# Scanning Electron Microscopy in Analysis and Fabrication of Nanostructures

# 0 Introduction

The Scanning Electron Microscope (SEM) has been one of the most versatile and widely used tools of modern science for about four decades. Applications are not only the imaging of objects, but also metrology and failure analysis.

The main benefit of a SEM is the imaging of solid surfaces and morphology with very high spatial resolution and high depth of focus. With an optical microscope, a spatial resolution down to 0.2 μm and a depth of focus of 1 μm (with magnification 100) is possible. In contrast, the SEM can achieve a resolution down to 5 nm and the depth of focus for a magnification of 100 is about 0.5 mm. Image generation and magnification is carried out electronically, not optically. Therefore, subsequent image capture and processing systems can come into operation for the analysis of the investigated structures.

The experiment at hand illustrates the basic function of a SEM as an imaging tool and the correlation of important operational parameters that are necessary for a high image quality.

# 1 Basics

## *1.1 Setup*

In a Scanning Electron Microscope (SEM) electrons are accelerated by a high voltage. When hitting a solid sample, these **primary electrons** (PE) are generating several interaction products like x-ray, backscattered electrons and secondary electrons. The SEM mainly uses the **secondary electrons** (SE) for imaging, these electrons have energies between 0 eV and 50 eV. Fig. 1 shows the basic setup of a SEM:

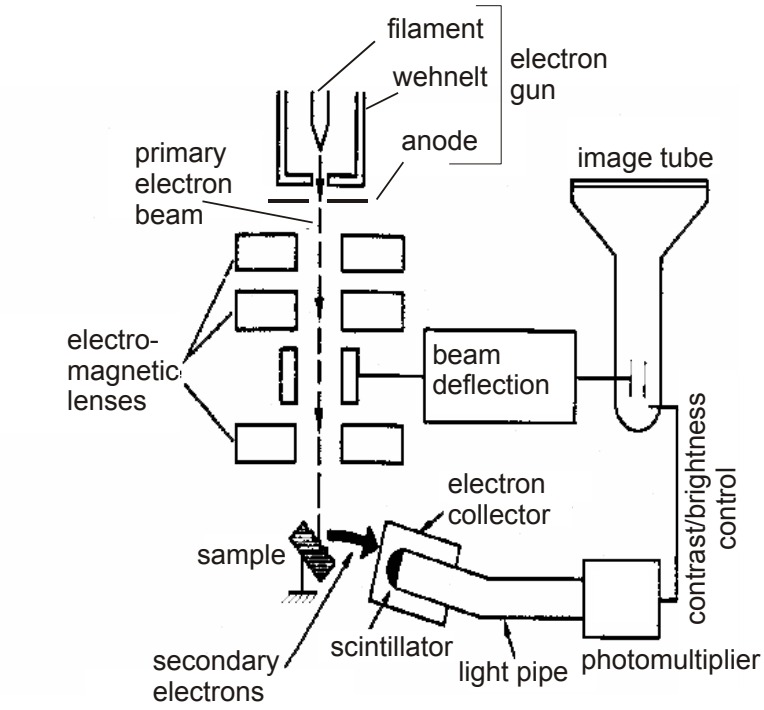


Fig. 1: Setup of a SEM

The electron gun consists of a directly heated tungsten filament (cathode), the wehnelt electrode and an anode. The wehnelt cylinder is negatively biased against the cathode, causing a cross over of the primary electron beam. This **cross over** acts as a virtual electron source with a diameter between 25 µm und 100 µm, depending on the geometry and the applied electric fields.
A voltage between 100 V and 100 kV accelerates the electrons from cathode to anode. With an energy of 100 keV, the PE achieve a speed of $1{,}64 \cdot 10^5$ km/s
The electromagnetic lenses are working based on the Lorentz force. They focus the cross over onto the sample surface with an reduction factor of about $10^4$, leading to a minimal electron beam diameter of about 5 nm. **Lens aberrations** (spherical aberration, astigmatism, diffraction error) as well as the electrostatic repulsion between the electrons limit the reduction of the beam diameter.

**Scan coils** are integrated into the lens system that allow a line-by-line scan of the sample surface by the electron beam. Finally, the beam hits the sample surface and generates secondary electrons.

## *1.2 Detection and Magnification*

The detection of the SE is performed by a scintillator-photomultiplier combination (Everhart-Thornley detector).

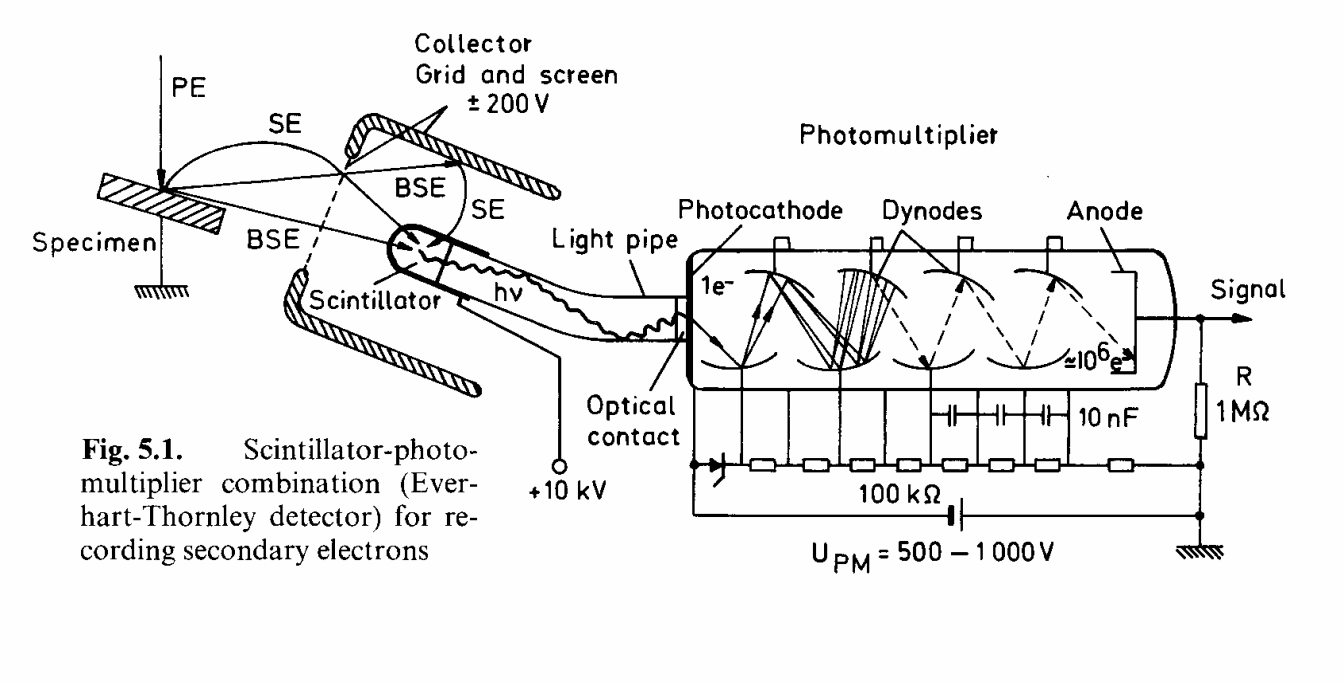


**Fig. 5.1.** Scintillator-photomultiplier combination (Everhart-Thornley detector) for recording secondary electrons

Fig. 2: Everhart-Thornley detector

The scintillator transforms the kinetic energy of the electrons into photons. These photons are guided through a light pipe to the photomultiplier, where photoelectrons are produced. By successive acceleration and generation of new secondary electrons, the dynode chain amplifies the current. Now, the output signal of the Everhart-Thornley detector modulates the electron beam of an image tube (monitor). For a correct image generation, the electron beam in the image tube must be synchronized with the scanning electron beam in the microscope. In this case, each point on the sample can be attributed to an image point on the monitor without ambiguity. This principle of synchronized scanning of sample surface and monitor is the base for the sample imaging.

**The ratio between the scanned sample area and the monitor size defines the magnification.** The scanning of a sample area and the synchronized imaging, leading to a specified magnification, is illustrated in Fig. 3.

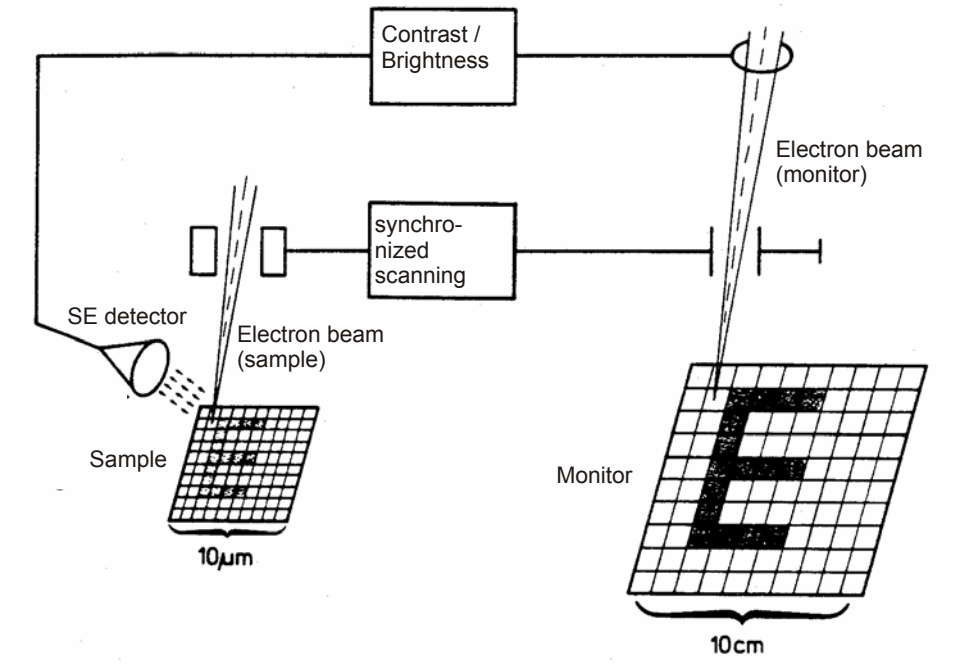


Fig. 3: Magnification in the SEM
Example: Magnification 1 : 10000

The considerations above show the main difference to the imaging in an optical microscope. In an optical microscope the light emitted by the sample is projected by the microscope optics to a screen or to the retina. In a SEM, the image is generated completely electronically. Therefore, a subsequent electronic image processing is very easy.

# 2 The SEM as analyzing tool

## *2.1 Surface topography*

How can we get information on the surface topography by SEM?
The SE yield $\delta$ shows a characteristic dependence on the incidence angle $\beta$ of the PE to the sample surface.

$$\delta \sim \frac{1}{\cos\beta} \qquad \left[\delta = \frac{\text{Number of SE}}{\text{Number of PE}}, \text{values between 30\% and 70\% are possible}\right]$$

The proportionality predicts a higher SE yield for areas that are tilted, i.e. areas with an angle $\beta > 0$ between surface normal and PE beam.

This increasing SE yield becomes plausible, when we consider the volume, in which the PE lose all their energy (the energy dissipation volume – EDV) as a function of $\beta$. Fig. 4 shows three results of numerical calculations, simulating the trajectories of the PE for different angles of incidence.

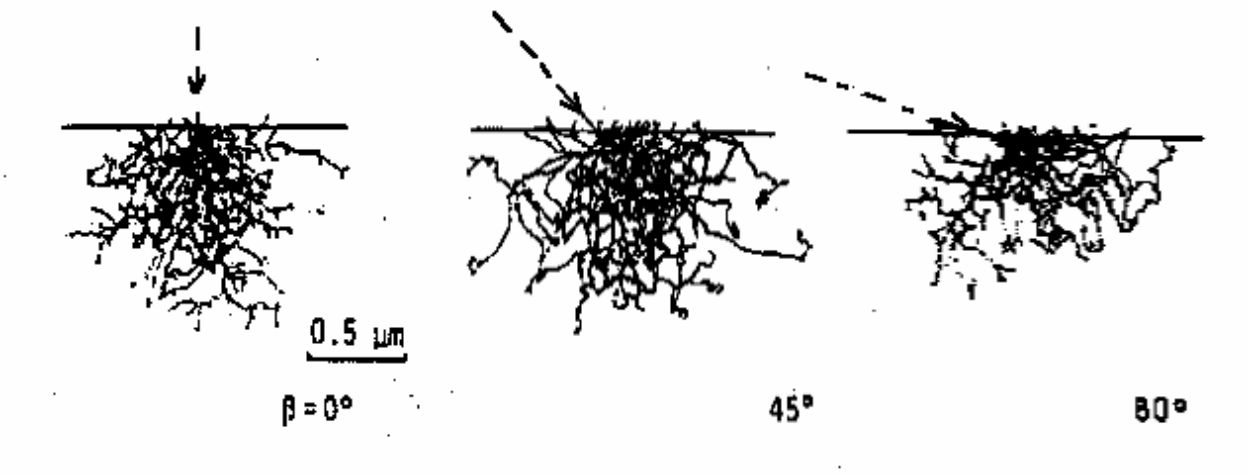


Fig. 4: Simulated electron trajectories in copper; $E_{PE}$ = 20 keV

Because the EDV shifts towards the surface with increasing angle $\beta$, the number of SE that can escape from the solid surface increases as well.

The dependence of the SE yield on $\beta$ can be observed both at polished surfaces and at surfaces with a distinct surface topography. Edge-like structures show as well an increased SE yield, and are thus visible as bright lines. Fig. 5a demonstrates the SE emission at plain surfaces for $\beta=0$ (left) and $\beta>0$ (right). Fig. 5b shows the SE yields for different surface topographies. The white oval areas in Fig. 5 indicate the EDV.

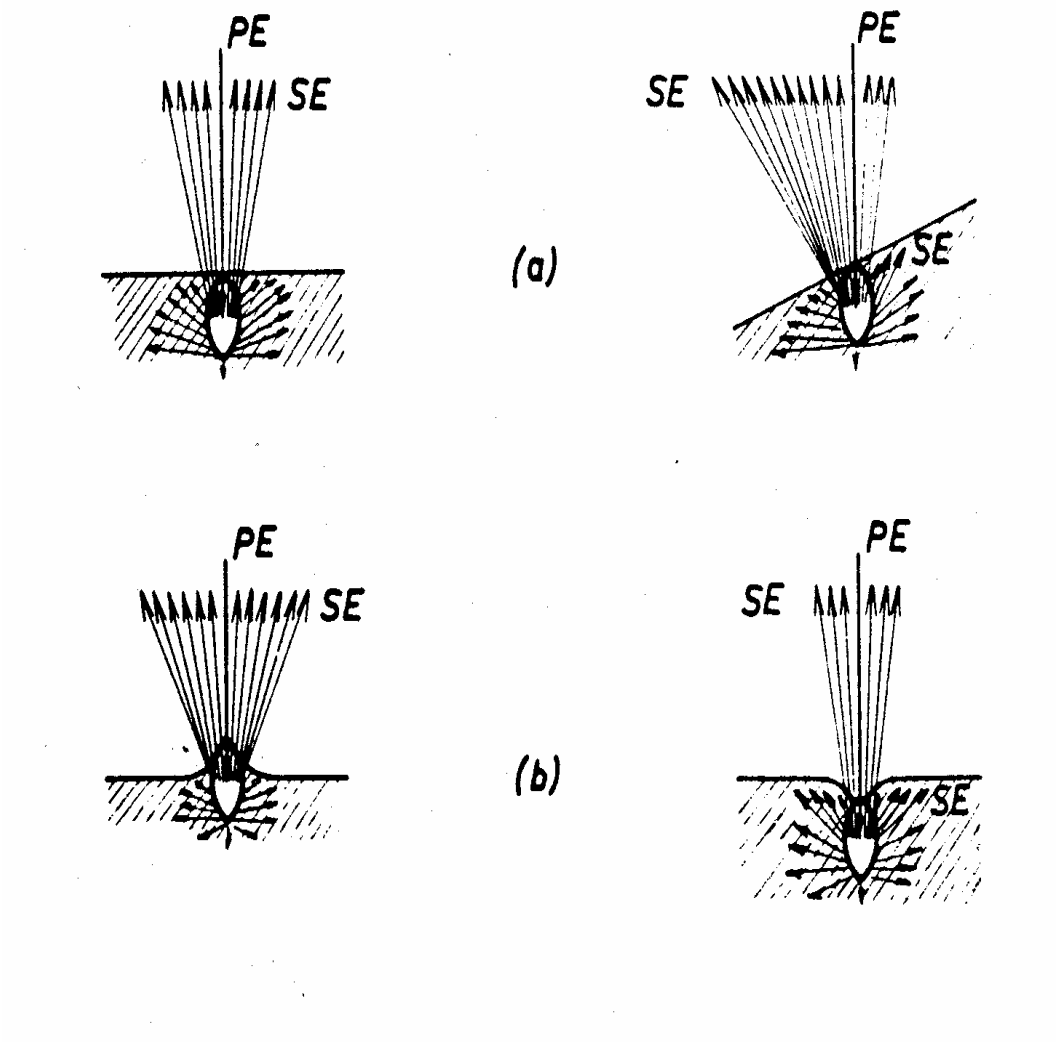


Fig. 5: SE emission (schematically)

## *2.2 Resolution*

The lateral resolution of a SEM is defined mainly by the following three factors:

a) electron beam diameter
b) scattering volume and SE emission in the solid
c) signal/noise ratio

### 2.2.1 Electron beam diameter

**Lens errors** have an critical impact on the electron beam diameter:

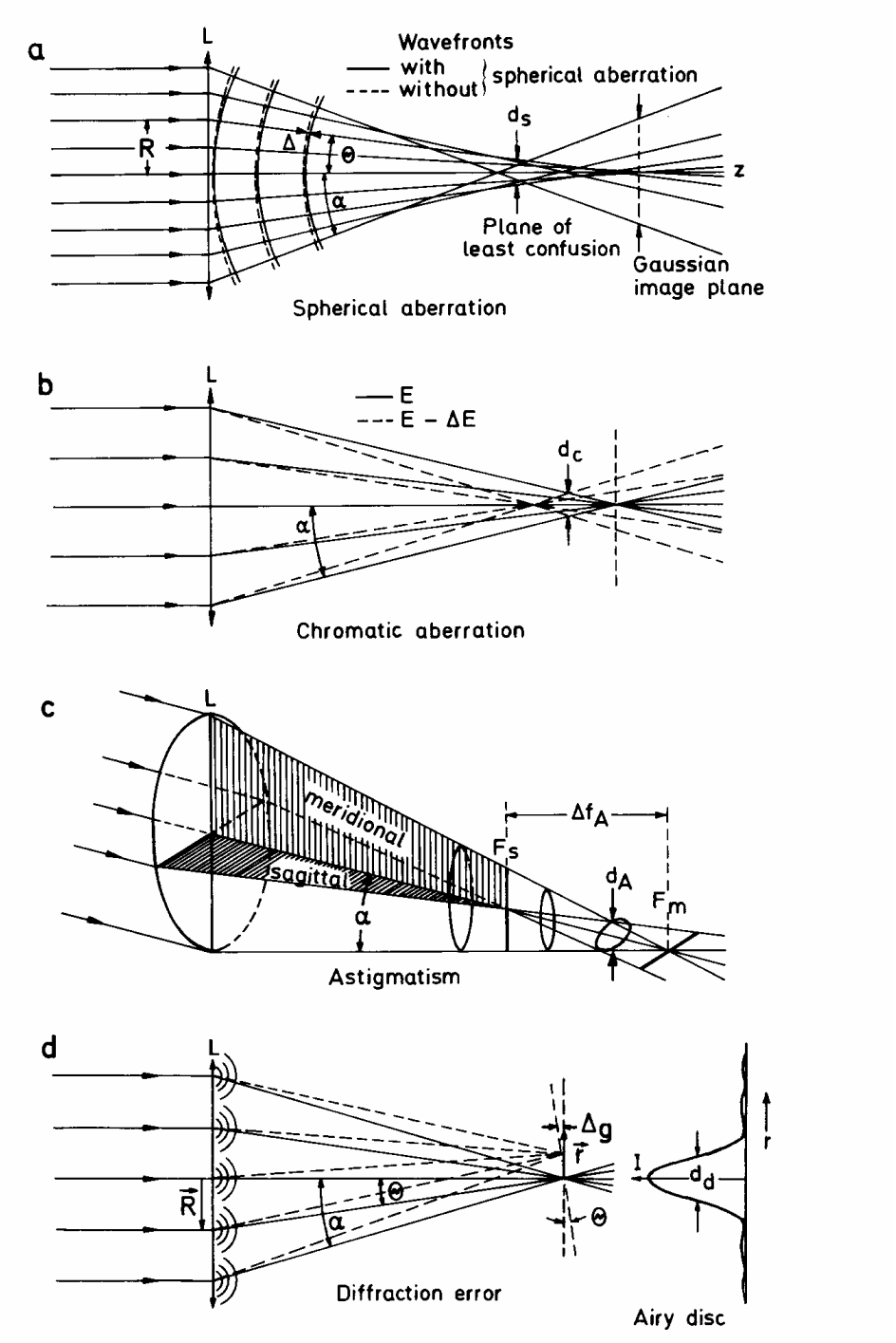


Fig. 6: The most important errors of an electromagnetic lens

The primary electrons are emitted from the cathode with a Maxwell energy distribution and therefore have a certain uncertainty ($\Delta E$ = 2 eV - 3 eV). On the other hand, the lens systems can be optimized for one electron speed only. As a consequence, the **chromatic aberration** is observed. It can be reduced to a certain degree by increasing the acceleration voltage.
Fluctuations of acceleration voltage and lens current contribute to the chromatic aberration as well.

The **spherical aberration** is due to different focal lengths between rays near to the lens center and rays near to the lens edge. Therefore a point in the object plane is projected into an error disk in the image plane (Fig. 6a).

Deviations from the rotational symmetry in the imaging system (due to various factors like fabrication tolerances in the lenses, and electromagnetic fields) cause the **astigmatism**. The cross section of the electron beam becomes elliptical. As illustrated in Fig. 6c, parallel rays are not focussed into one point but into two perpendicular lines in different image planes. This error can be compensated by inserting an electromagnetic cylindrical lens (the 'stigmator').

Even for ideal operating conditions of a SEM (i.e. no lens errors, sufficient centering of the electro-optic system, stable electron current and lens current etc.), the **diffraction error** must be considered (Fig. 6d). Electrons have both particle and wave nature, and due to the latter, they are diffracted at apertures. The radius of the diffraction disk $r_B$ is – similar to the optical microscope – proportional to the wavelength $\lambda$ and inversely proportional to the half aperture angle $\alpha$

$$r_B = \frac{0{,}6 \cdot \lambda}{\alpha}$$

The wavelength of an electron with a kinetic energy of 10 keV is about 12,2 pm. (In contrast: The wavelength of visible light is about 500 nm. This is one main reason for the extremely high resolution of a SEM, compared with an optical microscope.)

### 2.2.2 Scattering volume and SE emission in a solid

The resolution does not depend only on the possible probe diameter, but also on the emission area of the SE. The size of this area is strongly correlated with the **absorption length** $\lambda_A$, this is the average distance that the electrons can move in the solid after generation.

Furthermore, the resolution is decreased by the finite size of the EDV. The EDV is correlated with the sample material and the PE energy.

### 2.2.3 Signal noise ratio

In many cases, the resolution of ultrafine structures by a SEM is not primarily a matter of a sufficiently small probe diameter on the object, but of an adequate S/N ratio of the image-generating signal. The S/N ratio is proportional to the square root of the average number of electrons per time unit and per object point:

$$\frac{S}{N} \sim \sqrt{n}$$

The S/N ratio is improved with an increasing total number per image point. This can be achieved by a slowdown of the scanning speed and a high PE current.

Fine structures become visible only above a certain contrast threshold (for S/N constant).
Therefore, the behaviour of the signal contrast in dependence on the image integration time and on the PE current is of high interest:

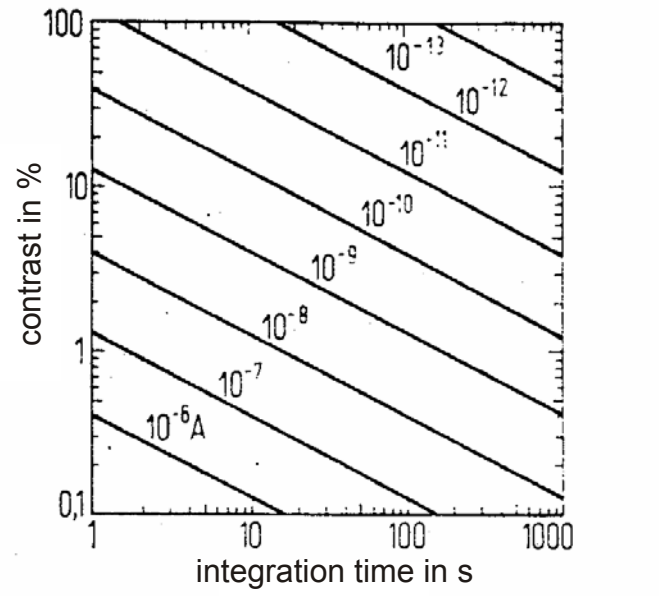


Fig. 7: Correlation between signal contrast and integration time for different values of the beam current

The contrast dependence on the beam current (Fig. 7) implicates a current as small as possible for high magnification. As this is in contradiction with the choice of a high beam current for improvement of the S/N ratio, a compromise must be found.

It should be pointed out that for SEM operation compromises are always necessary. But by tuning the parameters (acceleration voltage, lens currents, integration time etc.) one is able to optimize the mode of operation for the specific experiment.

## 2.3 Depth of focus

A very important property of the SEM is the exceptionally high depth of focus, due to the extremely small probe aperture angles (typically $\alpha = 10^{-2}$ rad ($< 1^{0}$). For comparison: Optical microscopes use aperture angles of $\alpha \approx 70^{0}$.

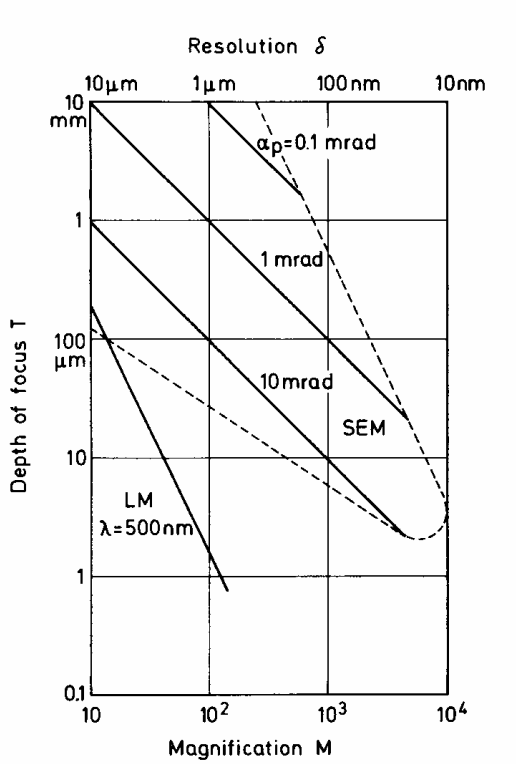


Fig. 8 : Depth of focus as a function of magnification and probe diameter for SEM and an optical microscope (LM).

Fig.8 shows the clear superiority of the SEM compared with the optical microscope. The depth of focus is dependent on the diameter of the last aperture:

$$F = \frac{d}{D} \cdot L$$

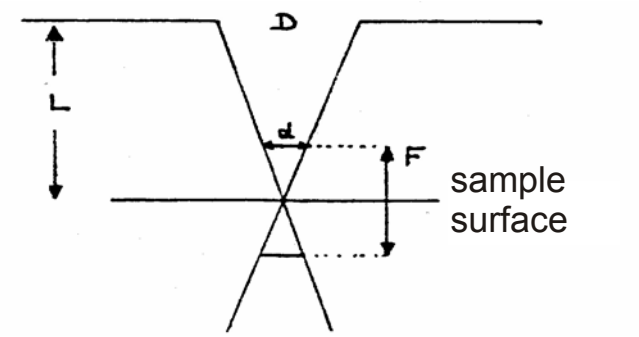


Fig. 9: geometric parameters behind the last aperture
*D* : Diameter of the last aperture
*L* : Working distance of the sample
*d* : resolvable structure size
*F* : depth of focus

# 3 Experiment

## *3.1 Correlation between depth of focus and aperture diameter*

With a mechanical lever, the aperture of the last lens above the sample can be changed easily. The depth of focus is correlated with the aperture diameter, as mentioned before.

For demonstration, a tilted screw is mounted in the SEM. The screw thread allows an easy estimation of the depth of focus in dependence of the aperture diameter.

## *3.2 Correlation between SE yield and incidence angle $\beta$*

For the SE yield $\delta$ applies the proportionality:

$$\delta \sim \cos^{-1} \beta$$

with $\beta$ : Angle between surface normal and PE beam.

A brass block with tilted surfaces serves as an example for this relation.
Outline the relation $\delta(\beta)$ and discuss:

- Why is this effect responsible for the so-called topographic contrast and the quite graphic images in the SEM?
- What angles $\beta$ are useful to get a high contrast for topographic structures?

### *3.3 Optimizing the resolution*

The interaction between operating parameters like beam current, PE energy, aperture diameters and scan speed affect the resolution of the SEM, as discussed before. By tuning these parameters and optimizing the resolution, their influence is illustrated.

– Summarize briefly the steps that are necessary to achieve high resolution and image quality.

## 4 Comprehension questions

1. What is the basic setup of a SEM?
2. What is the mechanism for magnification in a SEM?
3. What are the limiting factors concerning the resolution?

## 5 Literature

Scanning electron microscopy
L. Reimer,
Springer-Verlag, Berlin