

Transmission electron Microscopy

Image formation of a concave lens in geometrical optics

Some basic features of the transmission electron microscope (TEM) can be understood from by analogy with the operation of a concave lens in geometrical optics. Figure 1 shows the image formation in a concave lens.

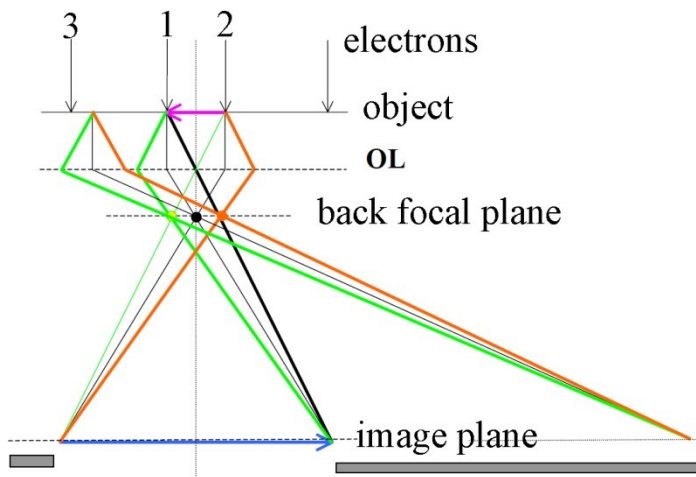


Figure 1: image formation of a concave lens

As you remember from geometrical optics, a real magnified image is only obtained if the object is placed at a distance, t from the lens: $f < t < 2f$, where f is the focal distance of the lens.

The image can be constructed with two known ray paths: A/ Rays running parallel to the optical axis will go through the back focal point (back means the other side of the lens as compared to the position of the object and the illumination). B/ Rays passing through the center of the lens (the crossing point of the optical axis with the plane of the lens) continue without changing direction.

The steps of construction:

- These 2 rays were used for object points 1 and 2 in Fig. 1 to obtain the image points, which determine the image plane.
- After we have constructed these image points, we can use the fact that all rays starting from a single object point must meet each other at the conjugate image point, irrespective of their directions (since this is a real image). In Fig.1 we drew rays from point 1 parallel to the ray drawn from point 2 and vice versa. As a result, we can see that all parallel rays meet at a single point in the back focal plane. The different points at the back focal plane will correspond to different scattering directions. So, the different point of the pattern at the back focal plane will correspond to different values of the scattering vector, which is the reciprocal lattice vector. This pattern is called a diffraction pattern.
- After we constructed the above points (1 and 2), we can make use of the previous observations about the parallel rays and construct the image of object point 3 by drawing rays parallel to the directions previously used during the construction of image points 1 and 2 (these rays must pass through the respective back focal plane points, determined by their directions). (Obviously, that type of construction is only possible after points 1 and 2 have been constructed as above.)

Main modes of operation of TEM from this optical analogy

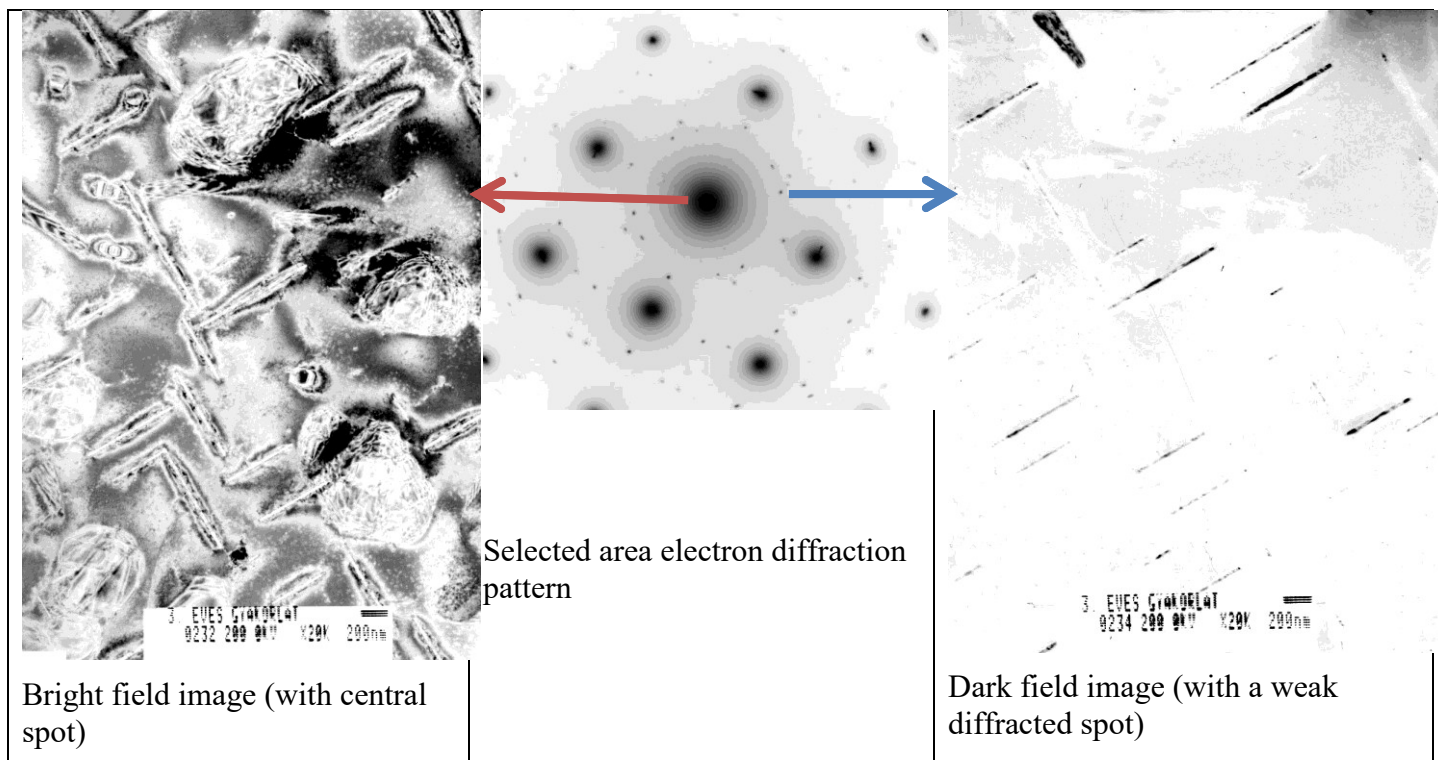
Fig.1 shows the optical analogy of the objective lens of the TEM. For the magnetic lenses in the TEM there is an additional rotation of the image, too, but it is easy to treat the rotation separately from the deflections towards and away from the optical axis, which is shown in Fig. 1. The image plane shows a magnified image of the sample, i.e. gives real space information. The back focal plane shows the diffraction pattern, which is a plane section of the 3D reciprocal space. We only need to select which plane to transfer to the plane of observation (image recording).

Selection is done by setting the focal lengths of the projection lenses, which are situated between the image plane and the plane of observation. If the image plane is projected to the plane of observation we have imaging mode. When the back focal plane of Fig.1 is projected to the plane of observation we have diffraction mode.

Contrast of the image

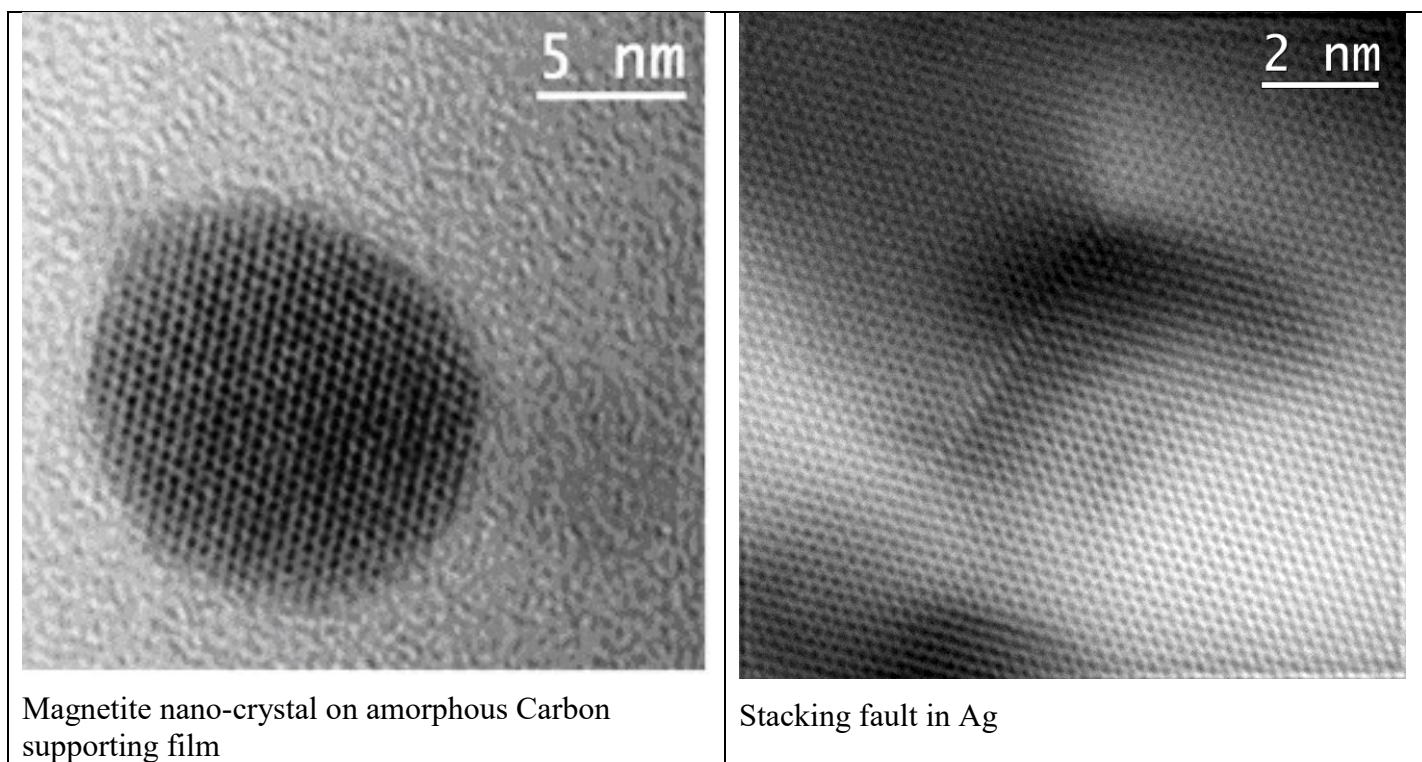
Imaging and diffraction theory is based on elastic scattering of electrons. The simplest theory is single scattering (=kinematic) theory. That is why we try to adjust experimental conditions to approach kinematic elastic scattering conditions. Since the electrons (as charged particles) interact with matter very strongly only the thinnest (a few times 10 nm thick) samples approach this condition. That is why we intentionally select only very thin samples for examination to facilitate interpretation of the results. As a consequence, absorption of electrons can be neglected in the examined samples with the result that the intensity distribution of the image points will correspond to the illumination distribution of the object points. Since we use a plane wave (i.e. parallel and homogeneous) illumination there will be no contrast in the image, we shall see nothing unless we intervene artificially.

While we observe the image we insert an aperture (a metal plane with a small hole) in the back focal plane. First we intentionally select such a small hole that only one of the rays shown in the back focal plane of Fig.1 can pass the hole. That condition ensures that if we see contrast it can only originate from a change in the amplitude of that single ray (since its phase is lost when the intensity was recorded). So, this is an amplitude contrast mechanism. However, the information content of the amplitude contrast image varies as a function of the position of this aperture within the back focal plane. If it is positioned centrally, only the beams parallel to the optical axis pass through it. In that case image points are only bright if there was no strong scattering in any direction in the object point, which correspond to this image point. If there were no object inserted, no scattering could have happened in any direction and all image points of the entire empty field of view would be bright. This position of the aperture produces bright field (BF) image. If the aperture is shifted to any of the side beams in the back focal plane only points of the image will be bright, which correspond to object points, which scatter in the single pre-selected direction. Without a sample there was no scattering in that direction and the empty field of view would be dark. Hence the name dark field (DF) image. Both BF and DF images are formed with amplitude contrast mechanism.



You can see that the BF image is affected by too many effects, while the contrast of the DF image is only determined by the single selected diffraction spot (a faint reflection of a precipitate in the example).

If the size of the hole in the aperture is increased, amplitude contrast is decreased (since we exclude fewer beams) but the possibility for a new contrast mechanism arises. When there are more beams present they can interfere and carry information about the phase difference between these beams. The resulting contrast mechanism is called phase contrast.

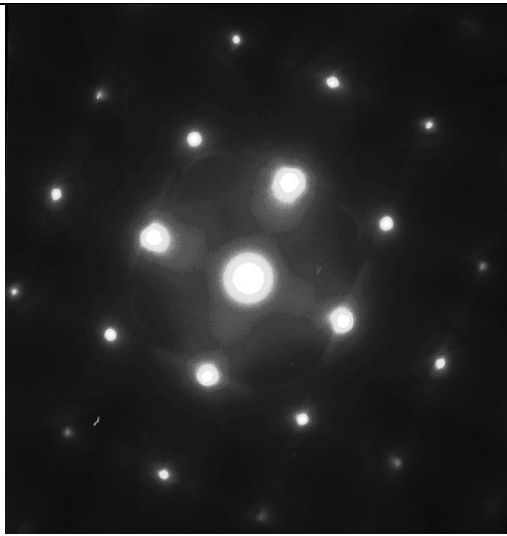


Examples of phase contrast high resolution (HRTEM) image

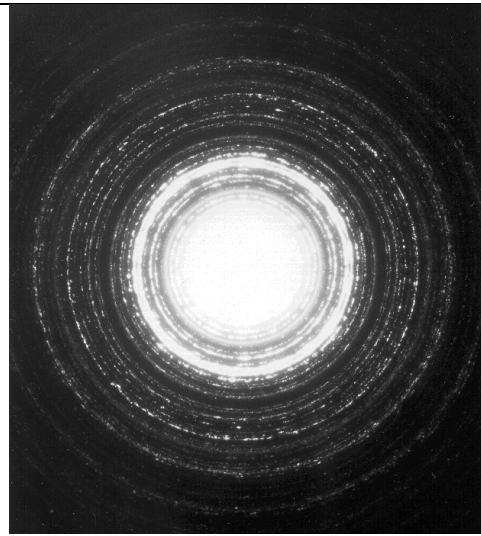
Localization of diffraction information

The diffraction pattern at the back focal plane contains structural information about the entire excited volume (i.e. the entire illuminated area) of the sample. Since we use homogeneous illumination over a large area this is global information unless we localize it artificially. While observing the diffraction pattern we insert an aperture into the image plane (so we observe the pattern through this hole from the direction of the plane of observation). Assuming thermal cathode (as in our case in the lab) the superposition of rays from distant areas of the sample is incoherent, so we only see the contribution of scattering from an area whose image falls into the aperture in the image plane. That aperture is called the area selecting aperture and the corresponding diffraction mode is selected area electron diffraction (SAED).

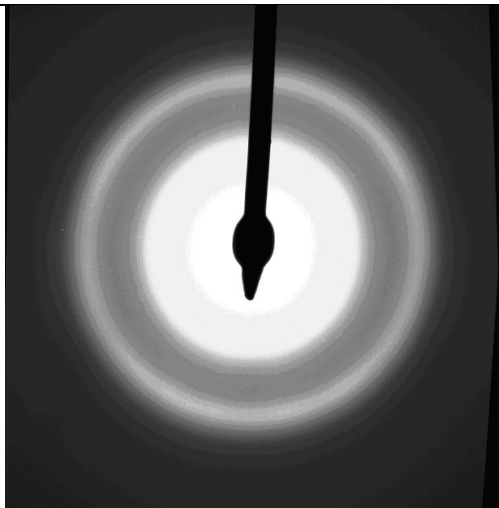
Basic types of SAED patterns (=parallel illumination)



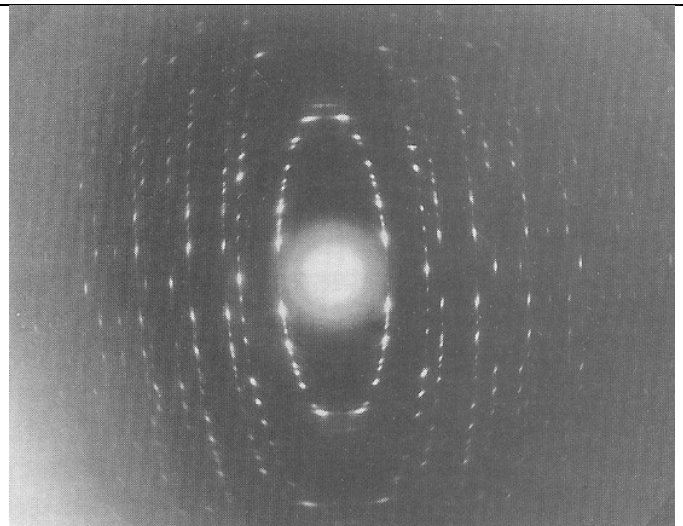
Single crystal pattern



Polycrystal pattern (either random orientation distribution or fiber textured looked from texture axis)



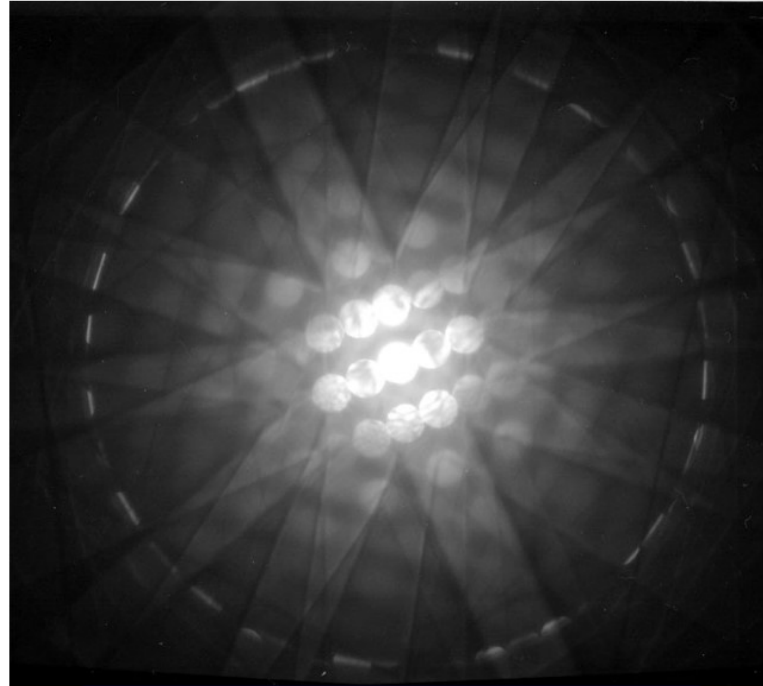
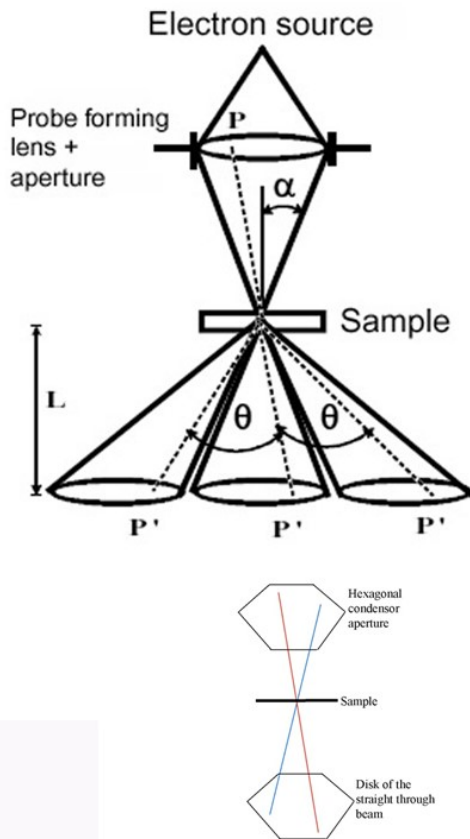
Amorphous pattern



Polycrystal pattern (tilted fiber texture)

We shall encounter the first two types of patterns during the laboratory practice (single crystal and polycrystal with random orientation distribution of grains).

Convergent illumination: CBED

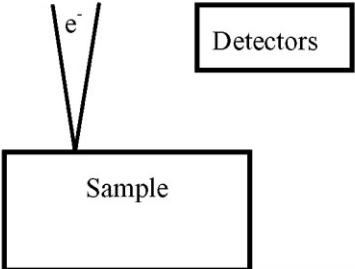
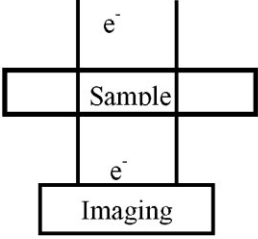
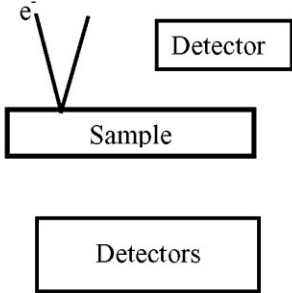


ZOLZ: Zero order Laue Zone
HOLZ: Higher Order Laue Zones
3D information from a single pattern

A diffraction pattern recorded with convergent beam illumination contains more information. It corresponds to many SAED patterns, each recorded with slightly different tilt of the beam and placed side-by-side.

Four features worth noting: 1/ The central part looks like a SAED with spots replaced by disks. 2/ Disks are missing in a circular band around this central part. 3/ Sections of a bright, sharp circle are seen outside this belt. 4/ Bright linear bands are seen in the background. These features will be discussed during the lab.

Different electron microscopes

SEM	TEM	STEM (AEM)
Bulk sample	Thin sample	Thin sample
0.2-50 kV	80-1250 kV (typical 100-400 kV)	100-300 kV
Image formation is electronic (and NOT optical)	Image formation is based on optical principle (lenses after the sample)	Characteristic imaging is electronic
Typical signals: SE, BE, AE, EBIC/EBIV, roentgen, EBSD	Typical signal: TE	Typical signal: TE, X-rays
Characteristic information: surface topography, average atomic number, potential, crystal orientation, composition	Characteristic information: grain structure, crystallography, defect structure	Characteristic information: average atomic number, composition, crystallography
		

In the present laboratory practice we study TEM (central column above). Main characteristics: thin sample, high energy electrons, mainly parallel illumination, principle of image formation is analogous to optical image formation.

In another practice the SEM is studied (left column). Main characteristics: bulk sample, lower energy electrons, convergent (focused) illumination, principle of image formation is electronic.