Electron Microscopy
Microscopes are used as magnifying tools (although not exclusively as will see later on). The resolution of the human eye is limited and can only distinguish points separated by about **100 microns**. Anything below this requires some sort of magnification.
A common misconception in microscopy is that more magnification is always better. Very often people ask “how much does the instrument magnify?” This is not the correct question, which should be “how little can it resolve?”.

An empty magnification occurs when the magnification exceeds the limits imposed by resolution, i.e., no additional information is provided by the optical system in spite of the high magnification.

Why microscopy?

<table>
<thead>
<tr>
<th>Magnification</th>
<th>Resolvable Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1µm - (10,000 Å)</td>
</tr>
<tr>
<td>1,000</td>
<td>0.1µm - (1,000 Å)</td>
</tr>
<tr>
<td>10,000</td>
<td>0.01µm - (100 Å)</td>
</tr>
<tr>
<td>1,000,000</td>
<td>0.0001µm - (1 Å)</td>
</tr>
</tbody>
</table>

Resolution of the Human Eye ~ 0.1 mm

Apparent resolution of the Eye for a Magnified Object is:

- Detail resolved
- Unresolved
If two image points are far away from each other, they are easily recognized as separate objects. However, when the distance between them is reduced, a limit point is reached when the maximum of the first Airy disk coincides with the first minimum of the second Airy disk. The superimposed profiles display two brightness maxima that are separated by a valley. The intensity in the valley is reduced by approximately 20 percent compared with the two maxima. This is just sufficient for the human eye to see two separate points, a limit that is referred to as the Rayleigh criterion.
Resolution of an optical system

Diffraction at an aperture - Rayleigh criterion

The Rayleigh criterion for the resolution of an optical system states that two points can be resolved if the maximum of the intensity of the Airy ring from one of them coincides with the first minimum intensity of the Airy ring of the other. This implies that the resolution, $\rho$ (strictly speaking, the resolving power) is given by:

$$\rho = \frac{1.22\lambda}{2(n \sin \mu)} = 0.61\lambda NA$$

where $\lambda$ is the wavelength, $n$ the refractive index and $\mu$ is the semi-angle at the specimen. NA is the numerical aperture:

- $\rho$ should be small!

<table>
<thead>
<tr>
<th>Minimum resolvable detail</th>
<th>NA = (n)sin(μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 point</td>
<td>(a) $\mu = 7^\circ$ NA = 0.12</td>
</tr>
<tr>
<td>2 points resolved</td>
<td>(b) $\mu = 20^\circ$ NA = 0.34</td>
</tr>
<tr>
<td>2 points unresolved</td>
<td>(c) $\mu = 60^\circ$ NA = 0.87</td>
</tr>
</tbody>
</table>

Intensity Distributions

- 1 point
- 2 points resolved
- 2 points unresolved

http://micro.magnet.fsu.edu/primer
Electron Microscopy

Introduction and History

- Electron microscopes are scientific instruments that use a beam of energetic electrons to examine objects on a very fine scale.

- Electron microscopes were developed due to the limitations of Light Microscopes which are limited by the physics of light.

- In the early 1930's this theoretical limit had been reached and there was a scientific desire to see the fine details of the interior structures of organic cells (nucleus, mitochondria...etc.).

- This required 10,000x plus magnification which was not possible using current optical microscopes.
Dates

• The transmission electron microscope (TEM) was the first type of Electron Microscope to be developed and is patterned exactly on the light transmission microscope except that a focused beam of electrons is used instead of light to "see through" the specimen. It was developed by Max Knoll and Ernst Ruska in Germany in 1931.

• The first scanning electron microscope (SEM) debuted in 1938 (Von Ardenne) with the first commercial instruments around 1965. Its late development was due to the electronics involved in "scanning" the beam of electrons across the sample.
Comparison between Optical and Electron Microscopy:

- In many ways, electron microscopes (Scanning and Transmission) are analogous to light microscopes.

- Fundamentally and functionally, electron microscopes (EM) and optical microscopes (OM) are identical.

- That is, both types of microscopes serve to magnify objects normally invisible to the naked eyes.

- Basically, component terminology of an EM is similar to that of an OM. Both microscopes consist on the following:
(a) **Source of Illumination** as light source
   – Electron Gun produces an electron beam by thermionic or field emission - EM
   – Lamp produces light beam (including uv rays) - OM

(b) **Condenser Lens system** projects a near parallel radiation on to the specimen
   – Electro-magnets of variable focal length are the lenses in EM.
   – Curved transparent substance - OM

(c) **Series of Imaging Lenses** form the Image of the specimen
Comparison of OM, TEM and SEM

Principal features of an optical microscope, a transmission electron microscope and a scanning electron microscope, drawn to emphasize the similarities of overall design.
<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>OPTICAL MICROSCOPE</th>
<th>ELECTRON MICROSCOPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illuminating Beam</td>
<td>Light Beam</td>
<td>Electron Beam</td>
</tr>
<tr>
<td>Wavelength</td>
<td>7,500Å (visible)</td>
<td>0.859Å (20 kV)</td>
</tr>
<tr>
<td></td>
<td>~2,000Å (ultraviolet)</td>
<td>~0.0370Å (100 kV)</td>
</tr>
<tr>
<td>Medium</td>
<td>Atmosphere</td>
<td>Vacuum</td>
</tr>
<tr>
<td>Lens</td>
<td>Optical lens (glass)</td>
<td>Electron Lens (magnetic or electrostatic)</td>
</tr>
<tr>
<td>Resolving Power</td>
<td>Visible: 3,000Å</td>
<td>Point to point: 3Å</td>
</tr>
<tr>
<td></td>
<td>Ultraviolet: 1,000Å</td>
<td>Lattice: 1.4Å</td>
</tr>
<tr>
<td>Aperture Angle</td>
<td>70º</td>
<td>~35’</td>
</tr>
<tr>
<td>Magnification</td>
<td>10x ~ 2,000x (lens exchange)</td>
<td>90x ~ 800,000x (continuously variable)</td>
</tr>
<tr>
<td>Focusing</td>
<td>Mechanically</td>
<td>Electrically</td>
</tr>
<tr>
<td>Contrast</td>
<td>Absorption, Reflection</td>
<td>Scattering absorption -SEM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diffraction, phase - TEM</td>
</tr>
<tr>
<td>Sample Type</td>
<td>Bulk sample</td>
<td>Bulk sample - SEM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thin foil (≤ 3 mm dia. and electron transparent, i.e. 1000 atoms in thickness) -TEM</td>
</tr>
<tr>
<td>Information</td>
<td>Grain size and shape</td>
<td>Grain size and shape</td>
</tr>
<tr>
<td></td>
<td>Distribution of phases (particles)</td>
<td>Distribution of phases (particles)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical composition, e.g Identify phases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crystal and defect structure</td>
</tr>
</tbody>
</table>
Principles of Electron Microscopy
Scanning electron microscopy is used to observe topographies of specimens at very high magnifications. SEM magnifications can go to more than 500,000 X but most applications require magnifications of less than 50,000 X.

During SEM inspection, a beam of electrons is focused on a spot volume of the specimen. These bombarding electrons, also referred to as primary electrons, removing electrons from the specimen itself. The outgoing electrons, also known as secondary electrons, are attracted and collected by a positively biased grid or detector.

To produce the SEM image, the electron beam is swept across the area being inspected. The signals are then amplified, analyzed, and translated into images of the topography being inspected. Finally, the image is shown on a CRT monitor.
SEM - Working principles

An electron gun generates electrons. A condenser lens focus the beam to form the smallest point possible. There are then scanning coils that deflect the beam and make it raster the sample surface.

When the beam hits the sample, it generates several signal types (the electrons are accelerated by 20-20 kV and have therefore a high kinetic energy). If a detector is used to detect one of those signal types we can attribute to each point a signal intensity. Therefore, if we feed a CRT monitor with the signal in a synchronized way with can build an image point by point.
Electron-Solid Interactions

When an electron beam strikes a sample, a large number of signals are generated.

We can divide the signals into two broad categories: a) electron signals, b) photon signals.
Figure 1. Summary of the various signals obtained by interaction of electrons with matter in an electron microscope.
SEM – Beam/specimen interactions

- Primary electron beam
- Sample
- Source of secondary electrons (~ 50 nm)
- Source of backscattered electrons (~ 1 - 2 μm)
- Source of electron-excited characteristic X-rays (~ 2 - 5 μm)
- 10Å-Auger electrons
- Secondary electrons
- Backscattered electrons
- Characteristic X-rays
- Continuum X-rays
- Secondary fluorescence by continuum and characteristic X-rays
- BSE spatial resolution
- X-ray resolution
Scanning Electron Microscopy (SEM)

- The energy of the primary electrons determines the quantity of secondary electrons collected during inspection. The emission of secondary electrons from the specimen increases as the energy of the primary electron beam increases, until a certain limit is reached. Beyond this limit, the collected secondary electrons diminish as the energy of the primary beam is increased, because the primary beam is already activating electrons deep below the surface of the specimen. Electrons coming from such depths usually recombine before reaching the surface for emission.

- Aside from secondary electrons, the primary electron beam results in the emission of backscattered (or reflected) electrons from the specimen. Backscattered electrons possess more energy than secondary electrons, and have a definite direction. As such, they can not be collected by a secondary electron detector, unless the detector is directly in their path of travel. All emissions above 50 eV are considered to be backscattered electrons.
ELECTRON SOURCES

• Electron sources in electron beam instruments are required to provide either
  – a large total current beam of about 50 µm diameter - low magnification and TEM, or
  – a high intensity probe of electrons as small as 0.5 nm in diameter - SEM

• There are three different types of electron source available
Electron gun cathodes

(FEG = Field Emission Gun)
• There are three different types of electron source available

a) **Thermionic tungsten hairpin filament**
   This is usually heated to about 2800 K by direct resistance heating. The surrounding grid, known as the Wehnelt cylinder and the anode, which is at earth potential, act as an electrostatic lens.

For an operating condition of 100 kV, the brightness is about $3 \times 10^5$ A cm$^{-2}$. 
b) **Lanthanium hexaboride crystal (LaB$_6$)**

The only difference between the conventional assembly and a modern LaB$_6$ assembly is that extra pumping holes are present in the Wehnelt cap to ensure a better pumping speed near the tip.

Higher current (greater than the tungsten) is obtainable in small probes.

The brightness of a LaB$_6$ can be as high as $10^7$ A cm$^{-2}$ at 100kV (3 x $10^5$ A cm$^{-2}$, in thermionic filaments).
c) **Field emission source**

This is usually a $<111>$ orientation crystal of tungsten, and a Wehnelt cylinder, which is raised to an extraction potential up to about 4 kV in order to cause emission from the tip of the crystal.

There is a requirement of high vacuum for this source.

The brightness of cold or thermal emission source can be about $10^4$ times of a conventional tungsten filament.

The high brightness of this source make them preferable for scanning instruments.
Electron gun – field emission

In the field emission gun, a very strong electric field ($10^9 \text{ Vm}^{-1}$) is used to extract electrons from a metal filament. Temperatures are lower than that needed for thermionic emission. This gives a higher source brightness that in thermionic guns, but requires a very good vacuum. In order to get high field strengths with low voltages, the field emitting tip has a strong curvature. The emitting region can be less than 10 nm.

The grid provides the field which extracts the electrons by a tunneling mechanism. The combination of a modest potential with a very small tip radius results in a very high field strength.

The anode is a positively charged metal plate (i.e., at earth potential), that has a hole in it. Its function it to accelerate the electron beam towards the specimen.
## Electron gun cathodes

**Electron Gun - Thermionic vs Field Emission**

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>Tungsten</th>
<th>LaB$_6$</th>
<th>FEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>K</td>
<td>2700</td>
<td>1700</td>
<td>300</td>
</tr>
<tr>
<td>Current Density</td>
<td>A/m$^2$</td>
<td>5x10$^{-4}$</td>
<td>10$^6$</td>
<td>10$^{10}$</td>
</tr>
<tr>
<td>Crossover size</td>
<td>$\mu$m</td>
<td>50</td>
<td>10</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Energy spread</td>
<td>eV</td>
<td>3</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Vacuum</td>
<td>Pa</td>
<td>10$^{-2}$</td>
<td>10$^{-4}$</td>
<td>10$^{-8}$</td>
</tr>
<tr>
<td>Lifetime</td>
<td>hr</td>
<td>100</td>
<td>500</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>
ELECTRON LENSES AND OPTICS
Electromagnetic lenses

The electron microscopes have electromagnetic lenses which are basically coils that generate an electromagnetic field that acts on the electrons, focusing them as glass lenses focuses light.

One of the practical differences between the optical microscope and the electron microscopes is that these have dynamic lenses like our eyes that can adapt as opposed to glass lens that have fixed characteristics. That is, if one wants to increase magnification in an optical microscope, it is necessary to change the objective, whereas in the electron microscope you just have to turn a knob and supply more current to the lens to make it stronger.
Electro-magnets steer the beam so it scans the sample.
SEM - Signal detection

SE = secondary electrons

BSE = Backscatter electrons

EDS = X-Ray Energy Dispersive Spectroscopy

VP = variable pressure (environmental SEM)

Stage base
SEM – Electron signal types

Energy distribution of SE and BSE

Plasmon losses

(Primary beam energy)
The detector consists primarily of a **scintillator inside a Faraday cage**. A low positive voltage is applied to the Faraday cage to **attract** the relatively low energy (less than 50 eV) **secondary electrons**. Other electrons within the specimen chamber are not attracted by this low voltage and will only reach the detector if their direction of travel takes them to it. The scintillator has a high positive voltage (~10 kV) to accelerate the incoming electrons to it where they can be converted to light photons. The direction of their travel is focused to the light guide by a metal coating on the scintillator acting as a mirror. In the light pipe the photons travel outside of the microscope's vacuum chamber to a photomultiplier tube for amplification.
SEM - Everhart-Thornley electron detector (SE)
Summary of Electron Microscope Components

1. Electron optical column consists of:
   - electron source to produce electrons
   - magnetic lenses to de-magnify the beam
   - magnetic coils to control and modify the beam
   - apertures to define the beam, prevent electron spray, etc.

2. Vacuum systems consists of:
   - chamber which “holds” vacuum, pumps to produce vacuum
   - valves to control vacuum, gauges to monitor vacuum

3. Signal Detection & Display consists of:
   - detectors which collect the signal
   - electronics which produce an image from the signal
Typical Information from Electron Microscope:

- **Imaging** (surface) can be characterized using secondary electrons, backscattered electrons, photoelectrons, Auger electrons and ion scattering.

- **Crystallography** or crystal structure information can be obtained from backscattered electrons (diffraction of photons or electrons).

- **Chemical composition** of materials can be obtained using electron microprobes to produce characteristic X-ray emissions and electron energy losses.

The various studies of materials exploit at least one of the above information, as well as the excellent **spatial resolution** of electron microscopes.
SEM - Topographic contrast (SE)
(where do the shades come from?)

Rippel E.M. Facility
SE are generated throughout the whole interaction volume (IV), but can only escape if they are originating from near the surface. In a hill there is more exposed surface of the IV: more SE escape and signal is higher. In the valleys there is less surface exposed and less SE escape. Hills appear as bright regions and valleys as dark regions in SE images.

SEM - Topographic contrast (SE)
(where do the shades come from?)

The images obtained with the SE signal look as if they had topographic contrast, how is this contrast formed?
SEM - Depth of field (SE)

The SEM has a great advantage its high depth of field. You can see in this image an object imaged with an OM and while you see some point in focus, the ones just below or just above are defocused. This does happen with the SEM image, where you see the whole object in focus.
**Depth of Field**

The distance parallel to the optical axis of the microscope that a feature on the specimen can be displaced without loss of resolution.

**Optical Microscope**

\[ d = \frac{\lambda \sqrt{\eta^2 - (NA)^2}}{(NA)^2} + \frac{250}{M^2} \]

**Electron Microscope**

\[ d = \frac{0.1 \text{ mm}}{M \alpha} \]

- \( \lambda \) = wavelength
- \( \eta \) = refractive index
- \( \alpha \) = semi angle
- \( M \) = total magnification
- NA = Numerical Aperture of lens
## Depth of Field

<table>
<thead>
<tr>
<th>Magnification</th>
<th>Depth of Focus</th>
<th>Optical</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>60 μm</td>
<td>1000 μm</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>8 μm</td>
<td>100 μm</td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td>0.2 μm</td>
<td>10 μm</td>
<td></td>
</tr>
<tr>
<td>10,000</td>
<td>-</td>
<td>1 μm</td>
<td></td>
</tr>
</tbody>
</table>
Resolution:

- Resolution defines the smallest separation of two points in the object, which may be distinctly reproduced in the image.
- The **resolving power** for light microscopy is determined by **diffraction aberration** and can be defined as

\[
\rho = \frac{k\lambda}{n \sin \alpha}
\]

- where \( \lambda \) is the wavelength of the illumination, \( n \) is the refractive index of the medium between the specimen and the lens, \( \alpha \) is the semi-angle (aperture angle) subtended by the object at the lens and \( k \) is a constant usually taken to be 0.61.
Light vs electrons

The wavelengths of electrons are much smaller and by using the Rayleigh criterion we can see that an optical microscope can resolve ~ 2000 Angstroms, while the electron microscope can resolve ~ angstroms.

\[ \rho = 0.61 \frac{\lambda}{(n \sin \alpha)} \]

<table>
<thead>
<tr>
<th>Light Microscope</th>
<th>Electron Microscope</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda = 0.5 , \mu m )</td>
<td>( \lambda \sim \sqrt{\frac{150}{V_0}} = 0.055 , \AA , (@50 , kV) )</td>
</tr>
<tr>
<td>( n = 1.5 ) (glass)</td>
<td>( n = 1.0 ) (Vacuum)</td>
</tr>
<tr>
<td>( \alpha = 70^\circ )</td>
<td>( \alpha = 1^\circ )</td>
</tr>
<tr>
<td>( \rho = 0.2 , \mu m = 2000 , \AA )</td>
<td>( \rho = 0.00016 , \mu m = 1.6 , \AA )</td>
</tr>
</tbody>
</table>

Nowadays TEMs can resolve in the sub-angstrom range…
### Variation of Electron Wavelength with applied voltage

<table>
<thead>
<tr>
<th>Applied Voltage (keV)</th>
<th>Wavelength, ( \lambda ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.008588</td>
</tr>
<tr>
<td>50</td>
<td>0.005355</td>
</tr>
<tr>
<td>80</td>
<td>0.00418</td>
</tr>
<tr>
<td>100</td>
<td>0.003702</td>
</tr>
<tr>
<td>200</td>
<td>0.002508</td>
</tr>
<tr>
<td>500</td>
<td>0.001421</td>
</tr>
<tr>
<td>1000</td>
<td>0.00872</td>
</tr>
</tbody>
</table>

The **ultimate resolution** of an **electron microscope** is dictated not by wavelength but by the defects in the imaging system (diffraction aberration) of the radiation employed.
SEM - Backscattered electron detector

BSE are primary electrons bounced by the sample that are not easily collected due to their high energy: their trajectory cannot be changed with an external potential (as with the SE detector), as this would induce perturbation of the primary beam. To maximize collection the detector is concentric and below the objective lens.
Conductive sample

High vacuum

Primary e-beam

Residual gas molecule

BSE Detector

Obj. lens
SEM - SE vs BSE electron images

Topographic contrast (SE mode)  Atomic number contrast (BSE mode)

BSE are used because their emission is sensitive to the atomic number, contrarily to the SE signal. The same region observed with the two signal types. The bright regions in the SE image correspond to hills, whereas the bright regions in the BSE image correspond to the presence of heavier elements. Heavier elements scatter electron more efficiently so show up brighter in the images. This atomic number contrast is a major advantage of the BSE detector.
SEM – Compositional contrast (BSE)

BSE images
Scanning Electron Microscopy (SEM)

- Backscattered electron imaging is useful in distinguishing one material from another, since the yield of the collected backscattered electrons increases monotonically with the specimen's atomic number. Backscatter imaging can distinguish elements with atomic number differences of at least 3, i.e., materials with atomic number differences of at least 3 would appear with good contrast on the image.

- A SEM may also be equipped with an EDX analysis system to perform compositional analysis on specimens. EDX analysis is useful in identifying materials and contaminants, as well as estimating their relative concentrations on the surface of the specimen.
Sample Preparation

Sample Coating

Q: Why?
A: Charging:

- Deflection of SE’s
- Increased emission of SE’s in cracks
- Periodic SE bursts
- Beam deflection

Solutions:
- Sputter coating with C, Cr, or Au-Pd
- Carbon tape, carbon paint, In foil
Sample preparation

- Samples need to be electrically conductive.
- Samples are analyzed under vacuum and biological samples need careful and complex preparation.
- How to turn a mosquito conductive?
SEM - Biological Sample Preparation

**Biological structures collapse under vacuum...**

**Fixation/dehydration/drying/mounting/coating**

**Fixation**: Stabilization of biological material. Chemical fixation (cross-linking) with Aldehydes or OsO₄.

**Dehydration**: Substitution of water with solvent (ethanol, acetone) Usually performed with gradient of different concentrations.

**Critical point drying**: replace ethanol with CO₂ brought to critical point (31.1 C and 1,073 psi), becomes dense vapor phase; Gaseous CO₂ vented slowly to avoid condensation.

**Or Hexametildisilizane (HMDS) drying**: transition from ethanol to HMDS (reduces capillarity effects during drying), left overnight in desiccator with silica gel.

**Mounting**: on a stub that can be inserted in the SEM sample holder.

**Coating**: with conductive layer: Prevent charging effects that hinder suitable image formation.
Typical SEM images

Coloured image of soybean cyst nematode and egg. The colour makes it easier for non-specialists to understand the structures.

SEM image of normal circulating human blood.

SEM image of an electronic component.

All except one image have a problem. Why?
No scale bar ...
Environmental SEM

Environmental secondary electrons detector

The environmental Secondary Detector uses gas ionization to amplify the secondary electron signal. In non-conductive samples, positive ions are attracted to the sample surface where negative charges from the beam tend to accumulate. The positive ions effectively suppress charge artifacts!!!

What are the implications for ceramic, polymer and biological samples observation?
What are the implications for ceramic, polymer and biological samples observation?

The negative charge accumulated in non-conductive samples is balanced by the positive ions: no-coating needed.
Environmental SEM

Known compromises:

- Gas-electron interactions radially scatter the primary electrons away from the intended landing point. Function of:
  - gas type,
  - pressure,
  - path length
  - acceleration voltage

- Primary beam current cannot be directly measured and it fluctuates with pressure (EDS X-ray maps are diffuse and point analysis require normalization.

Useful for biological samples as they can be observed without vacuum (even living).

Useful for non-conductive samples as the positive ions annihilate charge effects. No conducting coating is required but resolution is lower than with standard SEMs.

Most instruments can also operate at high vacuum and have a standard SE detector.
Crystallography:

• Crystal structure analysis is usually based on diffraction phenomena caused by the interaction of matter with X-rays, electrons, or neutrons.

• Therefore, when either X-rays or electrons interact with crystalline material, they are:
  
  (a) Subject to diffraction – have similar wave properties.
  
  (b) Monochromatic radiation - produce a series of strongly diffracted beams leaving the crystal in defined and predicted directions.
• The resultant diffraction pattern is given by Bragg’s Law, and this is given by

\[ n\lambda = 2d \sin \theta \]

where,
- \(d\): Interplanar spacing
- \(\theta\): Grazing angle of incidence (Bragg angle)
- \(n\): Integer (0, 1, 2, 3 \ldots)
- \(\lambda\): Wavelength of the incident electrons

• Note
  - With diffraction, we use Reciprocal lattice in which sets of lattice planes are represented simply by a set of points in reciprocal space.
Table 1. Characteristics of Light and Radiations Used for Diffraction.

<table>
<thead>
<tr>
<th></th>
<th>Light</th>
<th>Neutrons</th>
<th>X-rays</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength [nm]</td>
<td>400-700</td>
<td>0.05 - 0.3</td>
<td>0.05 - 0.3</td>
<td>0.001 - 0.01</td>
</tr>
<tr>
<td>Energy [eV]</td>
<td>1</td>
<td>1.00E-02</td>
<td>1.00E+04</td>
<td>1.00E+05</td>
</tr>
<tr>
<td>Charge [C]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1.60E-19</td>
</tr>
<tr>
<td>Rest mass [g]</td>
<td>0</td>
<td>1.67E-24</td>
<td>0</td>
<td>9.11E-28</td>
</tr>
<tr>
<td>Penetration depth [mm]</td>
<td>0</td>
<td>10 - 100</td>
<td>0.01 - 0.1</td>
<td>1.00E-03</td>
</tr>
</tbody>
</table>

- Electrons are the only radiation in which their penetration depth and interaction volume is small enough to allow diffraction from individual grains (very small volume). Hence, only electrons can be used for **MICROTEXTURE**
CHEMICAL COMPOSITION

Energy dispersive X-ray spectroscopy (EDS)
Wavelength dispersive X-ray spectroscopy (WDS)
Advantages vs Disadvantages of SEM

- **Advantages**
  - high depth of field
  - direct observation of the external form of real objects at high magnifications
  - wide range of magnifications (below 50 x to over 100 000x)
  - local chemical and crystallographic analyzes

- **Disadvantages of SEM**
  - high vacuum environment of the specimen
    (difficult with porous materials, damaging for biological samples...)
  - inability to show internal detail
  - inability to obtain highest resolution
  - conductive samples: The samples need to be conductive because otherwise they tend to charge and eventually charging pertubates the primary beam and signal detection.