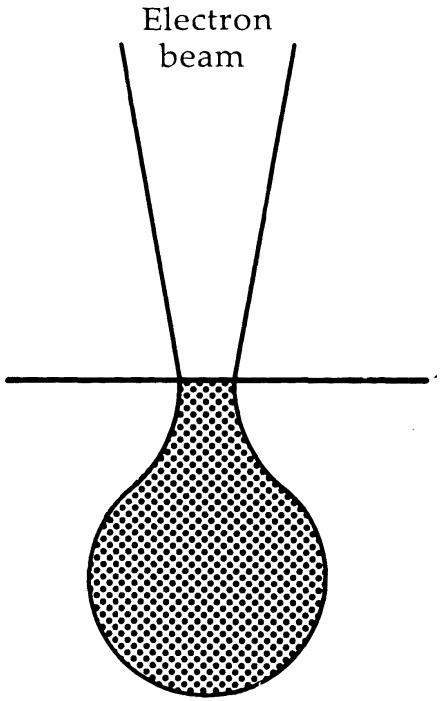


Source: http://en.wikipedia.org/wiki/Energy-dispersive_X-ray_spectroscopy

X-Ray Fluorescence (EDX)

- Signal: X-ray photons ($\rightarrow$ EDS)
- Usage: Wide range of applications; Study local composition of samples
- Contrast mechanism:
  - Emission rate
  - Photon energy

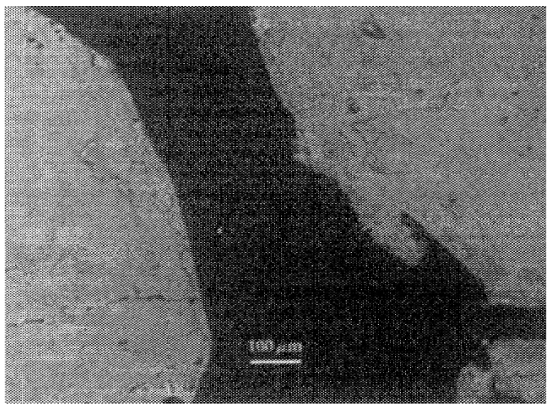
  $\Rightarrow$ **Depends on material**
- Results: **Spacial distribution** of elements ($\rightarrow$ dot map)
- Resolution: $\sim 5 - 30\,\mu\mathrm{m}$ (depends on material)



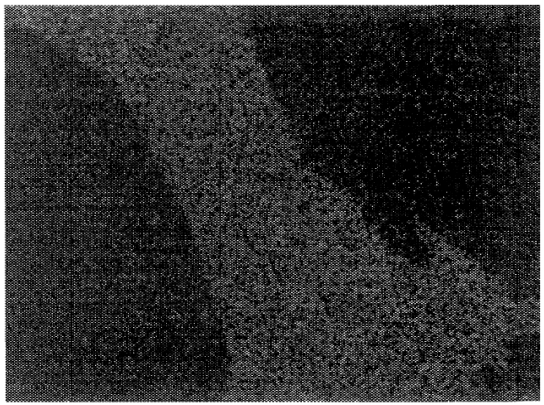
Source: [Flegler et al., 1993]

X-Ray Fluorescence (EDX): Example

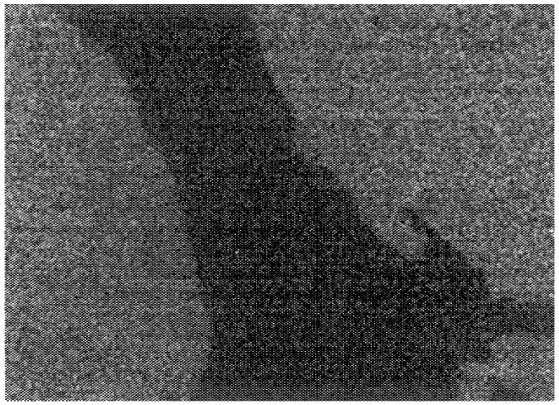
BSEI (left) and X-ray dot maps of Si (middle) and Cr (right).



BSE Image



X-ray dot map (Si)

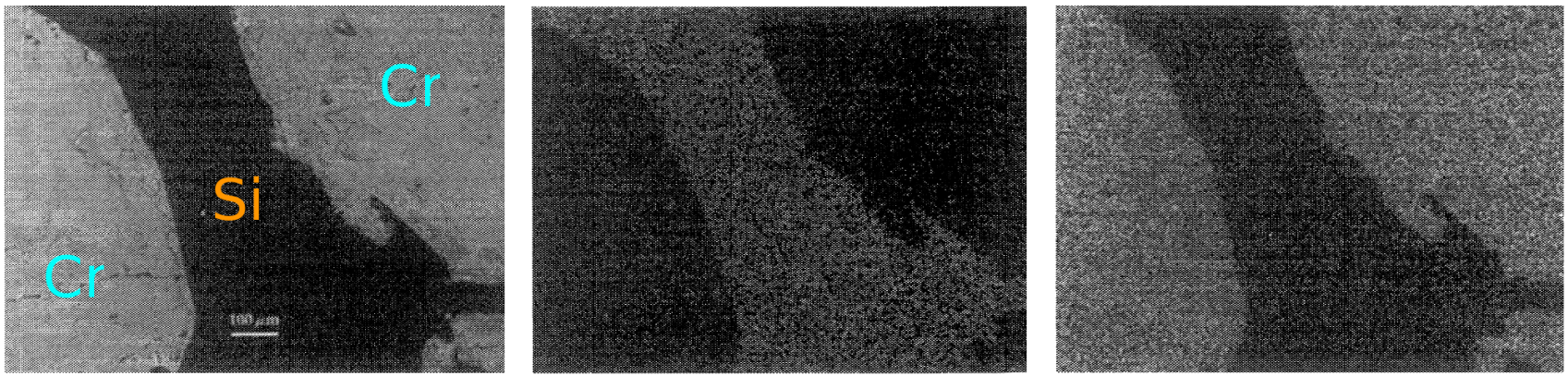


X-ray dot map (Cr)

Source: [Flegler et al., 1993]

X-Ray Fluorescence (EDX): Example

BSEI (left) and X-ray dot maps of Si (middle) and Cr (right).

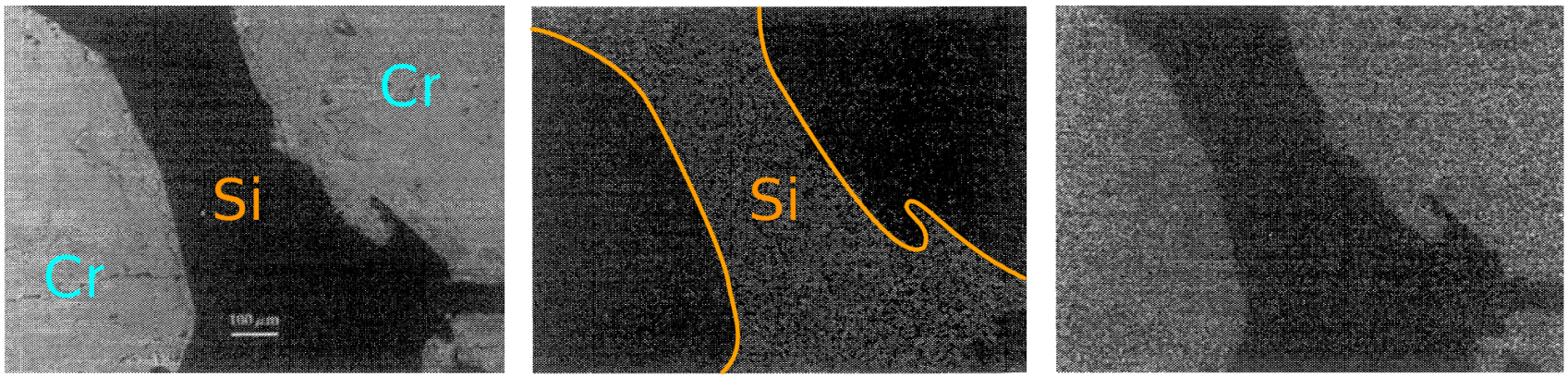


BSE Image | X-ray dot map (Si) | X-ray dot map (Cr)

Source: [Flegler et al., 1993]

X-Ray Fluorescence (EDX): Example

BSEI (left) and X-ray dot maps of Si (middle) and Cr (right).

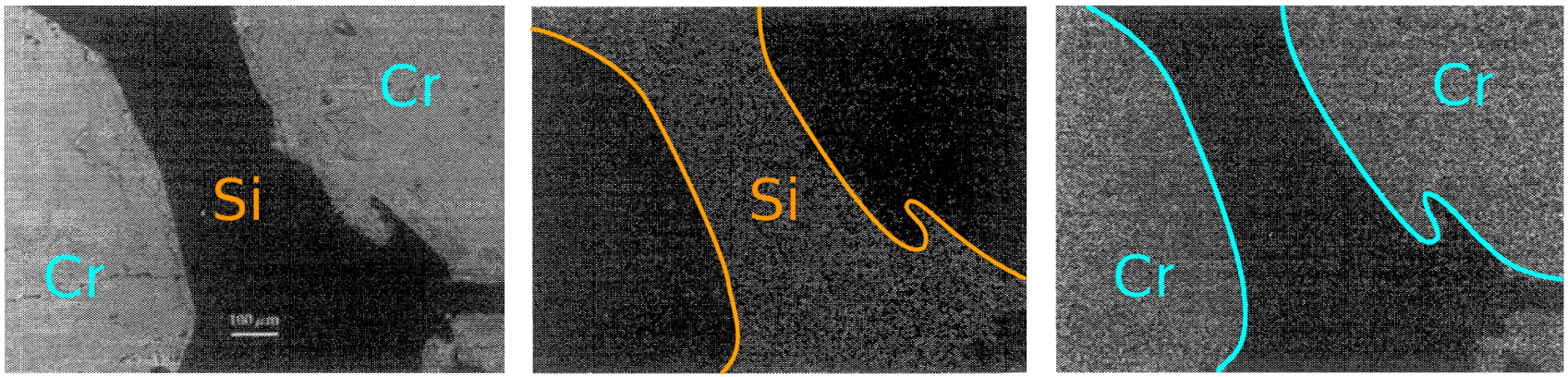


BSE Image | X-ray dot map (Si) | X-ray dot map (Cr)

Source: [Flegler et al., 1993]

X-Ray Fluorescence (EDX): Example

BSEI (left) and X-ray dot maps of Si (middle) and Cr (right).



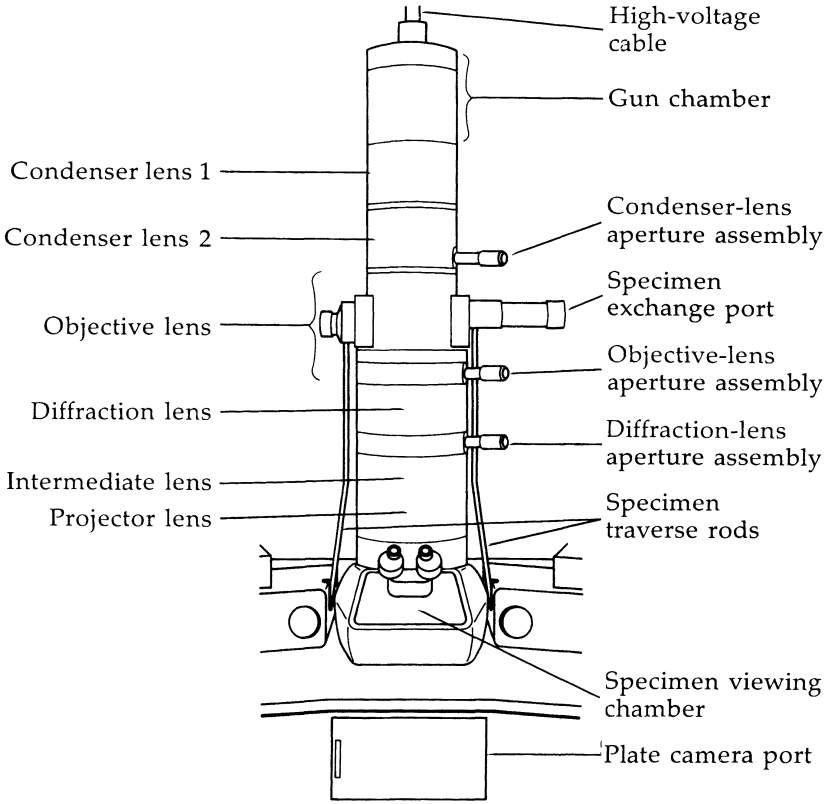
BSE Image | X-ray dot map (Si) | X-ray dot map (Cr)

Source: [Flegler et al., 1993]

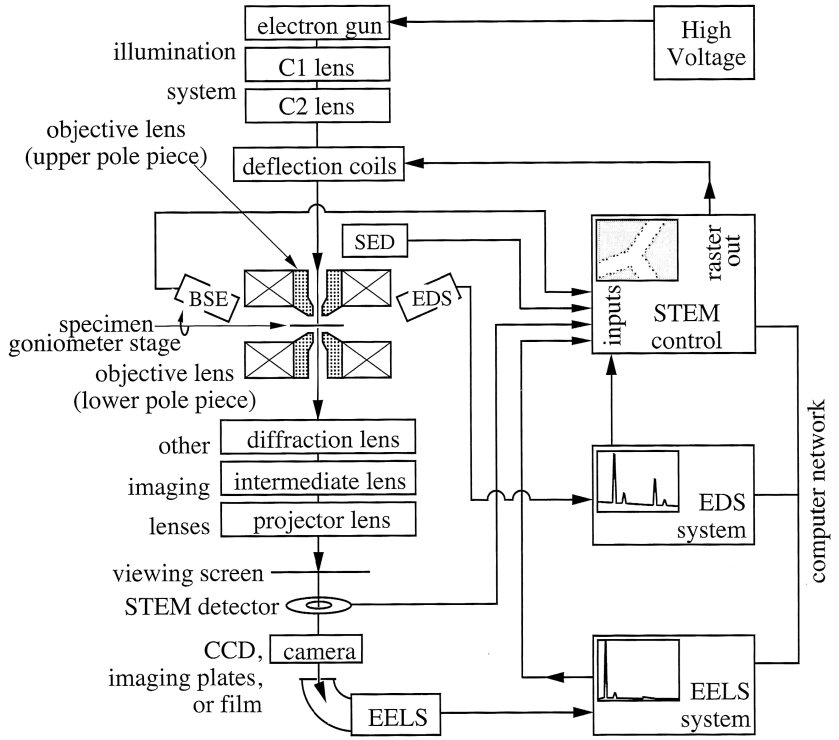
Overview: Transmission Electron Microscopy (TEM)

Overview: Technical Issues

Layout



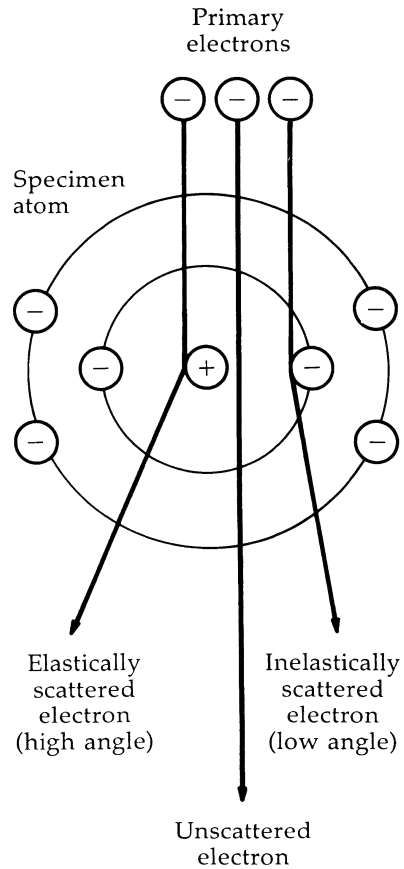
Source: [Flegler et al., 1993]



Source: [Fultz and Howe, 2002]

Electron-Specimen Interaction

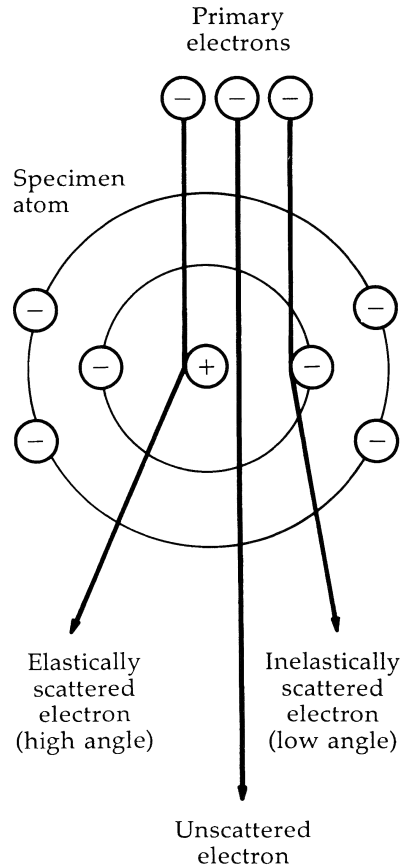
- Possible interactions:
  - Absorption
  - Elastic scattering
  - Inelastic scattering
  - Diffraction
- Absorption: does not contribute significantly to image contrast (cf. optical microscopy)
- Elastic scattering: due to **interactions with nuclei** ($\Rightarrow$ large deviation, little energy loss)
- Inelastic scattering: due to **interactions with electrons** of the specimen ($\Rightarrow$ slight deviation, significant energy loss)



Source: [Flegler et al., 1993]

Electron-Specimen Interaction

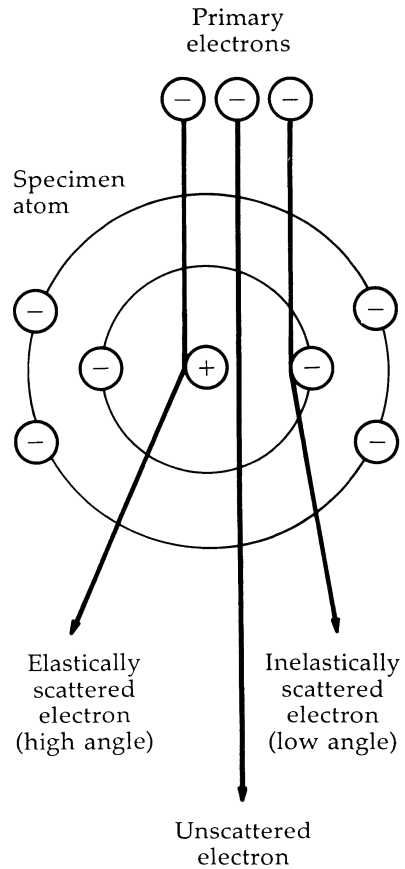
- Possible interactions:
  - Absorption
  - Elastic scattering
  - Inelastic scattering
  - Diffraction
- Absorption: does not contribute significantly to image contrast (cf. optical microscopy)
- Elastic scattering: due to **interactions with nuclei** ($\Rightarrow$ large deviation, little energy loss)
- Inelastic scattering: due to **interactions with electrons** of the specimen ($\Rightarrow$ slight deviation, significant energy loss)



Source: [Flegler et al., 1993]

Electron-Specimen Interaction

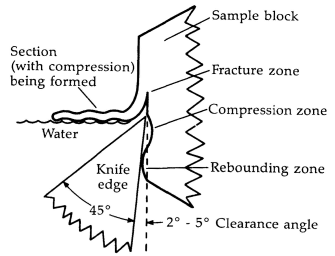
- Possible interactions:
  - Absorption
  - Elastic scattering
  - Inelastic scattering
  - Diffraction
- Absorption: does not contribute significantly to image contrast (cf. optical microscopy)
- Elastic scattering: due to **interactions with nuclei** ($\Rightarrow$ large deviation, little energy loss)
- Inelastic scattering: due to **interactions with electrons** of the specimen ($\Rightarrow$ slight deviation, significant energy loss)

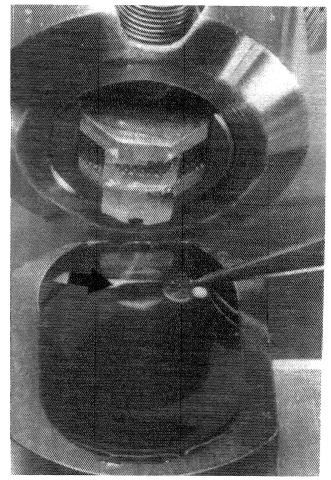


Source: [Flegler et al., 1993]

Sample Preparation

- Only thin ($\lesssim 100\,\mathrm{nm}$) samples can be imaged; often sectioning required (cf. SEM)
- Preparation is often an intricate procedure. Depends on …
  - material (organic samples, semiconductors, ...)
  - and imaging technique/contrast mechanism.
- Preparation techniques:
  - Fixation/Dehydration
  - Staining (heavy metals)
  - Ultrathin sectioning ($\rightarrow$ Microtome)
  - **Mechanical milling** ("Polishing")
  - **Chemical etching**
  - **Ion etching**

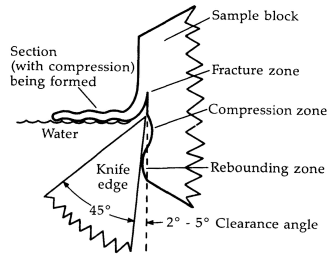


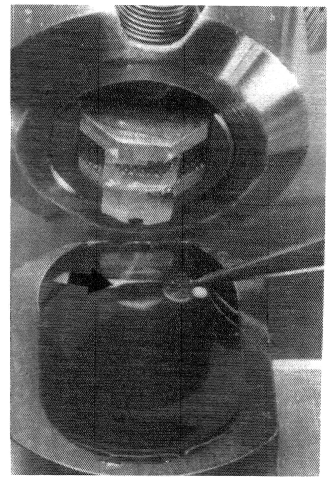


Source: [Flegler et al., 1993]

Sample Preparation

- Only thin ($\lesssim 100\,\mathrm{nm}$) samples can be imaged; often sectioning required (cf. SEM)
- Preparation is often an intricate procedure. Depends on ...
  - material (organic samples, semiconductors, ...)
  - and imaging technique/contrast mechanism.
- Preparation techniques:
  - Fixation/Dehydration
  - Staining (heavy metals)
  - Ultrathin sectioning ($\rightarrow$ Microtome)
  - **Mechanical milling** ("Polishing")
  - **Chemical etching**
  - **Ion etching**

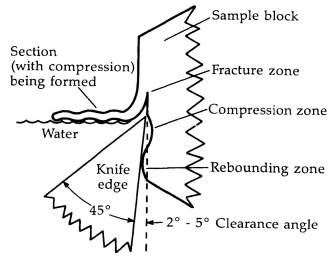


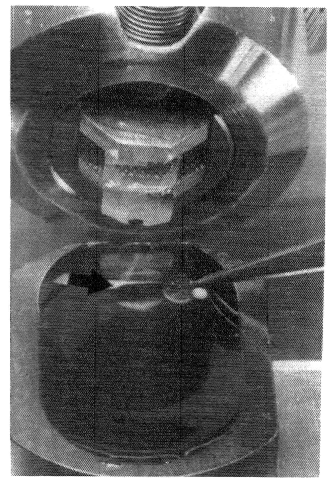


Source: [Flegler et al., 1993]

Sample Preparation

- Only thin ($\lesssim 100\,\mathrm{nm}$) samples can be imaged; often sectioning required (cf. SEM)
- Preparation is often an intricate procedure. Depends on ...
  - material (organic samples, semiconductors, ...)
  - and imaging technique/contrast mechanism.
- Preparation techniques:
  - Fixation/Dehydration
  - Staining (heavy metals)
  - Ultrathin sectioning ($\rightarrow$ Microtome)
  - **Mechanical milling** ("Polishing")
  - **Chemical etching**
  - **Ion etching**

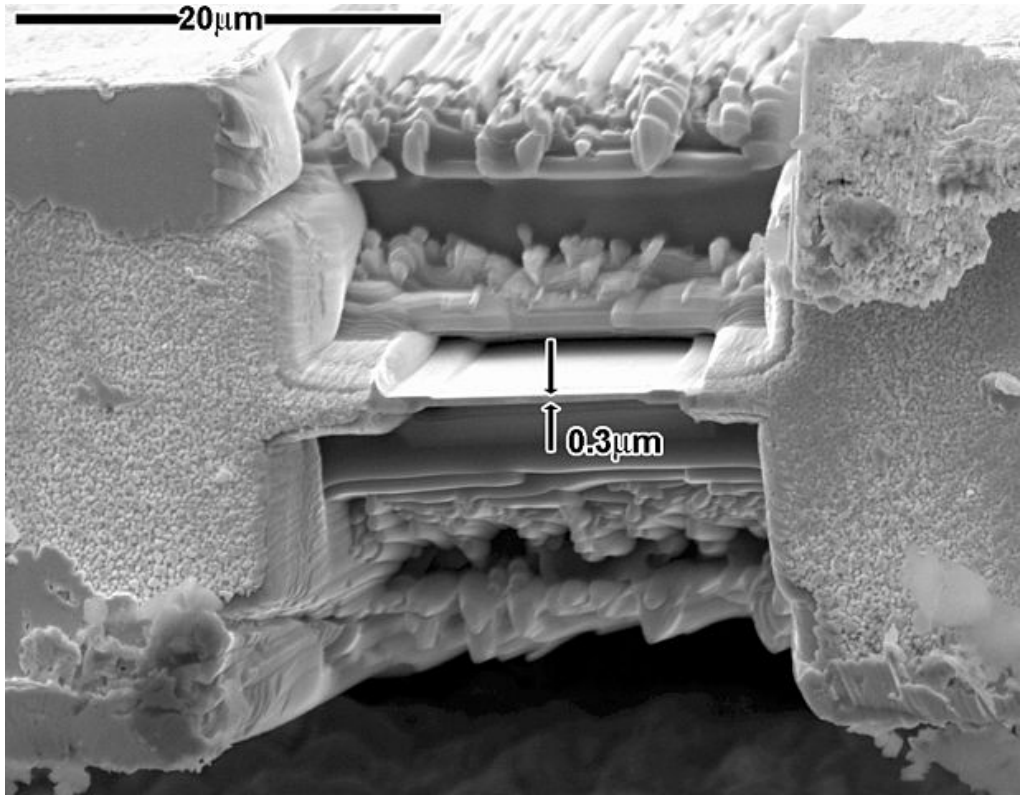




Source: [Flegler et al., 1993]

Sample Preparation: Example

Prepared TEM sample, milled by a focused ion beam.

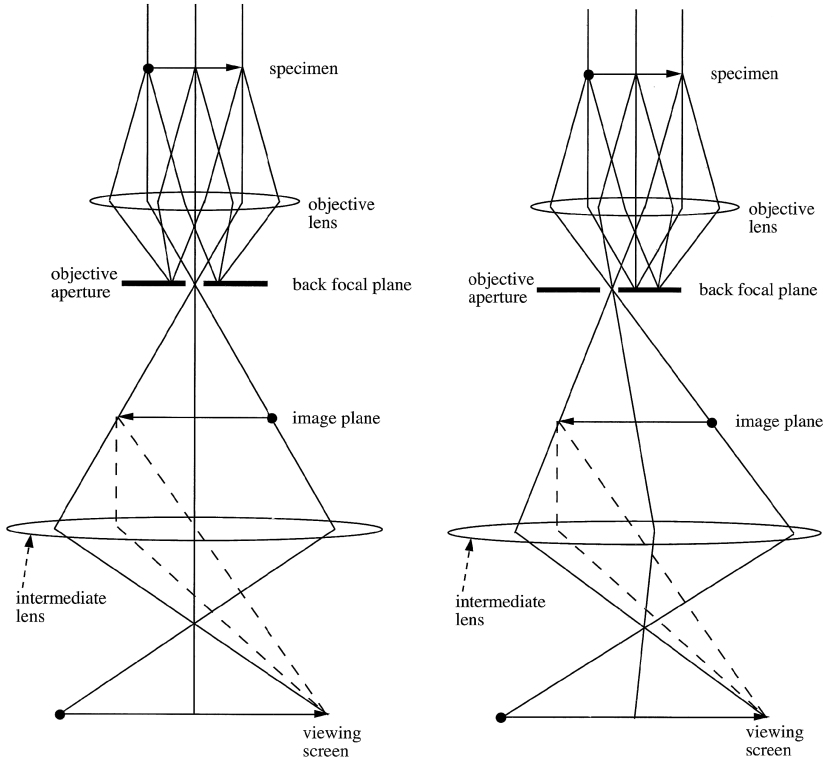


Source: http://en.wikipedia.org/wiki/Transmission_electron_microscopy

Overview: Operation Modes and Contrast Mechanisms

Bright-Field (BF) & Dark-Field (DF) Imaging

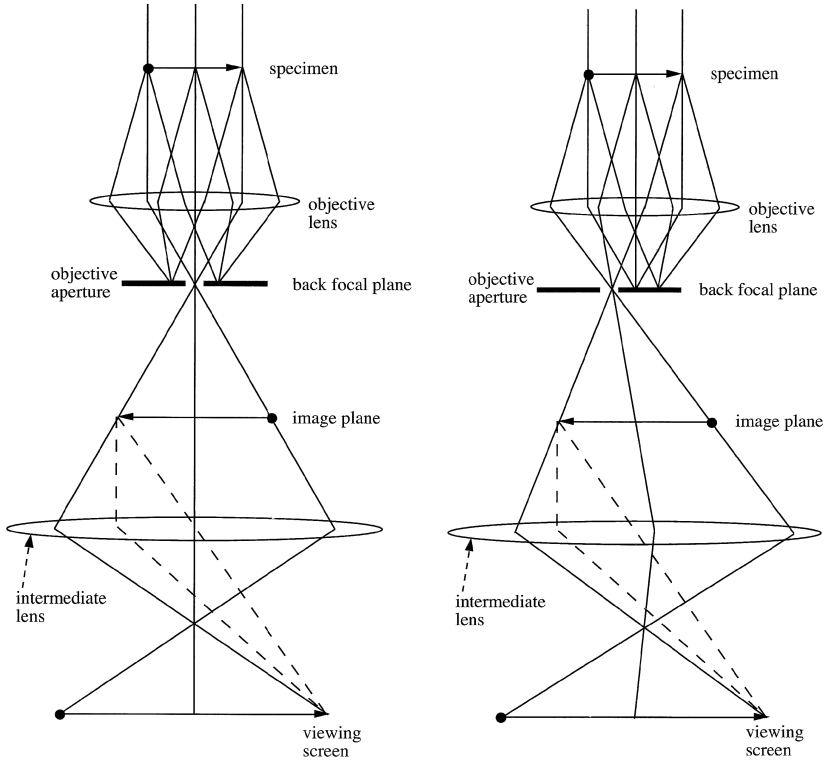
- Conventional imaging modes of TEM
- Setup: Intermediate lens focused on the **image plane** of the objective lens.
- Without objective aperture: little contrast ($\rightarrow$ Mass-thickness contrast)
- With objective aperture in **back focal plane**: Only electrons diffracted by a specific angle contribute to the image.
- *k*-space truncation
  $\Rightarrow$ **No atomic resolution possible**



Source: [Fultz and Howe, 2002]

Bright-Field (BF) & Dark-Field (DF) Imaging

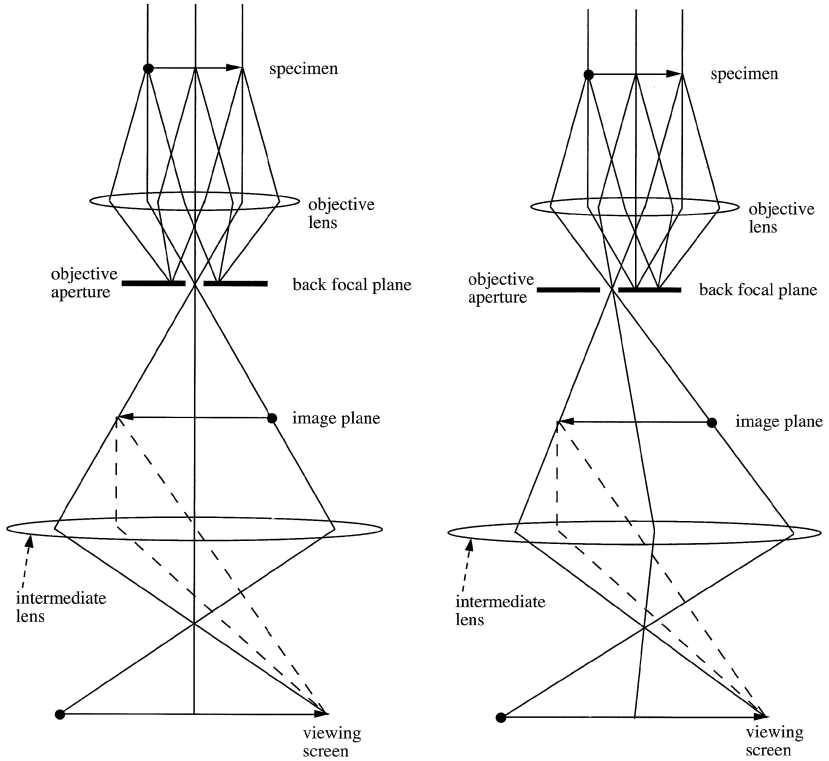
- Conventional imaging modes of TEM
- Setup: Intermediate lens focused on the **image plane** of the objective lens.
- Without objective aperture: little contrast ($\rightarrow$ Mass-thickness contrast)
- With objective aperture in **back focal plane**: Only electrons diffracted by a specific angle contribute to the image.
- *k*-space truncation
  $\Rightarrow$ **No atomic resolution possible**



Source: [Fultz and Howe, 2002]

Bright-Field (BF) & Dark-Field (DF) Imaging

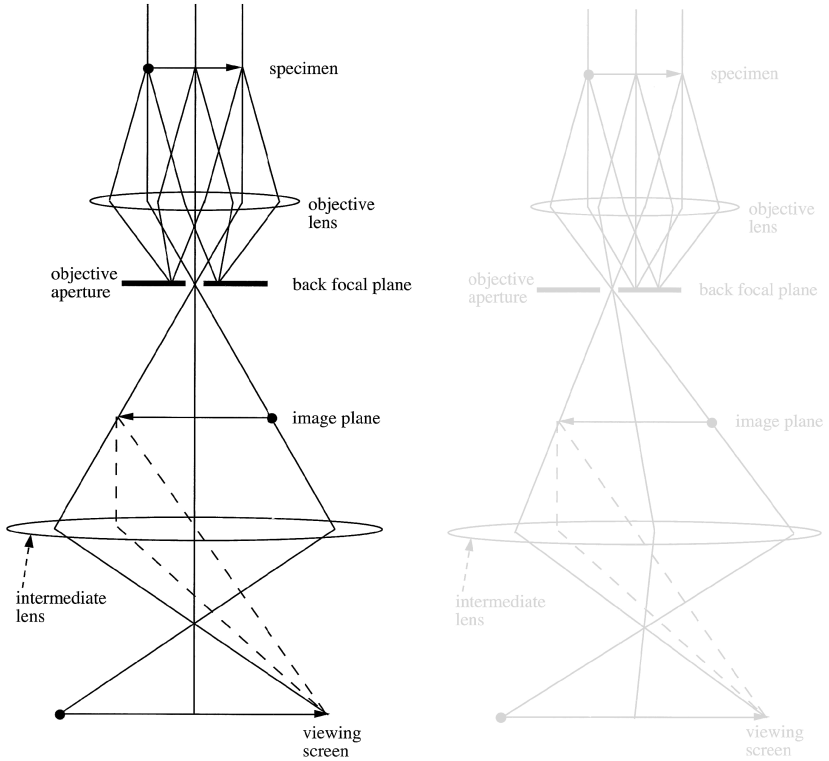
- Conventional imaging modes of TEM
- Setup: Intermediate lens focused on the **image plane** of the objective lens.
- Without objective aperture: little contrast ($\rightarrow$ Mass-thickness contrast)
- With objective aperture in **back focal plane**: Only electrons diffracted by a specific angle contribute to the image.
- *k*-space truncation
  $\Rightarrow$ **No atomic resolution possible**



Source: [Fultz and Howe, 2002]

Bright-Field (BF) & Dark-Field (DF) Imaging

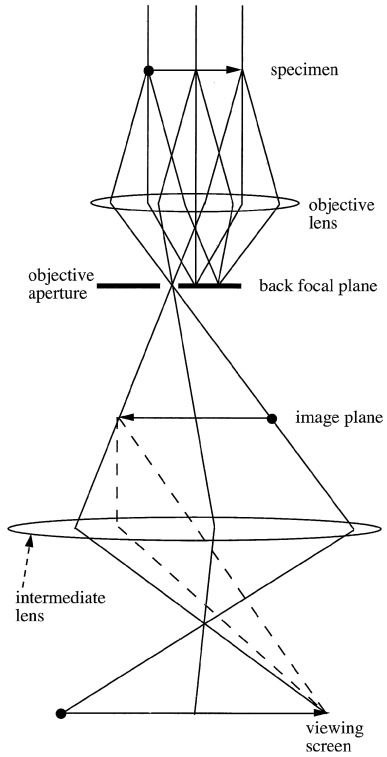
- Bright-field image:
  Transmitted electrons pass.
  - Mass-thickness contrast
    (⇒ areas with heavy atoms/ thick regions: dark)
  - Diffraction contrast
    (⇒ crystalline areas : dark)
  - Areas without sample ⇒ **bright**
- Dark-field image:
  Diffracted electrons pass.
  - Diffraction contrast
    (sensitive for lattice defects)
  - Areas without sample ⇒ **dark**



Source: [Fultz and Howe, 2002]

Bright-Field (BF) & Dark-Field (DF) Imaging

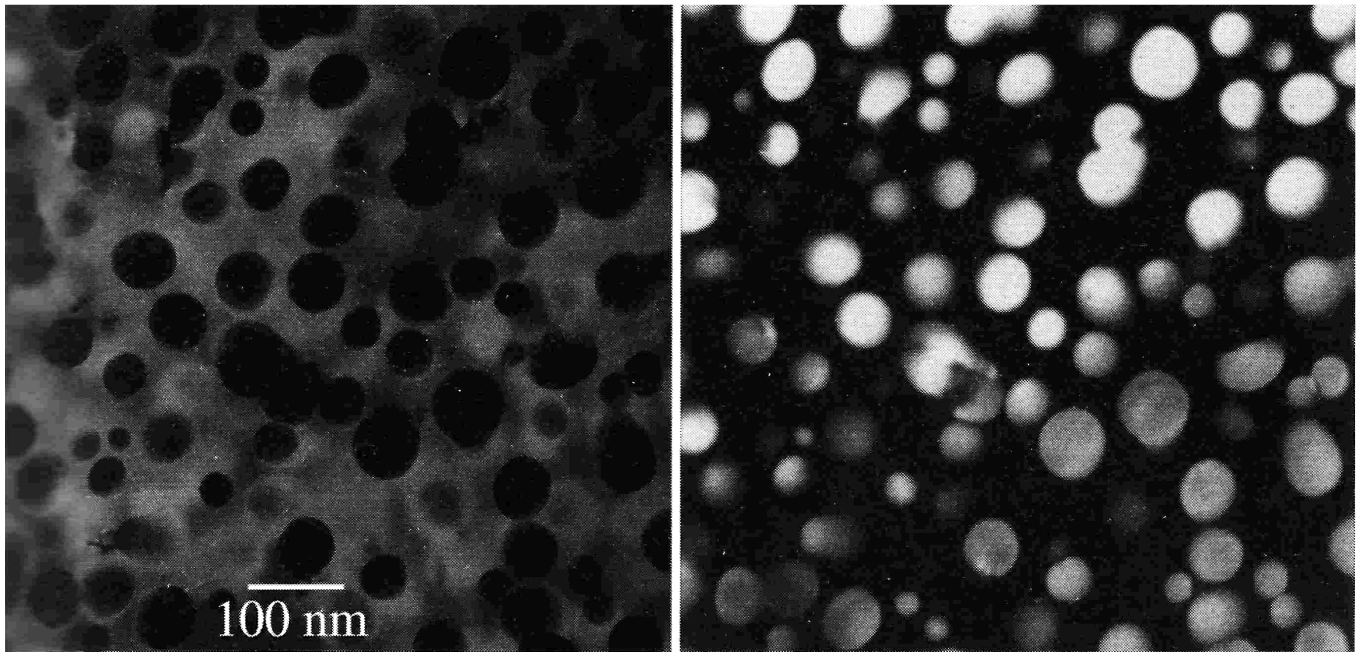
- Bright-field image:
  Transmitted electrons pass.
  - Mass-thickness contrast
    ($\Rightarrow$ areas with heavy atoms/ thick regions: dark)
  - Diffraction contrast
    ($\Rightarrow$ crystalline areas : dark)
  - Areas without sample $\Rightarrow$ **bright**
- Dark-field image:
  Diffracted electrons pass.
  - Diffraction contrast
    (sensitive for lattice defects)
  - Areas without sample $\Rightarrow$ **dark**



Source: [Fultz and Howe, 2002]

Bright-Field (BF) & Dark-Field (DF) Imaging: Example

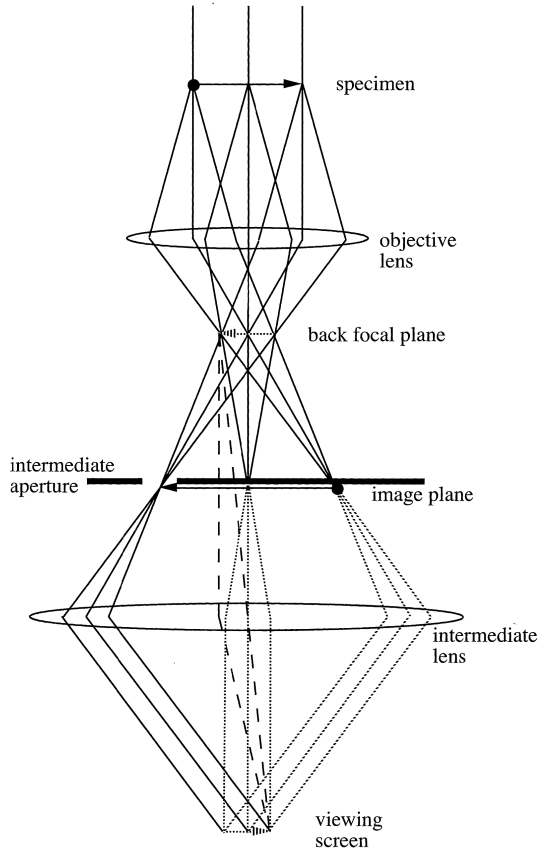
BF (left) versus DF (right) images of an Al-Li alloy.



Source: [Fultz and Howe, 2002]

Selected Area Diffraction (SAD)

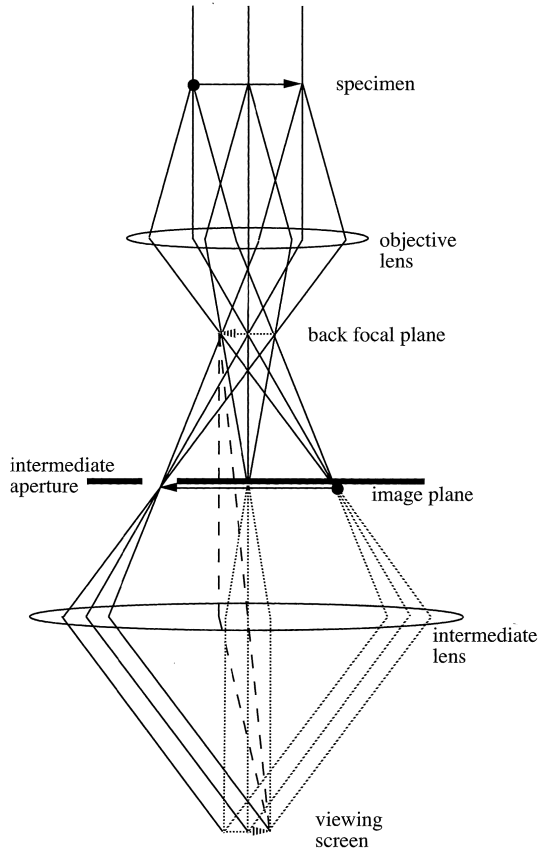
- Conventional imaging mode of TEM
- Setup: Intermediate lens focused on the **back focal plane** of the objective lens.
- Without intermediate aperture: Diffraction pattern of whole sample
- With intermediate aperture in **image plane**: Only electrons from the selected region contribute to the diffraction pattern ($\rightarrow$ SAD).
- Usage: Analysis of **polycrystalline** specimens / lattice defects; preparation for DF imaging



Source: [Fultz and Howe, 2002]

Selected Area Diffraction (SAD)

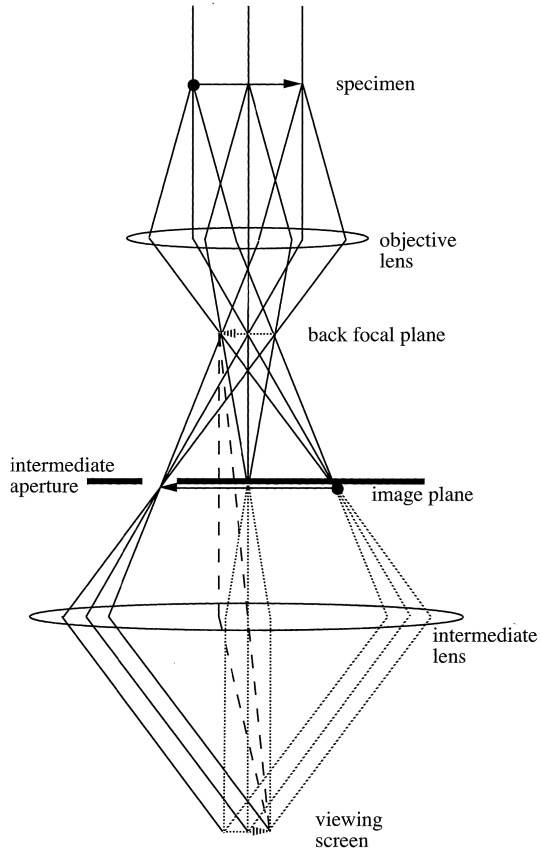
- Conventional imaging mode of TEM
- Setup: Intermediate lens focused on the **back focal plane** of the objective lens.
- Without intermediate aperture: Diffraction pattern of whole sample
- With intermediate aperture in **image plane**: Only electrons from the selected region contribute to the diffraction pattern ($\rightarrow$ SAD).
- Usage: Analysis of **polycrystalline** specimens / lattice defects; preparation for DF imaging



Source: [Fultz and Howe, 2002]

Selected Area Diffraction (SAD)

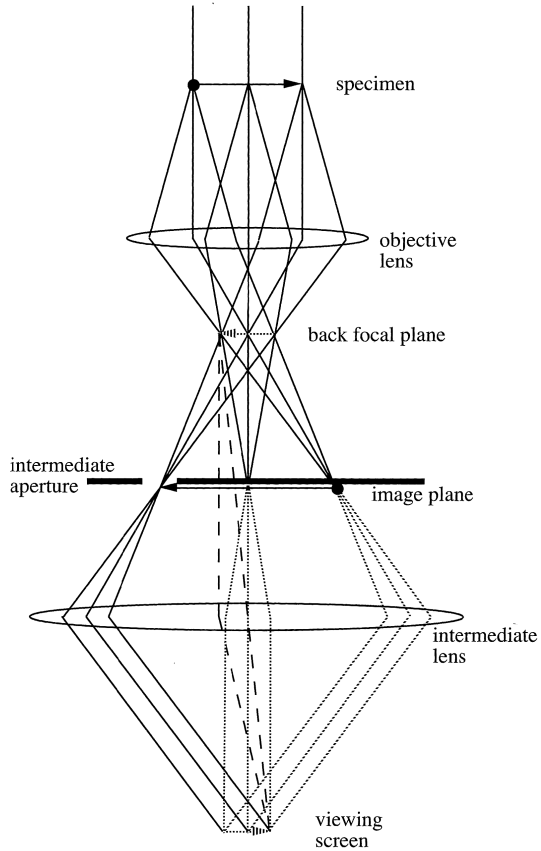
- Conventional imaging mode of TEM
- Setup: Intermediate lens focused on the **back focal plane** of the objective lens.
- Without intermediate aperture: Diffraction pattern of whole sample
- With intermediate aperture in **image plane**: Only electrons from the selected region contribute to the diffraction pattern ($\rightarrow$ SAD).
- Usage: Analysis of **polycrystalline** specimens / lattice defects; preparation for DF imaging



Source: [Fultz and Howe, 2002]

Selected Area Diffraction (SAD)

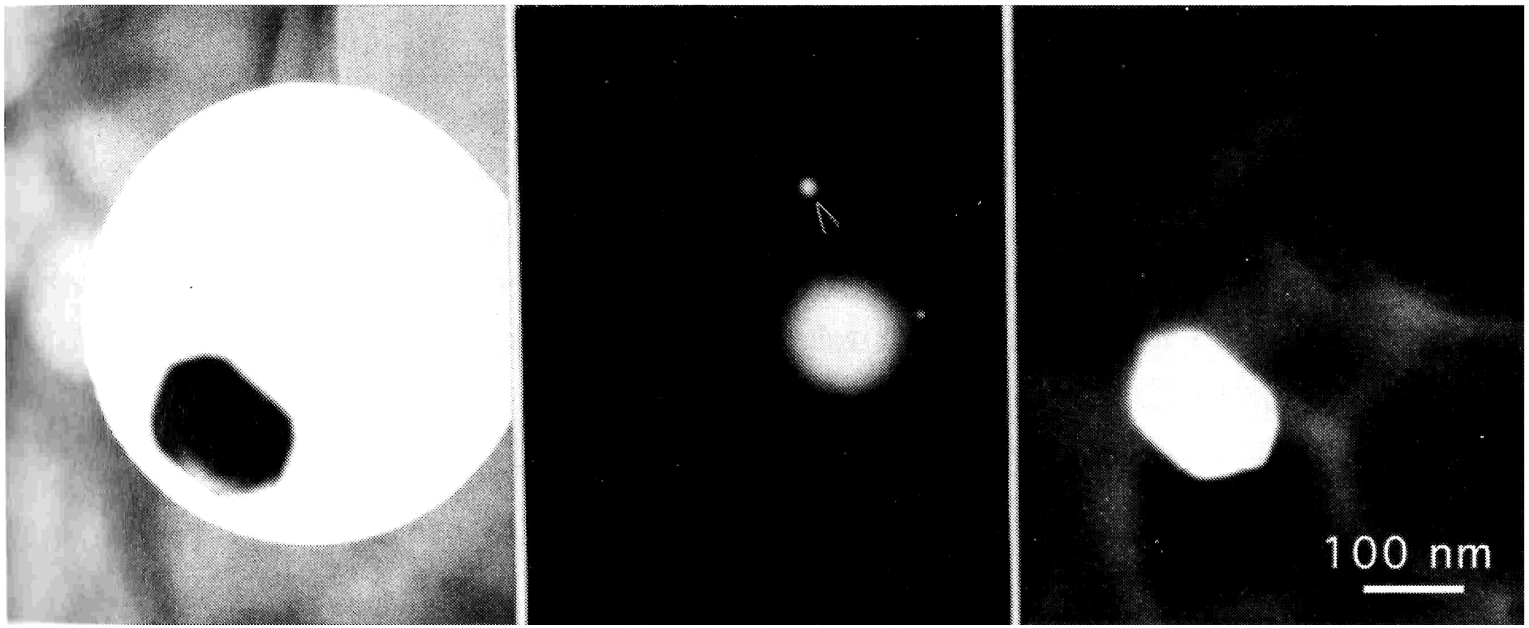
- Conventional imaging mode of TEM
- Setup: Intermediate lens focused on the **back focal plane** of the objective lens.
- Without intermediate aperture: Diffraction pattern of whole sample
- With intermediate aperture in **image plane**: Only electrons from the selected region contribute to the diffraction pattern ($\rightarrow$ SAD).
- Usage: Analysis of **polycrystalline** specimens / lattice defects; preparation for DF imaging



Source: [Fultz and Howe, 2002]

Selected Area Diffraction (SAD): Example

BF image of $Al_{12}Mn$ with SAD aperture (left), SAD image (middle) and DF image of the marked diffraction spot (right).



Source: [Fultz and Howe, 2002]

High-Resolution Imaging (HRTEM)

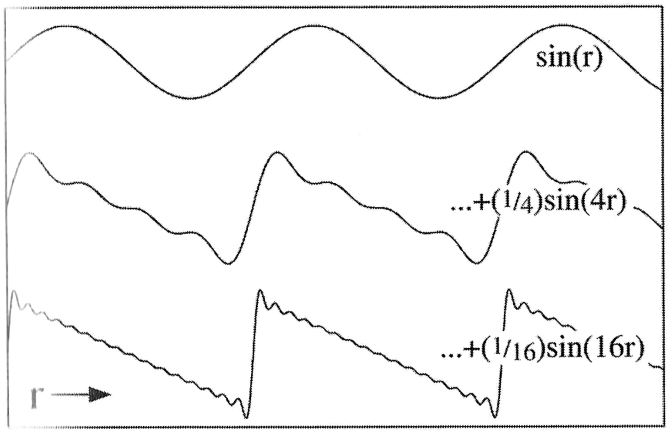
- Highest TEM resolution: $\gtrsim 0.05\,\mathrm{nm}$
- Setup: Intermediate lens focused on the **image plane** of the objective lens.
- Objective aperture in **image plane**: Large ($\Rightarrow$ transmitted and diffracted beam included)
- Phase contrast: **Interference** of transmitted and diffracted electrons
- Interpretation: Intricate. **Simulation** of specimen and microscope required.
- Usage: Analysis of crystallographic structures/defects and interfaces

High-Resolution Imaging (HRTEM)

- Highest TEM resolution: $\gtrsim 0.05\,\mathrm{nm}$
- Setup: Intermediate lens focused on the **image plane** of the objective lens.
- Objective aperture in **image plane**: Large ($\Rightarrow$ transmitted and diffracted beam included)
- Phase contrast: **Interference** of transmitted and diffracted electrons
- Interpretation: Intricate. **Simulation** of specimen and microscope required.
- Usage: Analysis of crystallographic structures/defects and interfaces

High-Resolution Imaging (HRTEM)

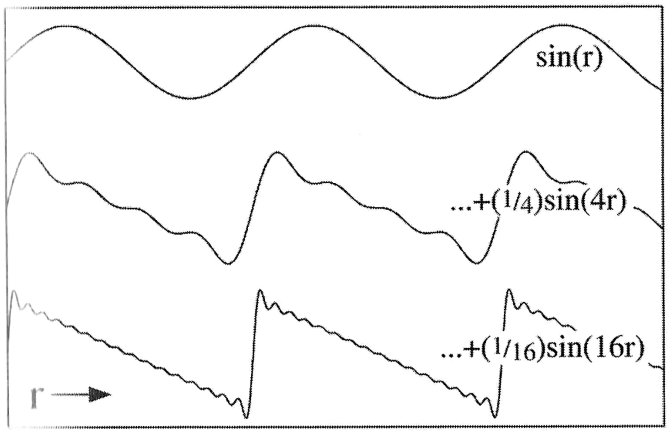
- Highest TEM resolution: $\gtrsim 0.05\,\mathrm{nm}$
- Setup: Intermediate lens focused on the **image plane** of the objective lens.
- Objective aperture in **image plane**: Large ($\Rightarrow$ transmitted and diffracted beam included)
- Phase contrast: **Interference** of transmitted and diffracted electrons
- Interpretation: Intricate. **Simulation** of specimen and microscope required.
- Usage: Analysis of crystallographic structures/defects and interfaces



Source: [Fultz and Howe, 2002]

High-Resolution Imaging (HRTEM)

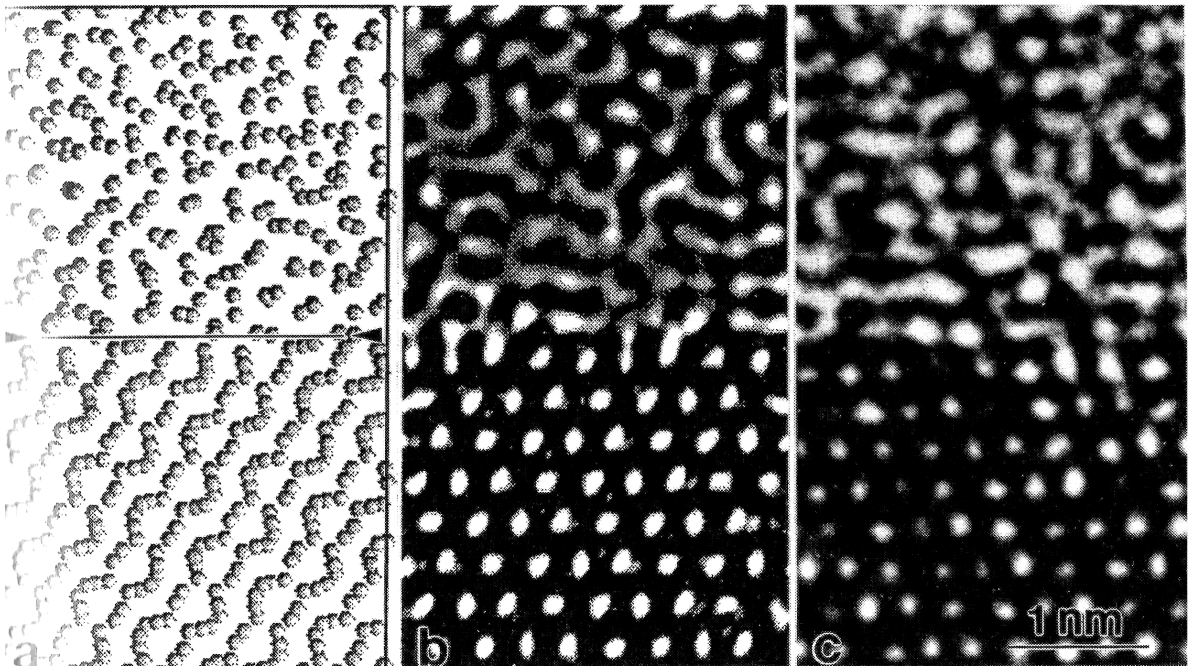
- Highest TEM resolution: $\gtrsim 0.05\,\mathrm{nm}$
- Setup: Intermediate lens focused on the **image plane** of the objective lens.
- Objective aperture in **image plane**: Large ($\Rightarrow$ transmitted and diffracted beam included)
- Phase contrast: **Interference** of transmitted and diffracted electrons
- Interpretation: Intricate. **Simulation** of specimen and microscope required.
- Usage: Analysis of crystallographic structures/defects and interfaces



Source: [Fultz and Howe, 2002]

High-Resolution Imaging (HRTEM): Example

Interface of crystalline $\mathrm{Pd_3Si}$ and amorphous $\mathrm{Pd_{80}Si_{20}}$
(Left: atomic model, Middle: simulation, Right: HRTEM image).



Source: [Fultz and Howe, 2002]

High-Resolution Imaging (HRTEM): DALI

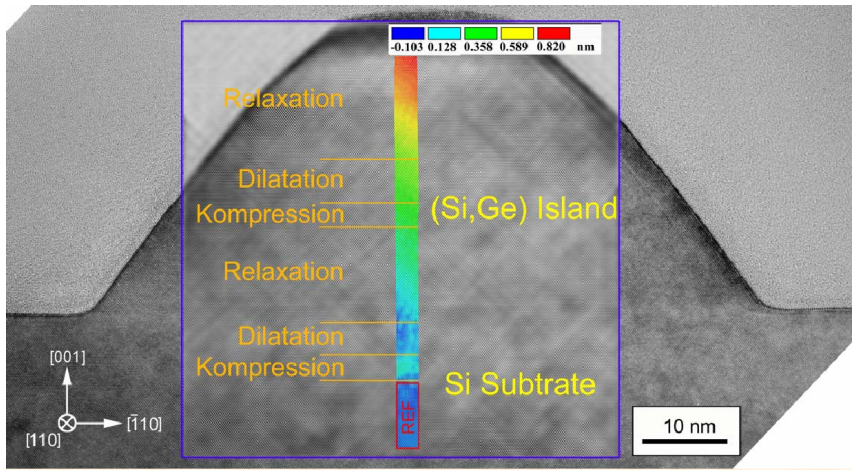
DALI = Digital Analysis of Lattice Images

- Digital analysis of HRTEM images:
  1. Detection of lattice sites
  2. Calculation of reference lattice
  3. Calculation of displacements
- Result: Vector field of lattice deformation
- Vegard's law $\Rightarrow$ Concentration map
- Application: Analysis of quantum dots/wells (cross-section)

High-Resolution Imaging (HRTEM): DALI

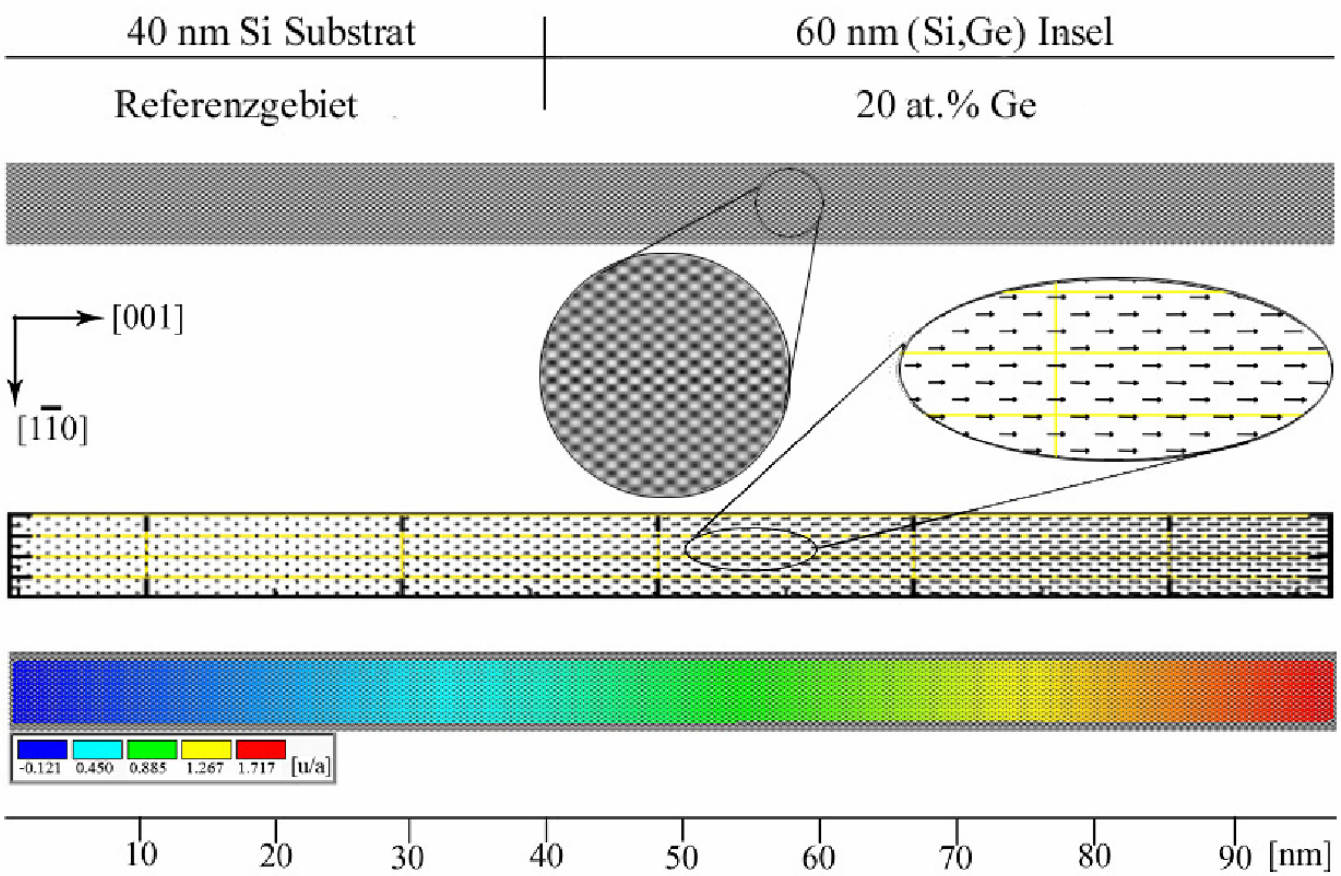
DALI = Digital Analysis of Lattice Images

- Digital analysis of HRTEM images:
  1. Detection of lattice sites
  2. Calculation of reference lattice
  3. Calculation of displacements
- Result: Vector field of lattice deformation
- Vegard's law $\Rightarrow$ Concentration map
- Application: Analysis of quantum dots/wells (cross-section)



Source: http://crysta.physik.hu-berlin.de/~ines/freiburg_2006_dgk/haeusler_vortrag_dgk_2006_freiburg.pdf

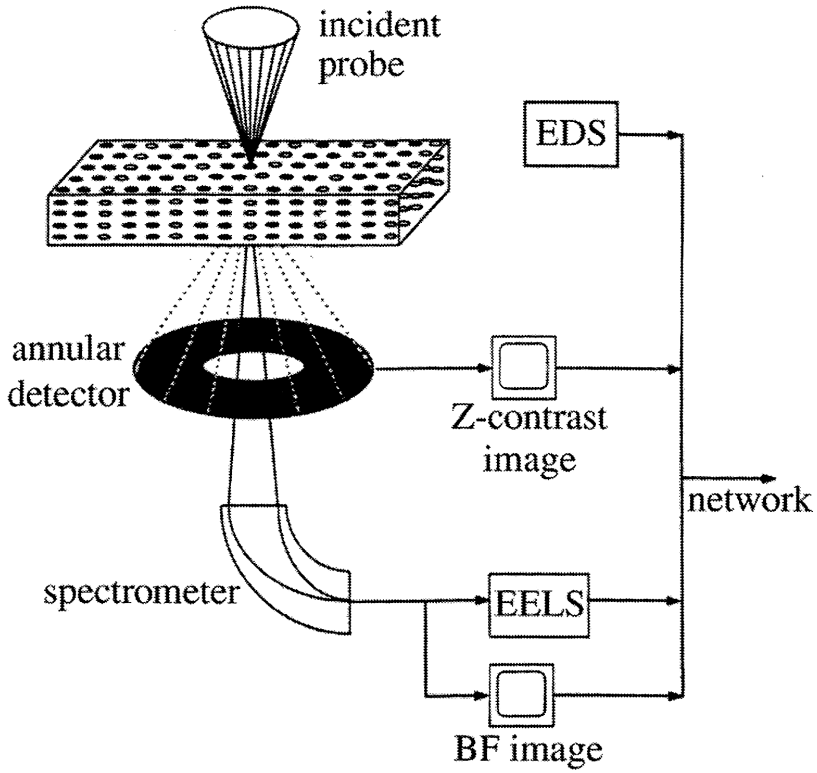
High-Resolution Imaging (HRTEM): DALI - Example



Source: http://crysta.physik.hu-berlin.de/~ines/freiburg_2006_dgk/haeusler_vortrag_dgk_2006_freiburg.pdf

High-Angle Annular Dark-Field (HAADF)

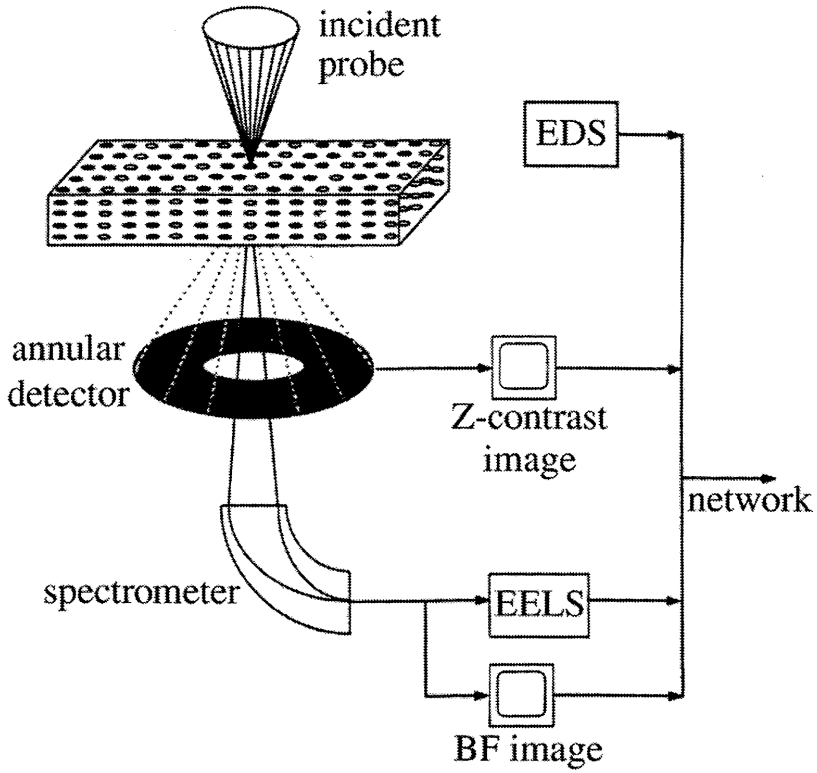
- High resolution imaging: $\sim 0.1\,\mathrm{nm}$
- Setup: **STEM** with annular detector
- Signal: high-angle ($\sim 6\,^\circ$) **incoherent** elastically scattered electrons (cf. HRTEM)
- Z-contrast: Scattering depends strongly on atomic number Z.
- Image: Atomic-resolution compositional map
- Allows parallel EELS measurement.



Source: [Fultz and Howe, 2002]

High-Angle Annular Dark-Field (HAADF)

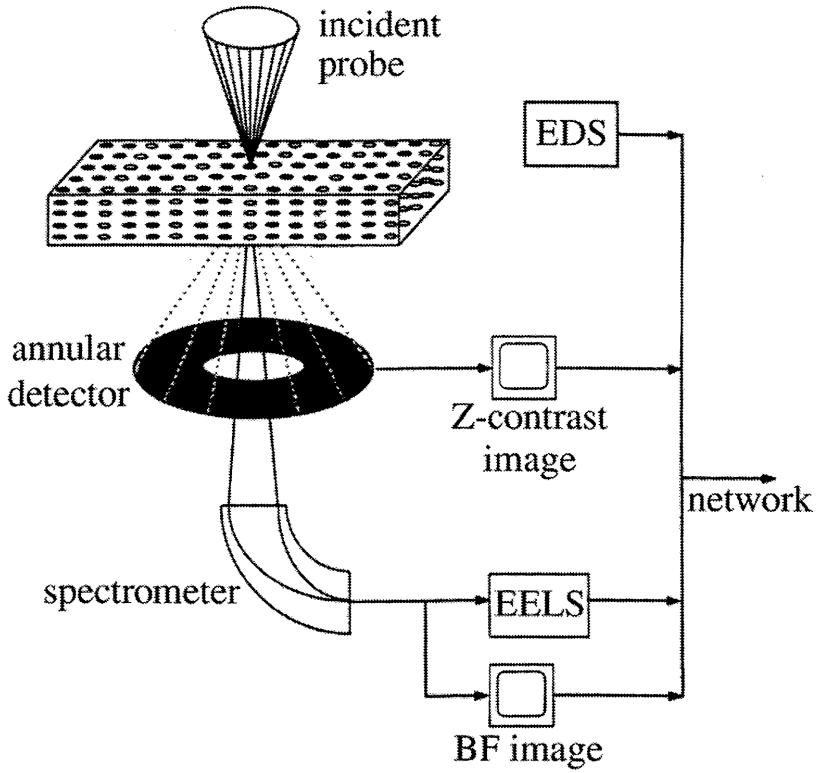
- High resolution imaging: $\sim 0.1\,\mathrm{nm}$
- Setup: **STEM** with annular detector
- Signal: high-angle ($\sim 6\,^\circ$) **incoherent** elastically scattered electrons (cf. HRTEM)
- Z-contrast: Scattering depends strongly on atomic number Z.
- Image: Atomic-resolution compositional map
- Allows parallel EELS measurement.



Source: [Fultz and Howe, 2002]

High-Angle Annular Dark-Field (HAADF)

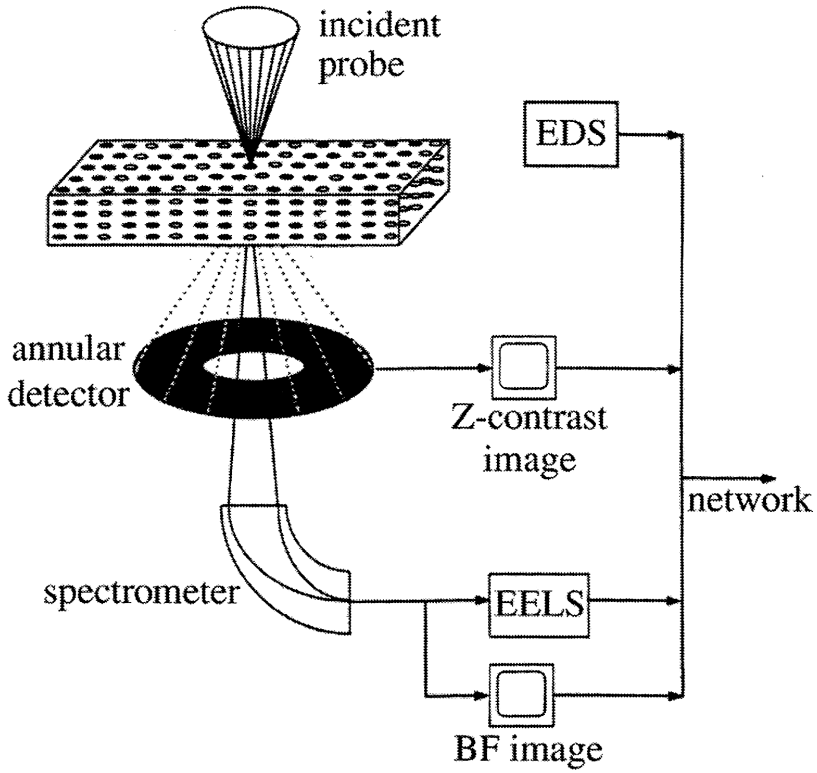
- High resolution imaging: $\sim 0.1\,\mathrm{nm}$
- Setup: **STEM** with annular detector
- Signal: high-angle ($\sim 6\,^\circ$) **incoherent** elastically scattered electrons (cf. HRTEM)
- Z-contrast: Scattering depends strongly on atomic number Z.
- Image: Atomic-resolution compositional map
- Allows parallel EELS measurement.



Source: [Fultz and Howe, 2002]

High-Angle Annular Dark-Field (HAADF)

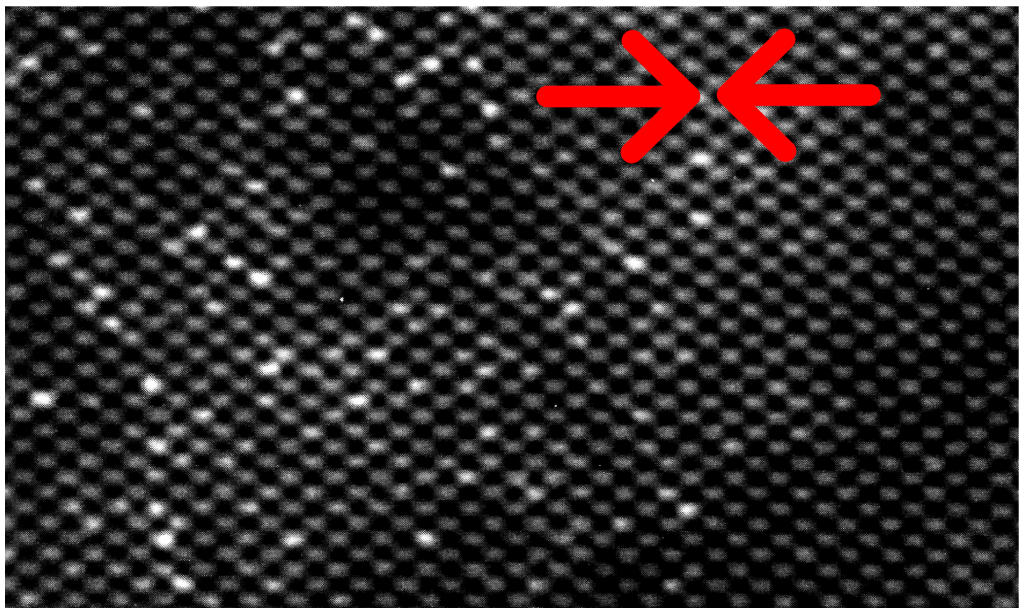
- High resolution imaging: $\sim 0.1\,\mathrm{nm}$
- Setup: **STEM** with annular detector
- Signal: high-angle ($\sim 6\,^\circ$) **incoherent** elastically scattered electrons (cf. HRTEM)
- Z-contrast: Scattering depends strongly on atomic number Z.
- Image: Atomic-resolution compositional map
- Allows parallel EELS measurement.



Source: [Fultz and Howe, 2002]

High-Angle Annular Dark-Field (HAADF): Example

HAADF image of an interface between
Sb-doped Si (left) and undoped Si (right).



Source: [Fultz and Howe, 2002]

That's it! Therefore ...

Thank you for your attention.

Source: http://www.zeiss.com/smt

References & Bibliography

[Flegler et al., 1993] Flegler, S., Heckman, J., and Klomparens, K. (1993).
Scanning and transmission electron microscopy: an introduction.
Oxford University Press.

[Fultz and Howe, 2002] Fultz, B. and Howe, J. (2002).
Transmission electron microscopy and diffractometry of materials.
Advanced Texts in Physics. Springer.

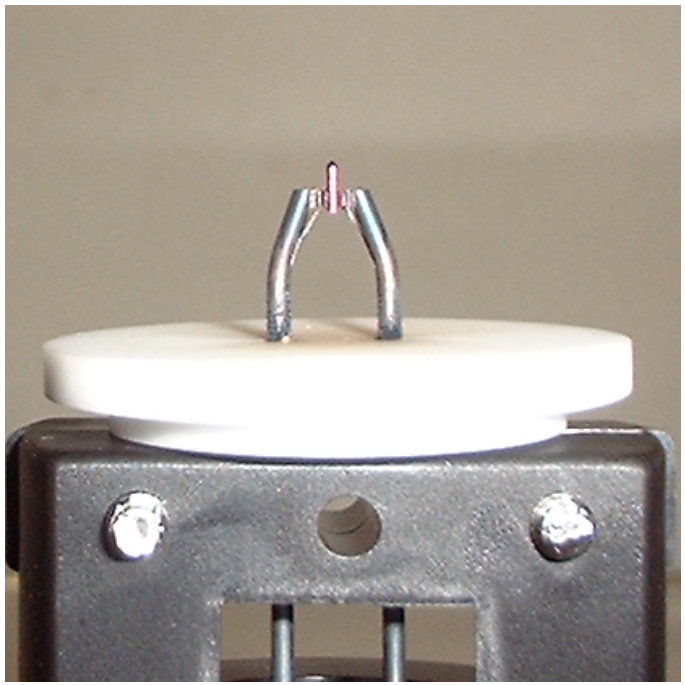
[Metzner, 200X] Metzner, S. (200X).
Spatio-time-resolved cathodoluminescence spectroscopy. Directly imaging microscopic energy relaxation in semipolar InGaN quantum wells via real space transfer.

[Newbury, 1986] Newbury, D. (1986).
Advanced scanning electron microscopy and x-ray microanalysis.
Plenum Pr.

[Reimer and Pfefferkorn, 1977] Reimer, L. and Pfefferkorn, G. (1977).
Raster-Elektronenmikroskopie.
Springer-Verlag.

Side Note: Lab-Six Gun

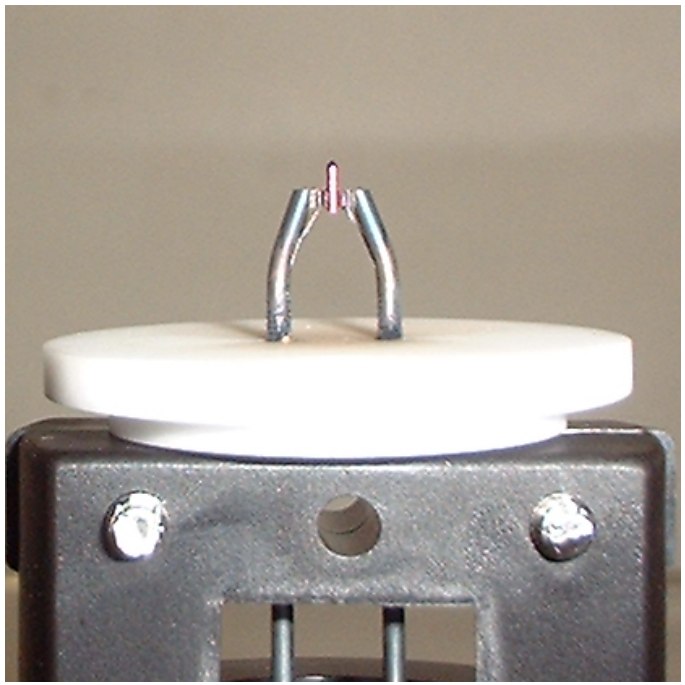
- Electron source:
  Heated LaB_6-crystal on tungsten wire
- Emission mechanism:
  Thermionic emission
- Usage:
  Second most common design



Source: http://www.snaggledworks.com/em_for_dummies/gun.html

Side Note: Lab-Six Gun

- Advantages:
  - Beam current up to 10 $\times$ that of a tungsten gun
  - Smaller area of emission
  - Energy spread is about 1/2
  - Duration of life 10 $\times$
- Disadvantages:
  - Better vacuum required
  - Finding saturation is more difficult
  - Much more expensive



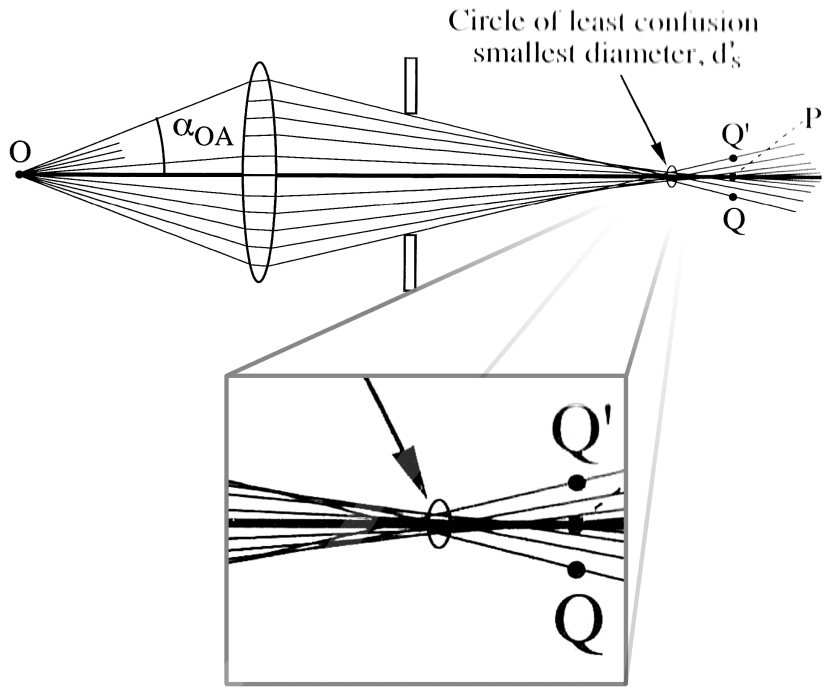
Source: http://www.snaggledworks.com/em_for_dummies/gun.html

Side Note: Spherical Aberration

- Effect: Changes focus of off-axis rays.
  $\Rightarrow$ Rays furthest from the optic axis are focused most strongly.
- Quantitative description:

$$d_s = 0.5 \cdot C_s\left(U_a, f\right) \cdot \alpha_{\mathrm{OA}}^3$$

- Counteractions:
  Complete elimination impossible.
  - Reducing the focal length f,
  - the aperture α_{OA}
  - and the accelerating voltage U_a.
- Relevance: Major factor; limits the practical resolution.



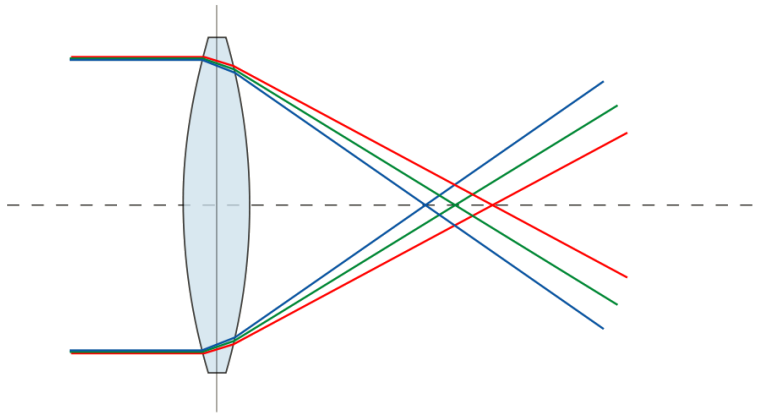
Source: [Fultz and Howe, 2002]

Side Note: Chromatic Aberration

- Effect: The focal length depends on the electron velocity/energy.
  $\Rightarrow E_1 > E_2$ implies $f_1 > f_2$.
- Quantitative description:

$$d_c = \Delta E/E \cdot C_c(f) \cdot \alpha_{\mathrm{OA}}$$

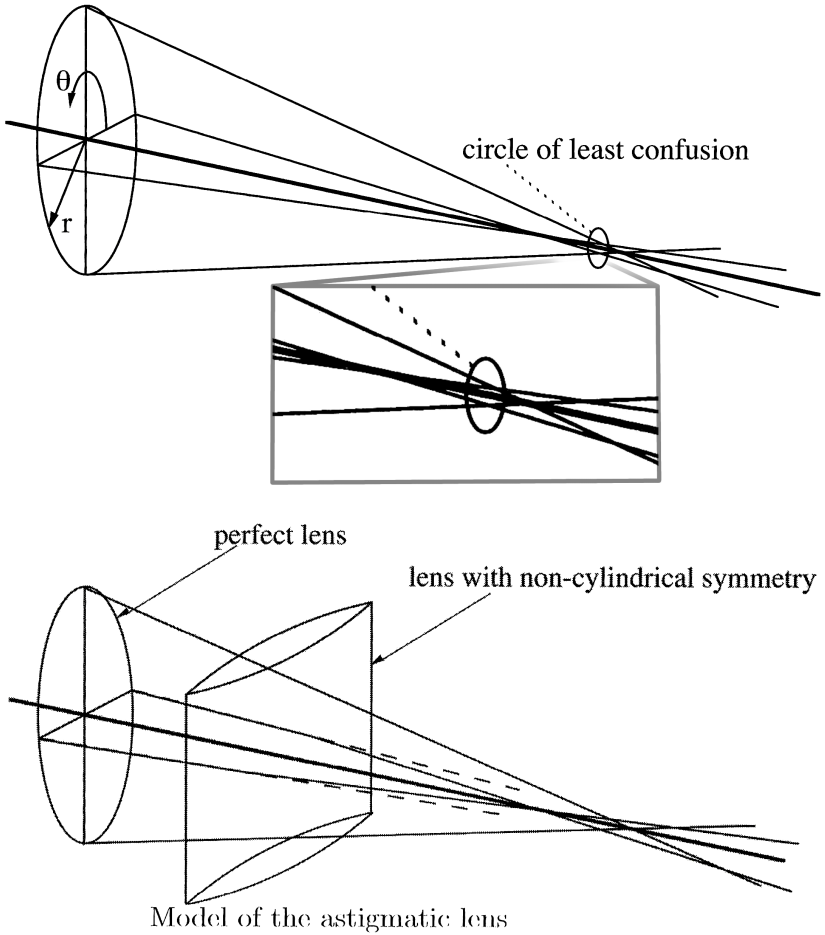
- Counteractions:
  - Reduction of the energy spread $\Delta E/E$ (high-quality electron guns, **thin samples**),
  - the aperture α_{OA}
  - and the focal length f.
- Relevance: Relevant factor; blurs the image.



Source: http://en.wikipedia.org/wiki/Chromatic_aberration

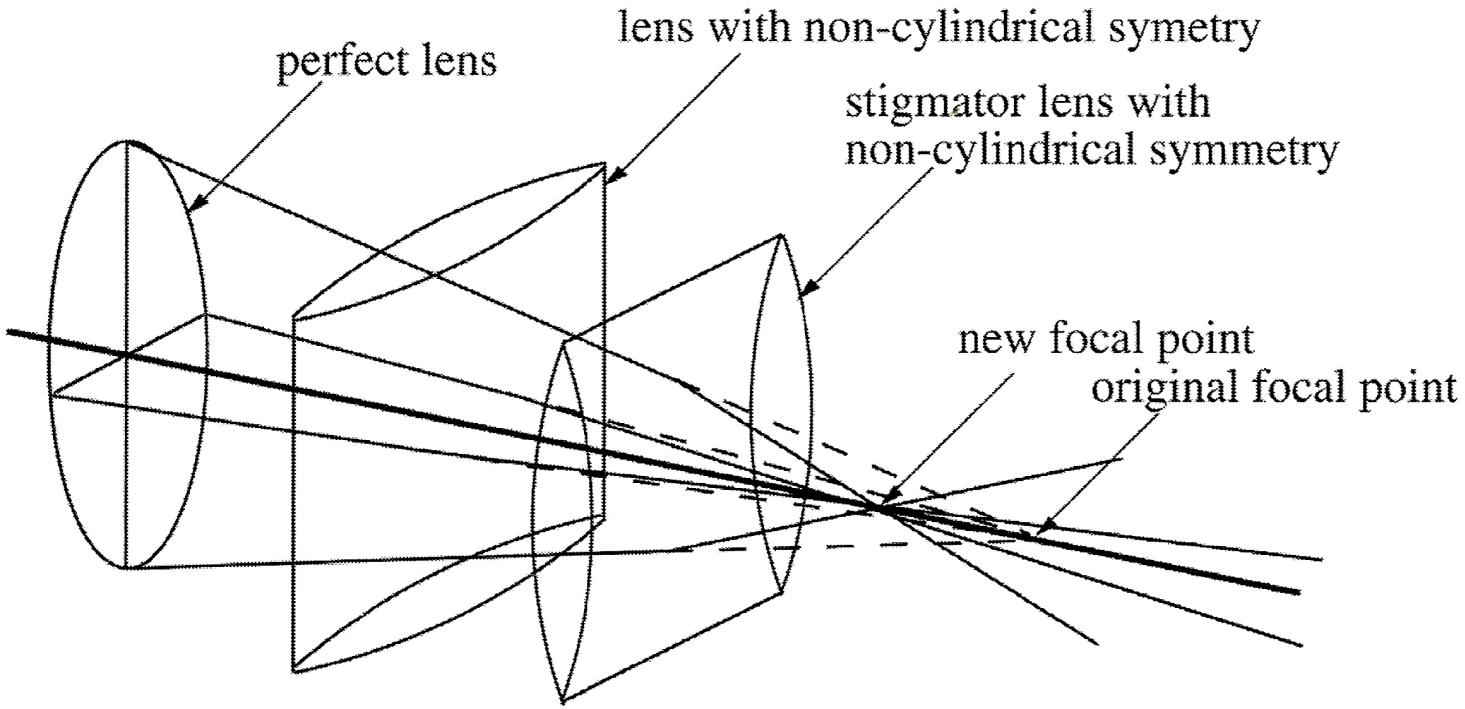
Side Note: Astigmatism

- Effect: Defects of lens symmetry cause anisotropic lens strengths.
  $\Rightarrow$ Distorted beam of electrons results in distorted images/reduced resolution.
- Counteractions:
  Well correctable problem.
  - Reduction of manufacturing defects (lenses & apertures)
  - and contaminations.
  - **Stigmator lenses** (octapole stigmator)
- Relevance: Common problem; Stigmation has to be performed frequently.



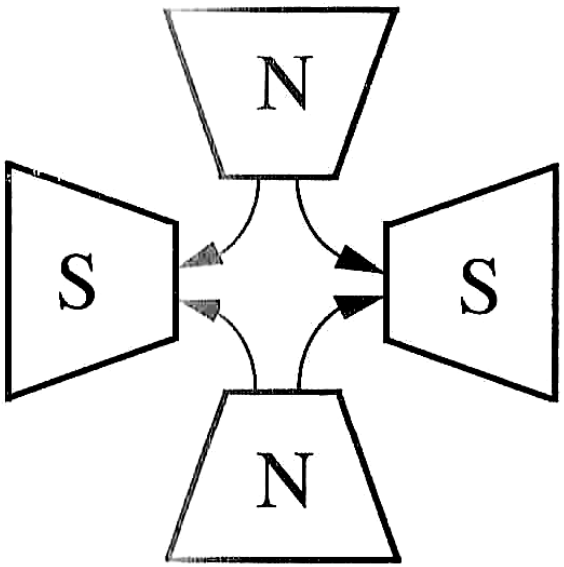
Source: [Fultz and Howe, 2002]

Side Note: Correcting Astigmatism ("Stigmation")

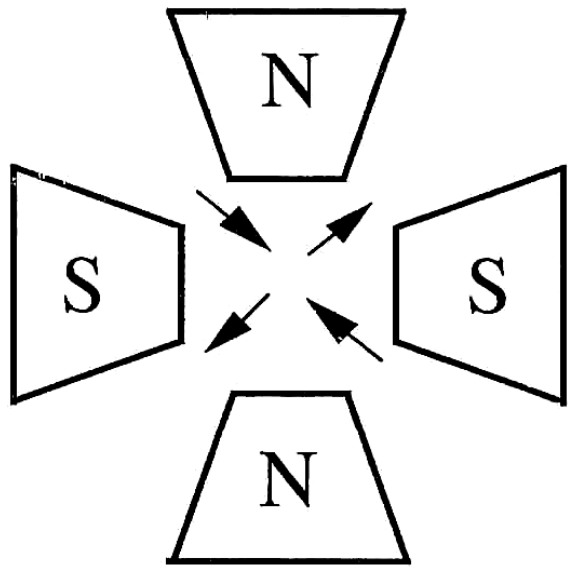


Source: [Fultz and Howe, 2002]

Side Note: Correcting Astigmatism ("Stigmation")



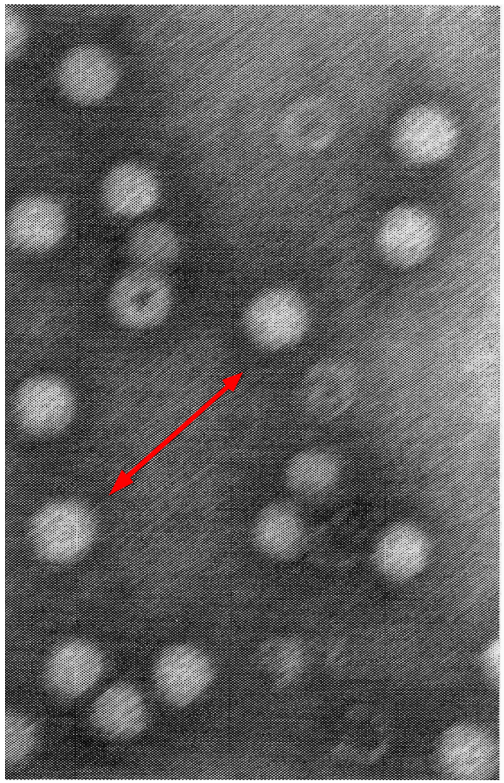
Fields



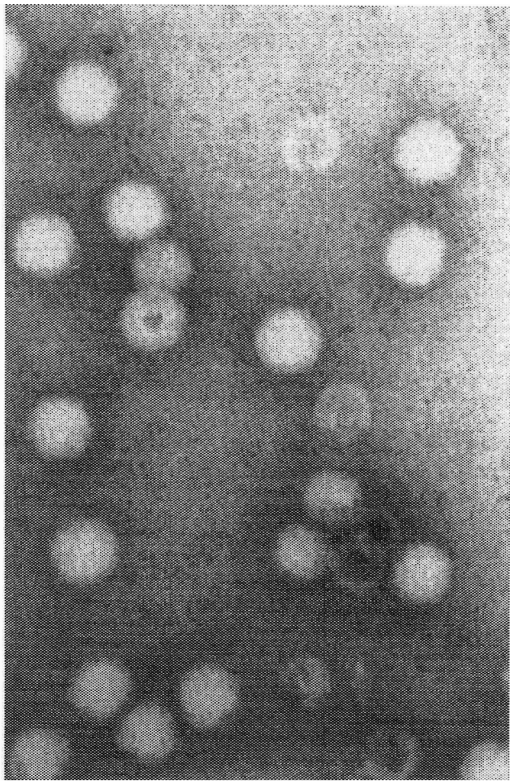
Forces

Source: [Fultz and Howe, 2002]

Side Note: Astigmatism and Stigmation - Example



Astigmatic objective-lens...



... after proper stigmation.

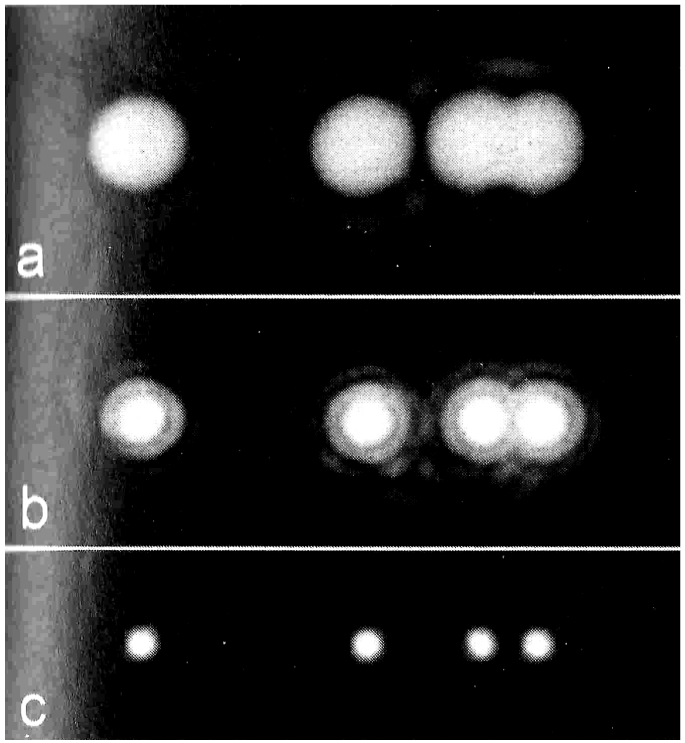
Source: [Flegler et al., 1993]

Side Note: Apertures and Diffraction

- Effect: Apertures truncate the k-space components. $\Leftrightarrow$ Diffraction of electrons at aperture fringes.
- Quantitative description (Rayleigh criterion):

$$d_d = 0.61 \cdot \lambda_e \cdot \alpha_{\mathrm{OA}}^{-1}$$

- Counteractions:
  - Maximising aperture angle α_{OA}
  - and energy (reducing λ_e).
- Relevance: Not relevant due to aforementioned aberrations (cf. optical microscopy).

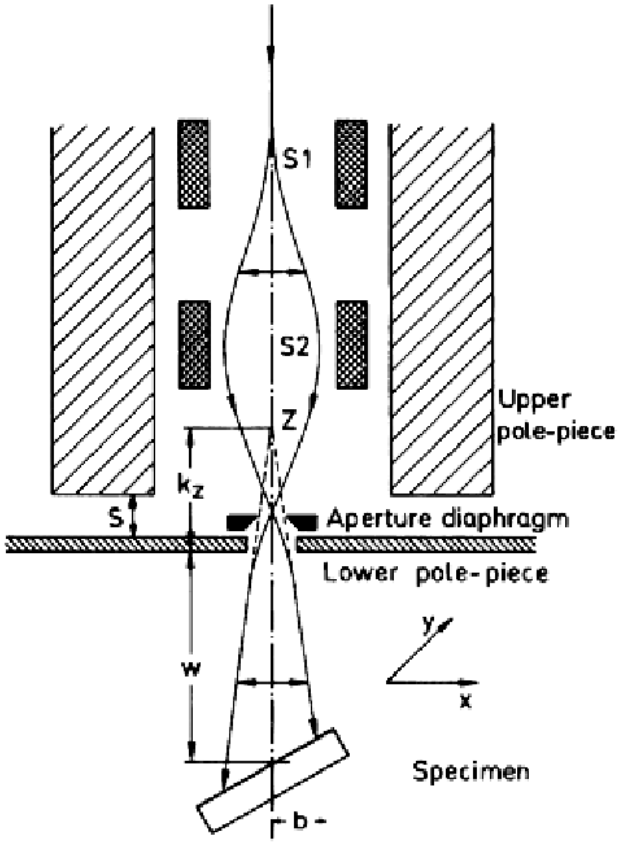


Source: [Fultz and Howe, 2002]

Side Note: Deflection Coils

- Location:
  Directly above the objective aperture.
- Mechanism:
  Electrostatic or electromagnetic deflection by multipole setups.
- Common setup:
  2 deflection units per direction (S1 and S2)
  $\Rightarrow$ Beam passes objective aperture.
- Magnification determined by scanned area:

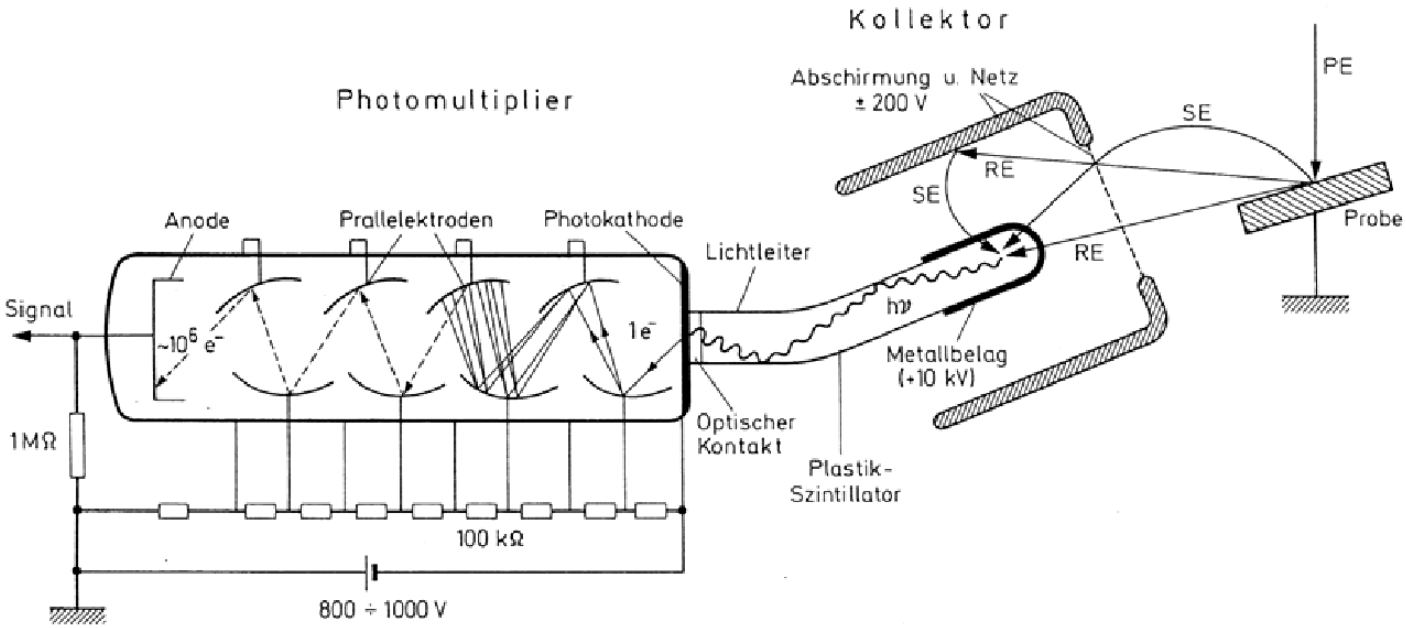
$$M = \frac{\text{Screen width}}{\text{Scan width}}$$



Source: [Reimer and Pfefferkorn, 1977]

Side Note: Everhart-Thornley Detector

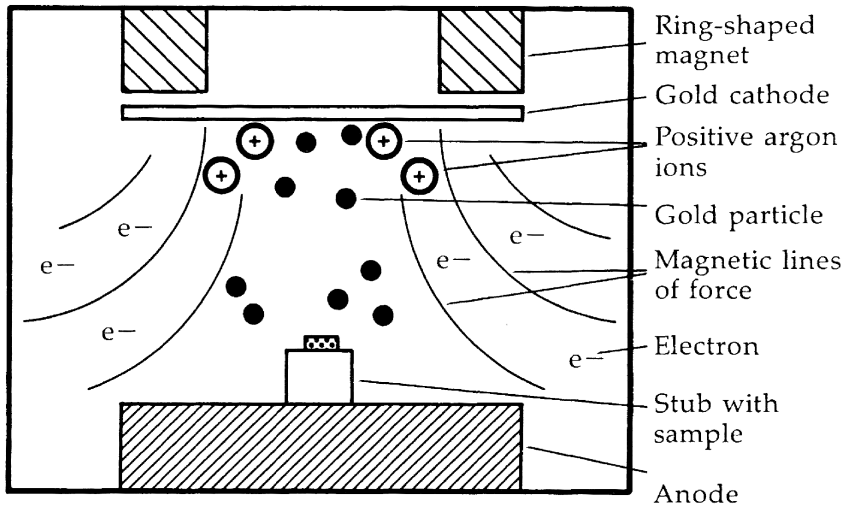
Detection of secondary electrons.



Source: [Reimer and Pfefferkorn, 1977]

Side Note: Sample Preparation

- Nonconducting samples: Beam of electrons → **charging**
- Charged areas cause abnormal contrasts in SE images.
- Coating with gold: used for SE imaging (→ sputter coater)
- Coating with carbon: used for BSE and X-ray analysis (→ carbon string evaporator)
- Uncoated samples: proper accelerating voltage required; ionised environment (→ ESEM).



Source: [Flegler et al., 1993]

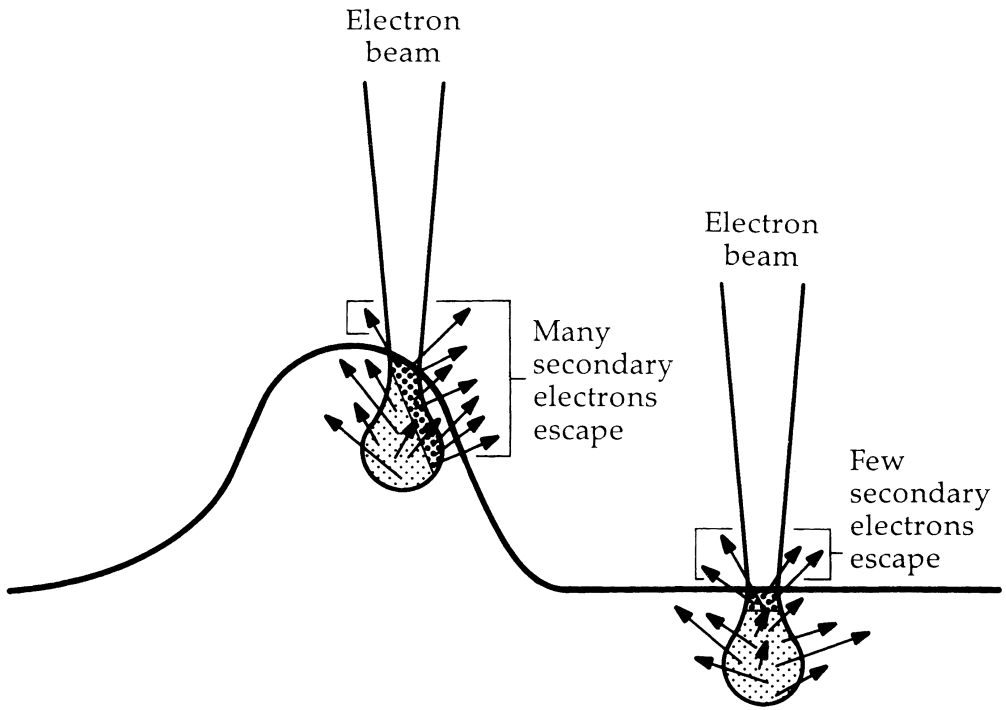
Side Note: Sample Preparation - Example

Gold coatet spider, prepared for SEM.

Source: http://en.wikipedia.org/wiki/Scanning_electron_microscope

Side Note: Edge Contrast

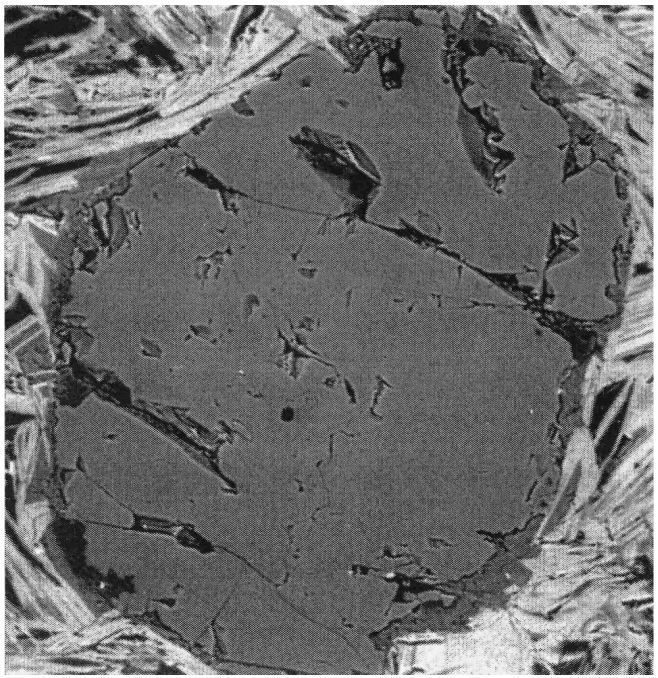
Tilted surfaces and edges are brighter than flat surfaces.

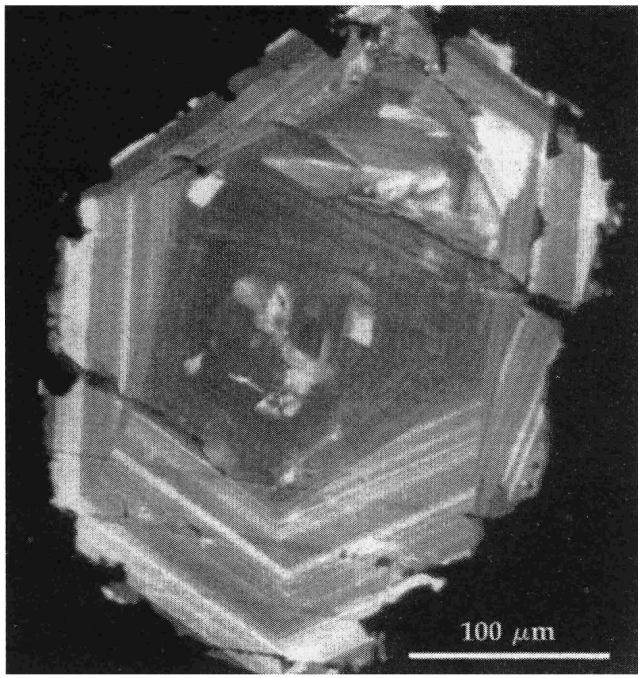


Source: [Flegler et al., 1993]

Side Note : Cathodoluminescence - Example

SEI (left) and CLI (right) of a polished corundum grain (Al_2O_3).

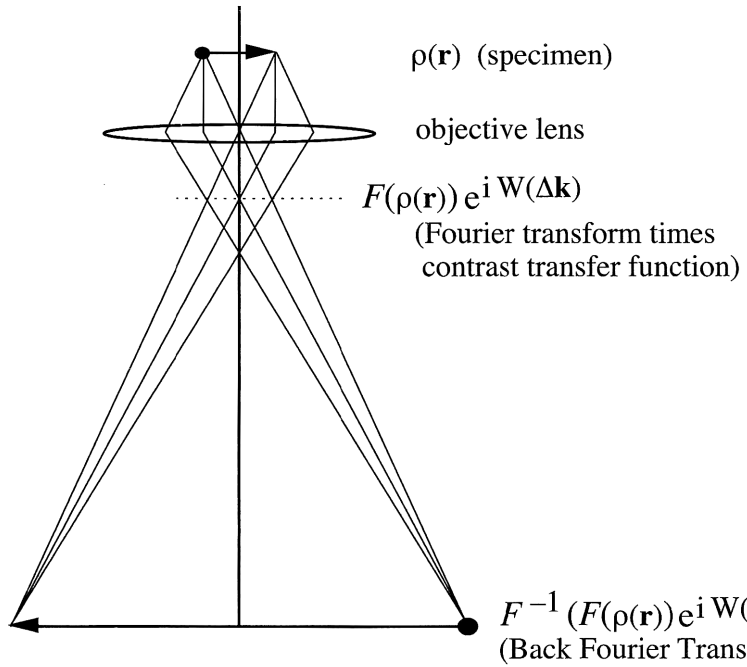




Source: [Flegler et al., 1993]

Side Note: Fourier Optics

- Diffraction of electrons determined by charge distribution $\rho(\mathbf{r})$.
- Objective lens creates **real image** and causes **phase distortion** $W(\Delta\mathbf{k})$ ($\rightarrow$ spherical aberration).
- Fourier plane (Back focal plane): Fourier transform $\mathcal{F}[\rho]$ of image.
- Gaussian plane (Image plane): (Distorted) image $\mathcal{F}^{-1}\left[\mathcal{F}[\rho] \cdot e^{iW}\right] \approx \rho(\mathbf{r})$.

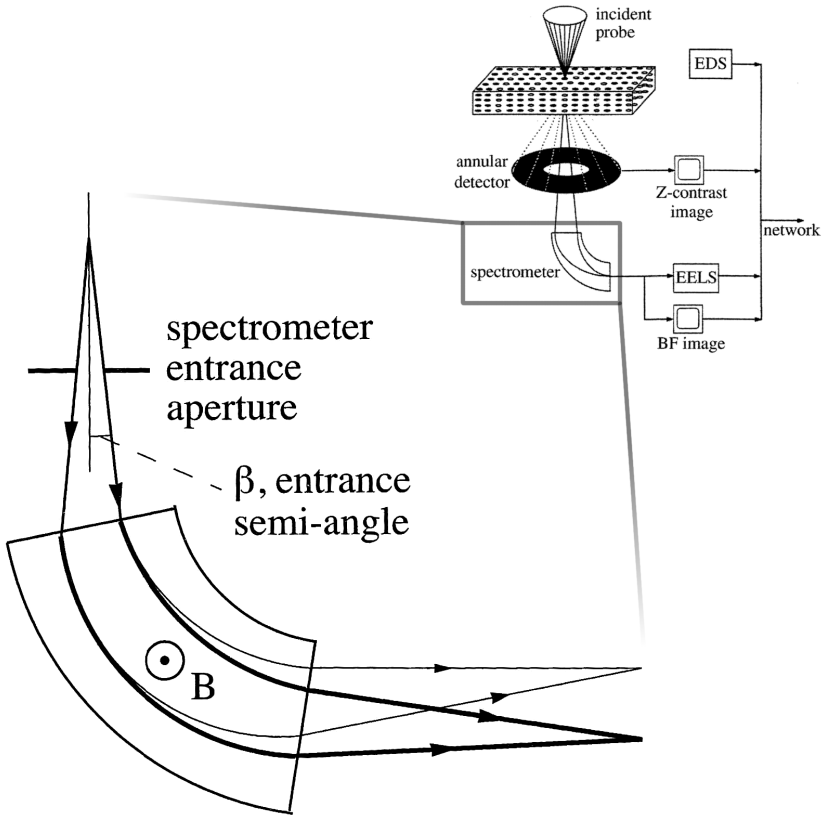


Source: [Fultz and Howe, 2002]

Side Note: Electron Energy Loss Spectroscopy (EELS)

- Analytical / imaging mode for **STEM**.
- Setup: Magnetic prism (energy dispersive element) below specimen.
- Signal: **Inelastically** scattered electrons
- Energy loss due to
  - Electronic transitions ($\rightarrow$ Band gap)
  - Inner shell ionization ($\rightarrow$ X-Rays)
  - Phonon/Plasmon excitations

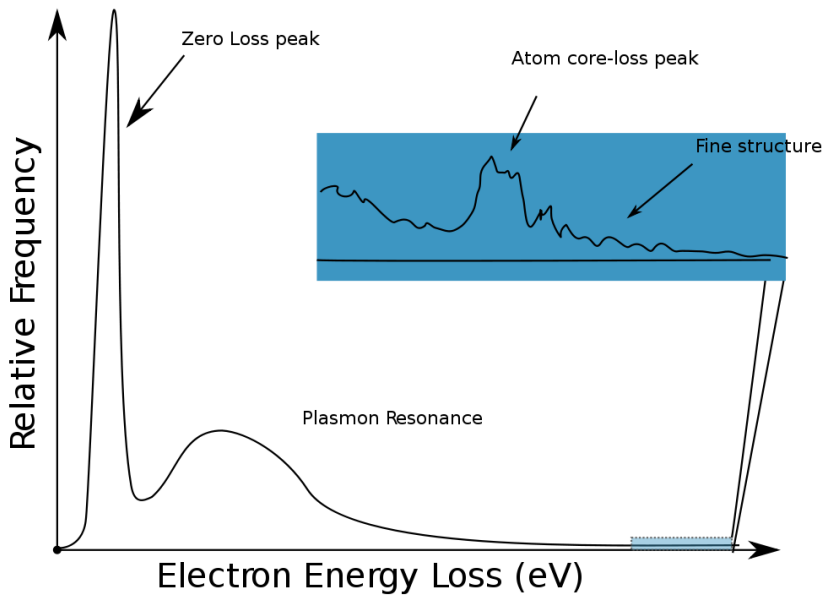
  $\Rightarrow$ Depends on material.
- Results: Compositional map.
  Area resolved ($\sim 1\,\mathrm{nm}$) pressure and thickness measurements.



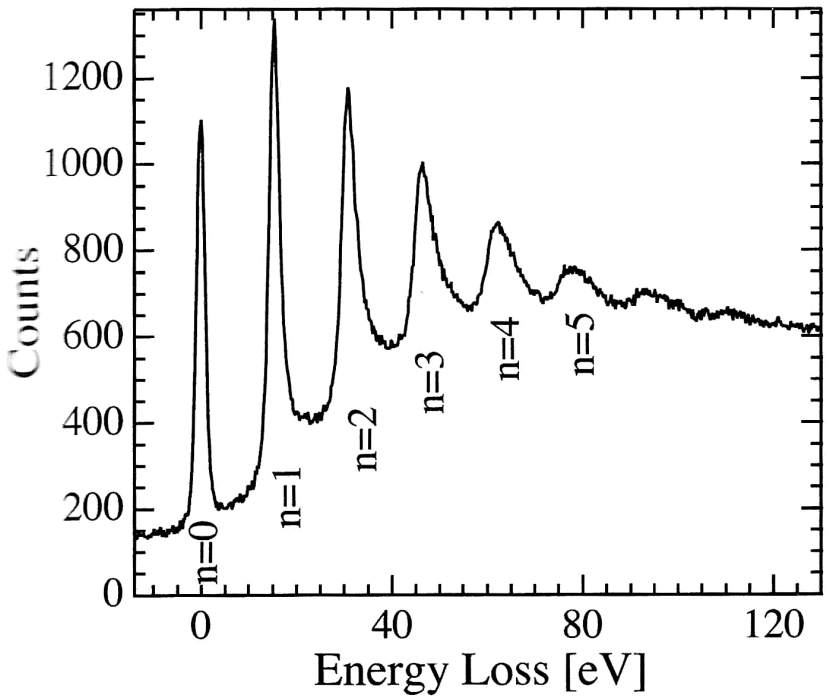
Source: [Fultz and Howe, 2002]

Side Note: EELS - Example

Schematic EELS (left) and high resolution spectrum of plasmon excitations (right).



Source: http://en.wikipedia.org/wiki/EELS



Source: [Fultz and Howe, 2002]