# Scanning Electron Microscopy (SEM)

# Electron Microscopy

## Introduction and History

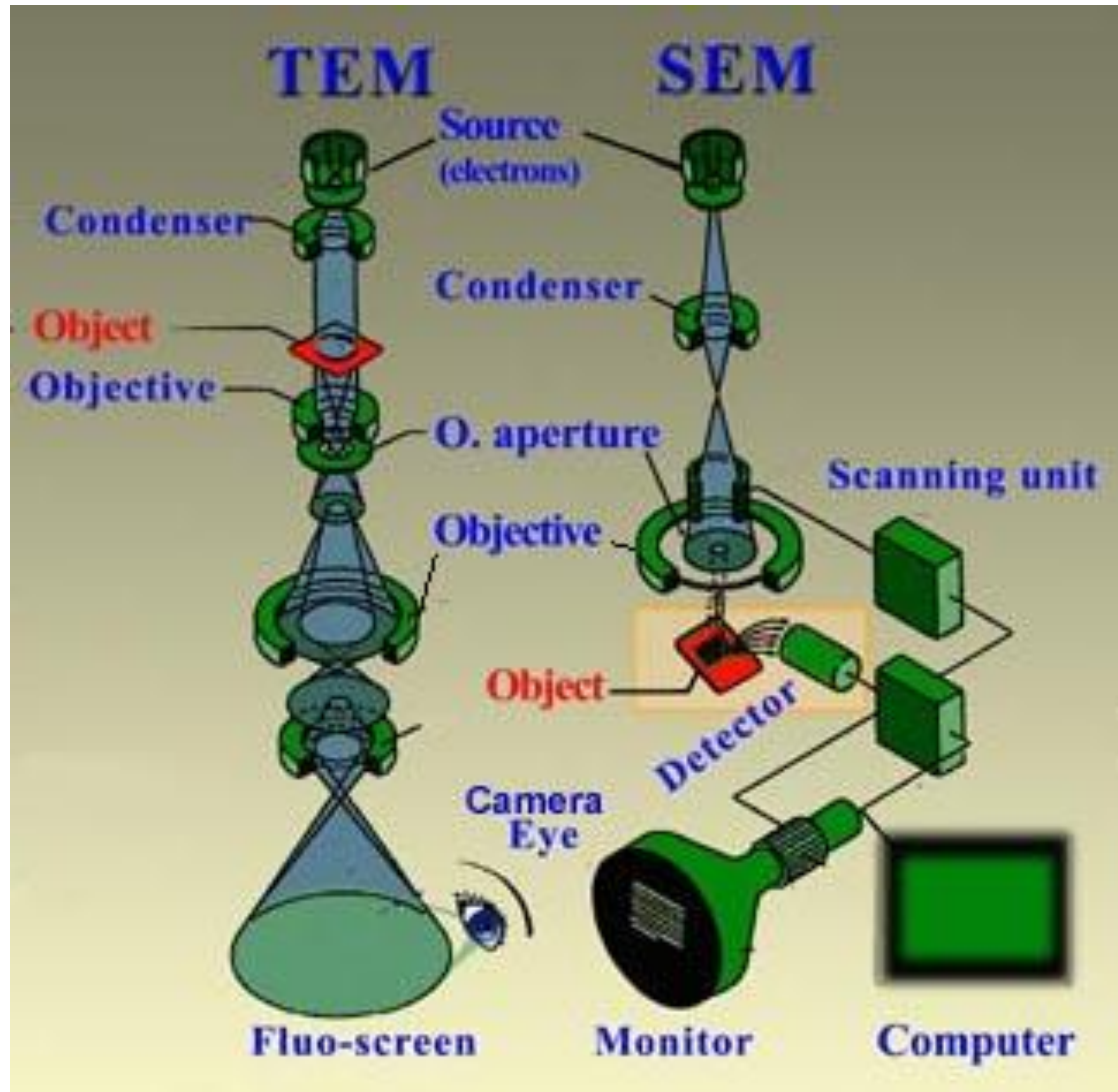
- Electron microscopes are scientific instruments that use a beam of energetic electrons to examine objects on a very fine scale.

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

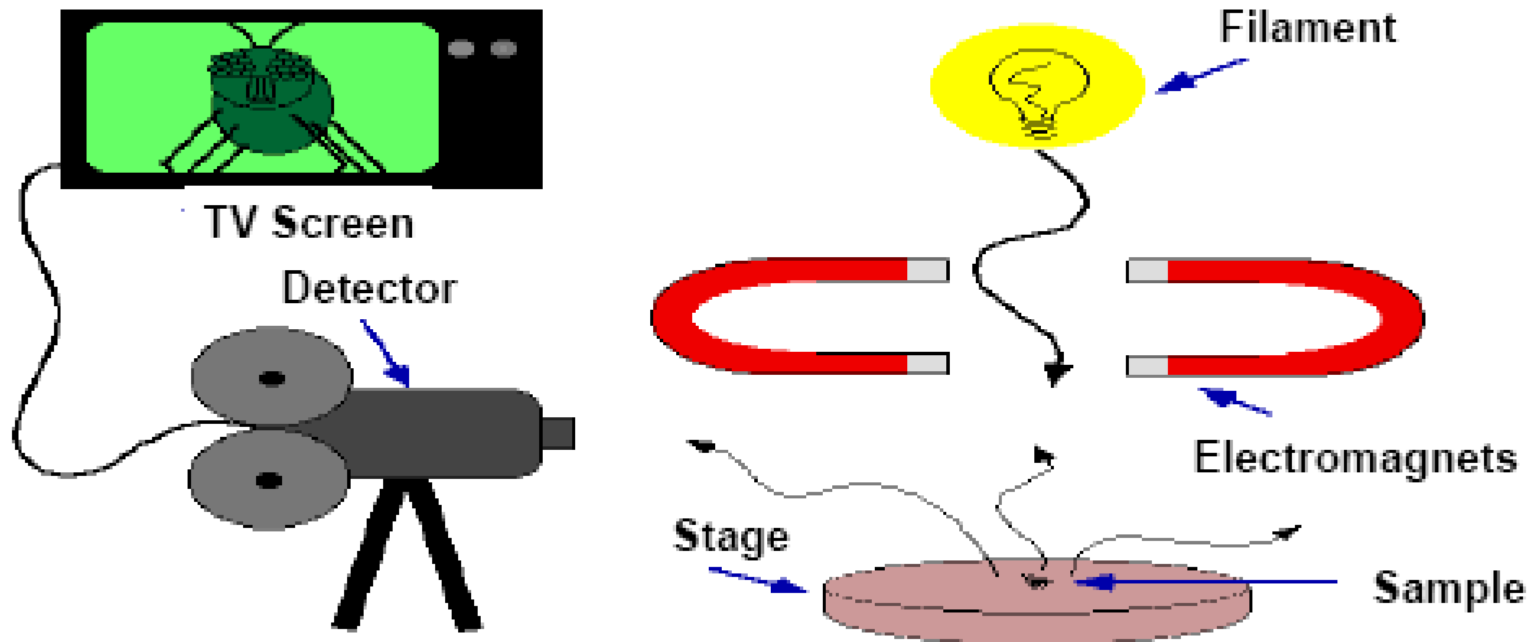
- In the early 1930's this theoretical limit had been reached and there was a scientific desire to see the fine details of the interior structures of organic cells (nucleus, mitochondria...etc.).

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

# (SEM) and TEM



# Breakdown of an Electron Microscope




In simplest terms, an SEM is really nothing more than a television. We use a filament to get electrons, magnets to move them around, and a detector acts like a camera to produce an image.

# Scanning Electron Microscopy (SEM)

Scanning electron microscopy is used for inspecting topographies of specimens at very high magnifications using a piece of equipment called the scanning electron microscope. SEM magnifications can go to more than 300,000 X but most semiconductor manufacturing applications require magnifications of less than 3,000 X only. SEM inspection is often used in the analysis of die/package cracks and fracture surfaces, bond failures, and physical defects on the die or package surface. During SEM inspection, a beam of electrons is focused on a spot volume of the specimen, resulting in the transfer of energy to the spot. These bombarding electrons, also referred to as primary electrons, dislodge electrons from the specimen itself. The dislodged electrons, also known as secondary electrons, are attracted and collected by a positively biased grid or detector, and then translated into a signal.

To produce the SEM image, the electron beam is swept across the area being inspected, producing many such signals. These signals are then amplified, analyzed, and translated into images of the topography being inspected. Finally, the image is shown on a CRT.

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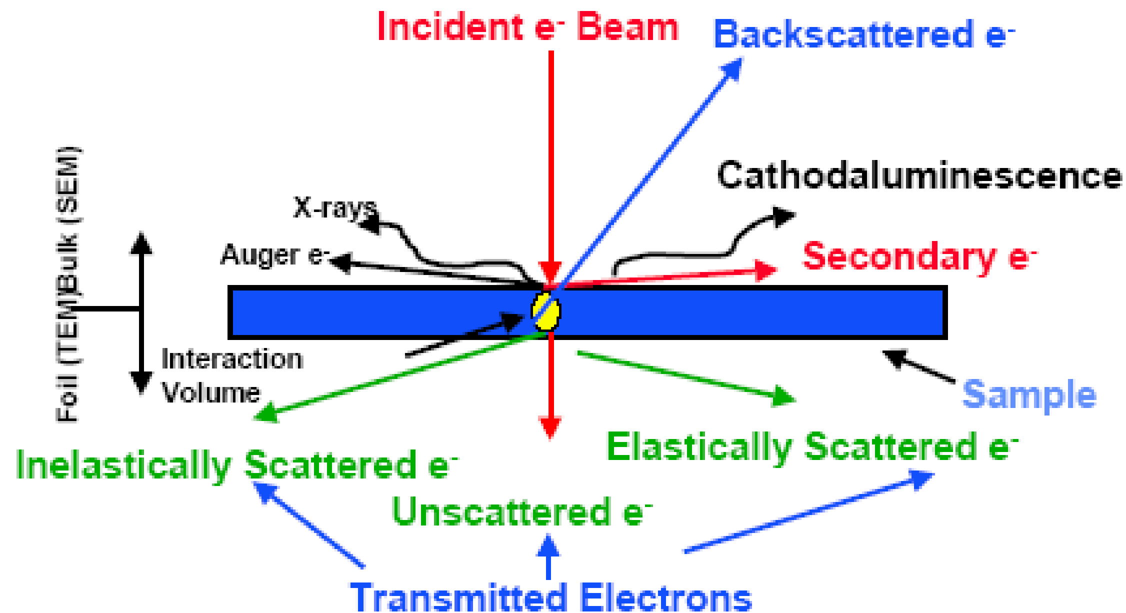
- Aside from secondary electrons, the primary electron beam results in the emission of backscattered (or reflected) electrons from the specimen. Backscattered electrons possess more energy than secondary electrons, and have a definite direction. As such, they can not be collected by a secondary electron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

# 2.1 Electron-Solid Interactions

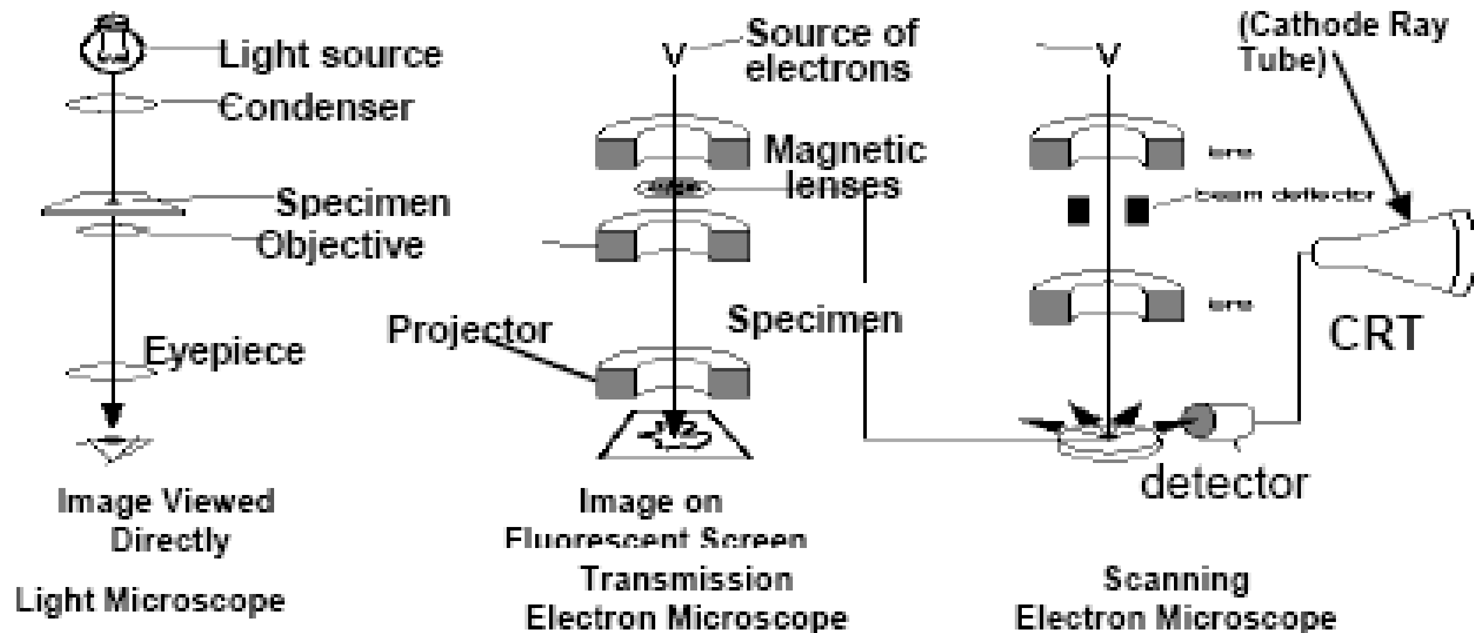
When an electron beam strikes a sample, a large number of signals are generated.




We can divide the signals into two *broad* categories:

a) electron signals, b) photon signals

# 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.

# 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.

# 1.1 Characteristic Information: SEM

## Topography

The surface features of an object or "how it looks", its texture; direct relation between these features and materials properties

## Morphology

The shape and size of the particles making up the object; direct relation between these structures and materials properties

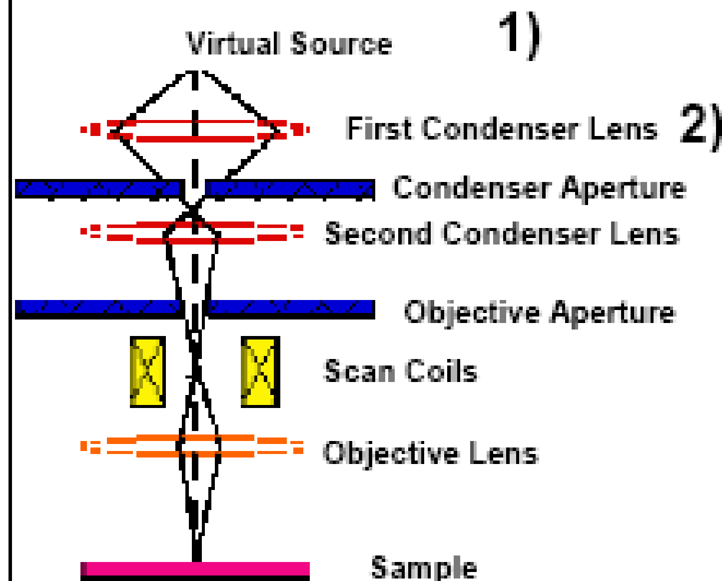
## Composition

The elements and compounds that the object is composed of and the relative amounts of them; direct relationship between composition and materials properties

## Crystallographic Information

How the atoms are arranged in the object; direct relation between these arrangements and material properties

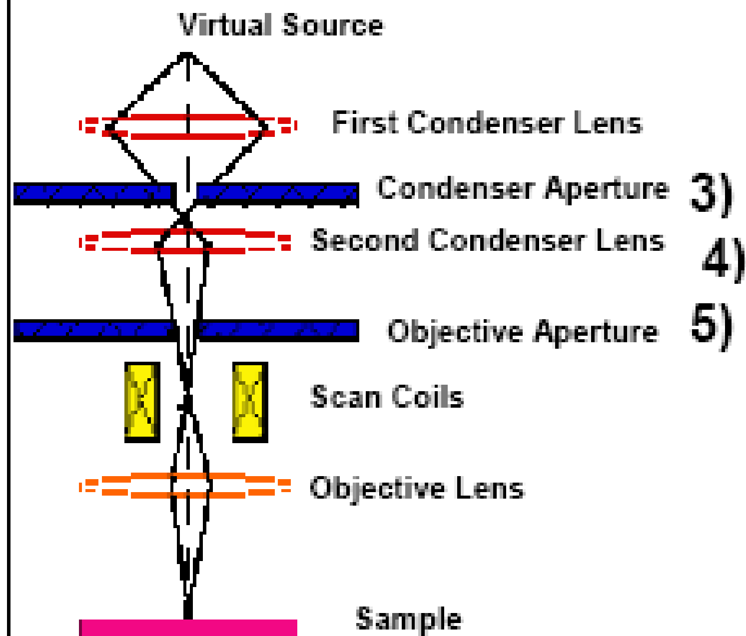
# Scanning Electron Microscope




1) The "Virtual Source" at the top represents the electron gun, producing a stream of monochromatic electrons.

2) The stream is condensed by the first condenser lens (usually controlled by the "coarse probe current knob"). This lens is used to both form the beam and limit the amount of current in the beam. It works in conjunction with the condenser aperture to eliminate the high-angle electrons from the beam.

# Scanning Electron Microscope

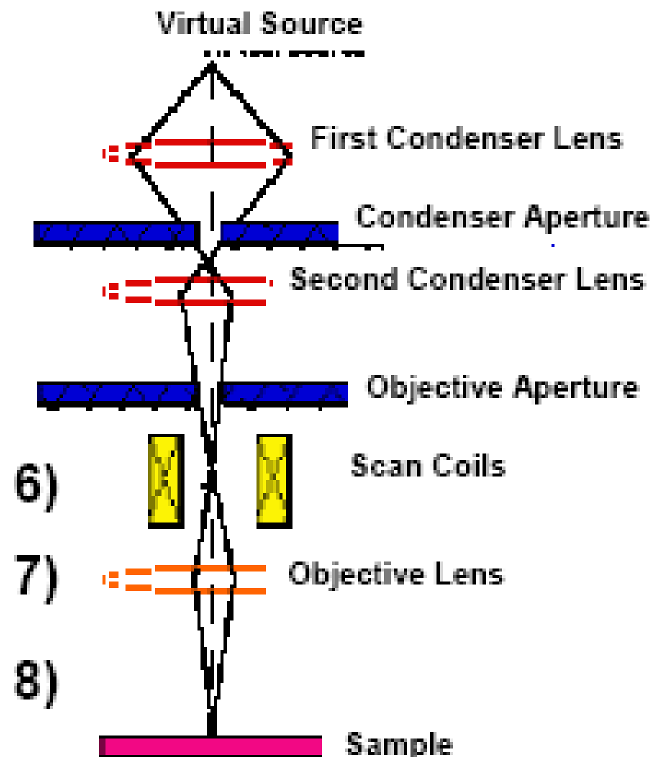



3) The beam is then constricted by the condenser aperture (usually not user selectable), eliminating some high-angle electrons.

4) The second condenser lens forms the electrons into a thin, tight, coherent beam and is usually controlled by the "fine probe current knob".

5) A user selectable objective aperture further eliminates high-angle electrons from the beam.

# Scanning Electron Microscope

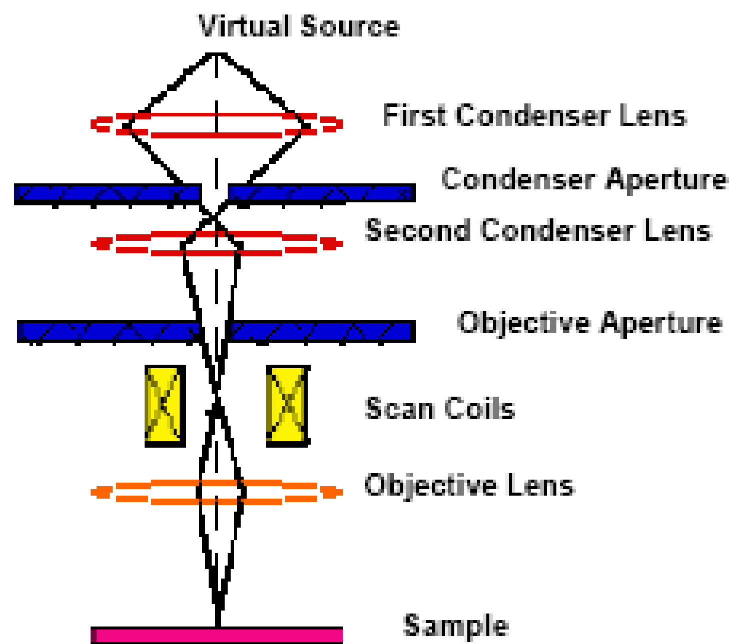



6) A set of coils then "scan" or "sweep" the beam in a grid fashion (like a television), dwelling on points for a period of time determined by the scan speed (usually in the microsecond range).

7) The final lens, the objective, focuses the scanning beam onto the part of the specimen desired.

8) When the beam strikes the sample (and dwells for a few microseconds) interactions occur inside the sample and are detected with various instruments.

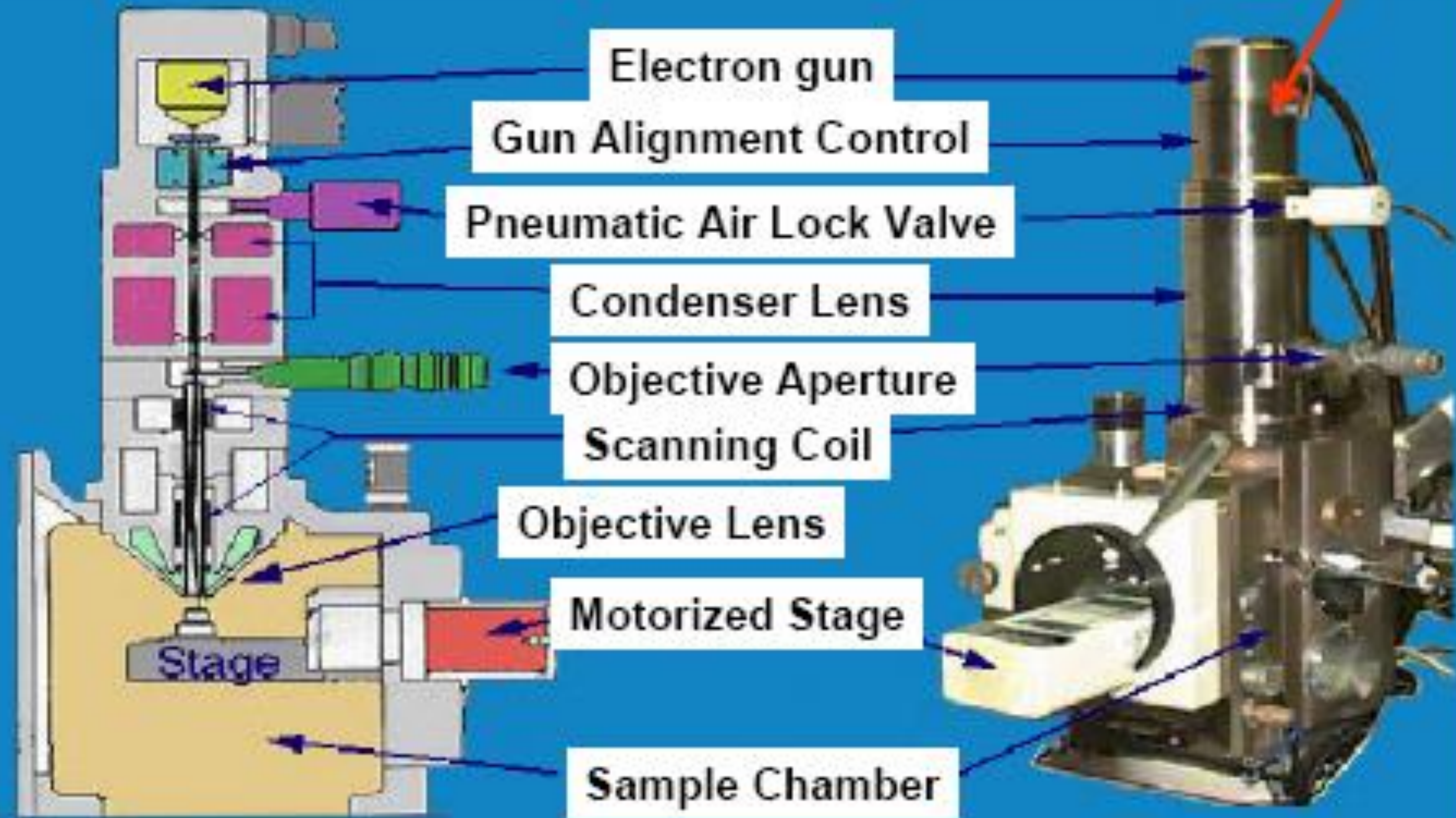
# Scanning Electron Microscope




9) Before the beam moves to its next dwell point these instruments count the number of $e^-$ interactions and display a pixel on a CRT whose intensity is determined by this number (the more reactions the brighter the pixel).

10) This process is repeated until the grid scan is finished and then repeated, the entire pattern can be scanned 30 times/sec.

# A Look Inside the Column



# 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

# Resolution

We can also improve the resolution by:

- Increasing the strength of the condenser lens
- Decreasing the size of the objective aperture
- Decreasing the working distance (WD = the distance the sample is from the objective lens)

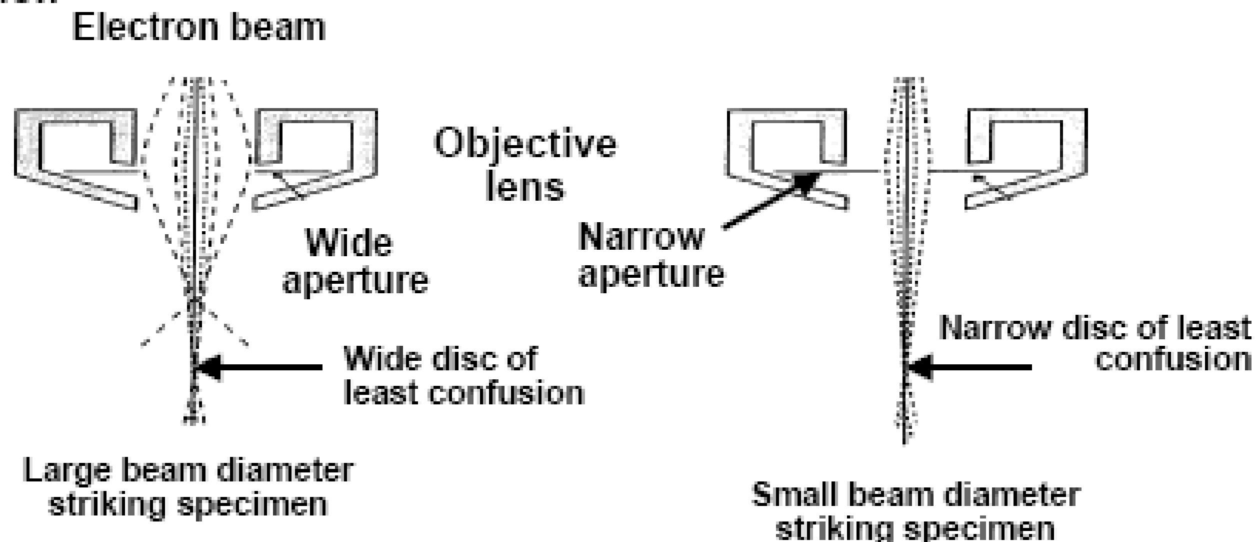
# Transmission Electron Microscopy (TEM)

# Electromagnetic Lenses

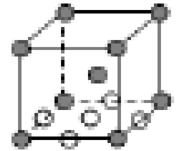
## The Objective Lens - Aperture

- Since the electrons coming from the electron gun have spread in kinetic energies and directions of movement, they may not be focused to the same plane to form a sharp spot.

- By inserting an aperture, the stray electrons are blocked and the remaining narrow beam will come to a narrow "Disc of Least Confusion"



# Probes used



- **Visible light**
  - Optical microscopy (OM)
- **X-ray**
  - X-ray diffraction (XD)
  - X-ray photo electron spectroscopy (XPS)
- **Neutron**
  - Neutron diffraction (ND)
- **Ion**
  - Secondary ion mass spectrometry (SIMS)
  - Cleaning and thinning samples
- **Electron**
  - Scanning electron microscopy (SEM)
  - Transmission electron microscopy (TEM)
  - Electron holography (EH)
  - Electron diffraction (ED)
  - Electron energy loss spectroscopy (EELS)
  - Energy dispersive x-ray spectroscopy (EDS)
  - Auger electron spectroscopy (AES)

# Electron-Solid Interactions

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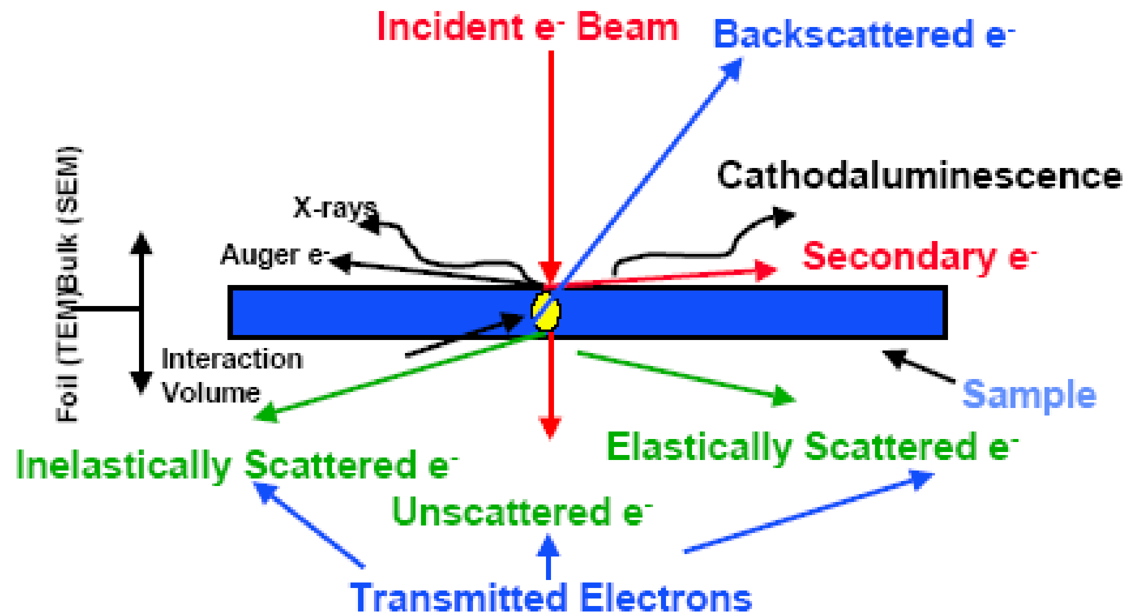


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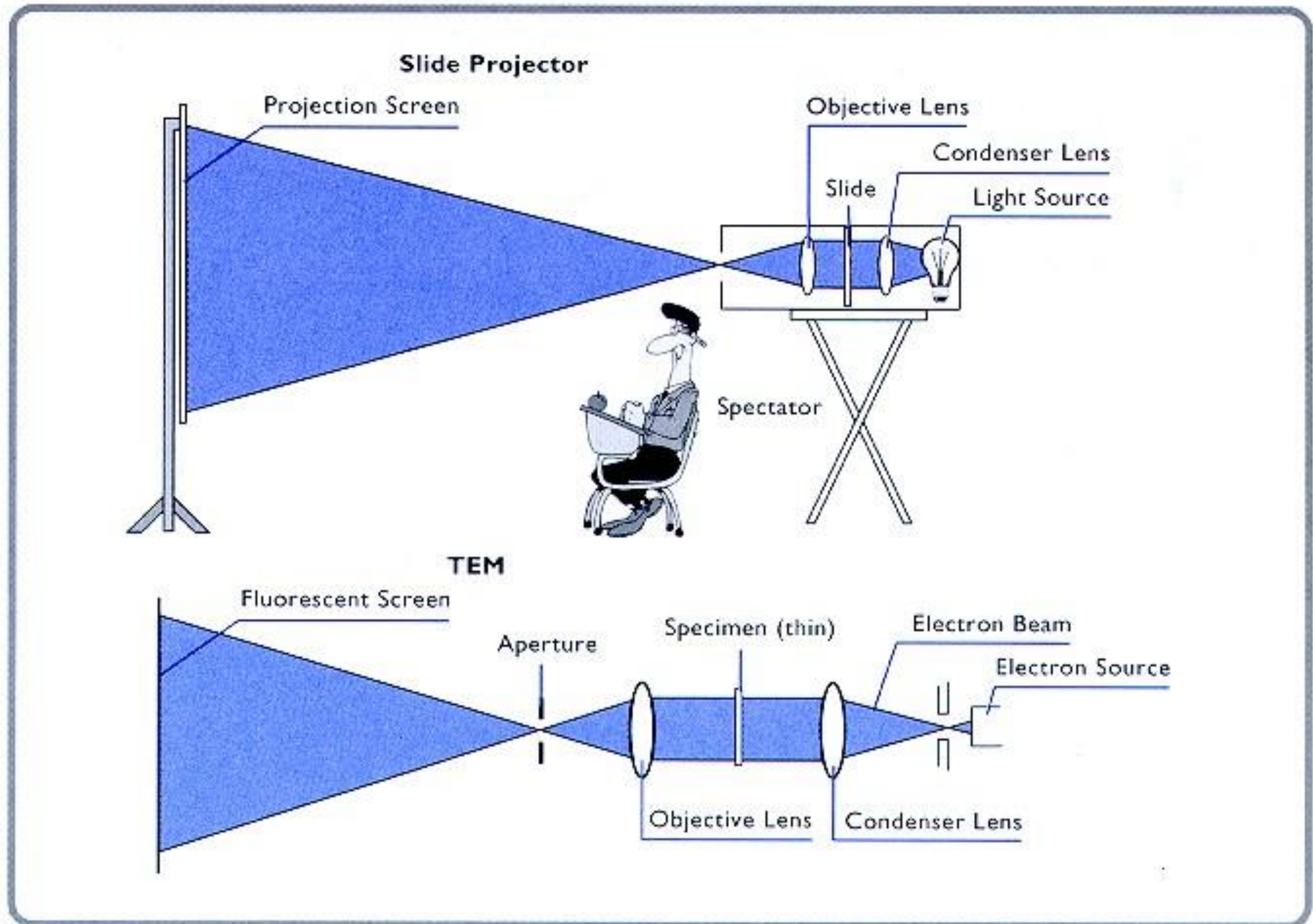
**A transmission Electron Microscope is anologous to a slide projector as indicated by Philips below**



# The Transmission Electron Microscope

I. Electron optics

II. The instrument

III. Image contrast

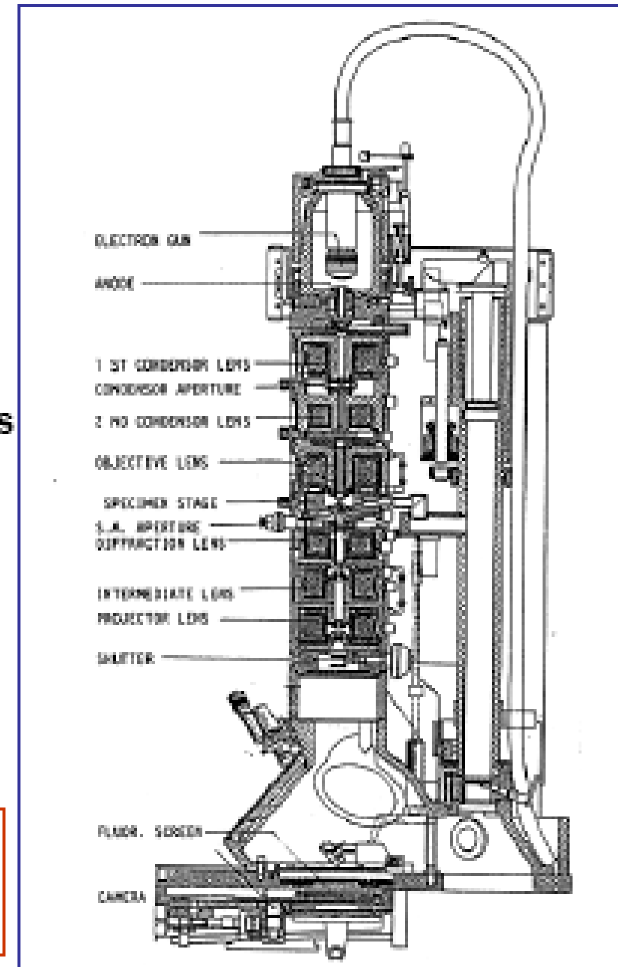
1. Mass-thickness contrast
2. Diffraction contrast
3. Phase contrast

IV. Specimen preparation

# II. The instrument

## EM

- TEM
- SEM
- Dedicate STEM
- TEM/STEM: TEM with scanning facilities
- HVTEM



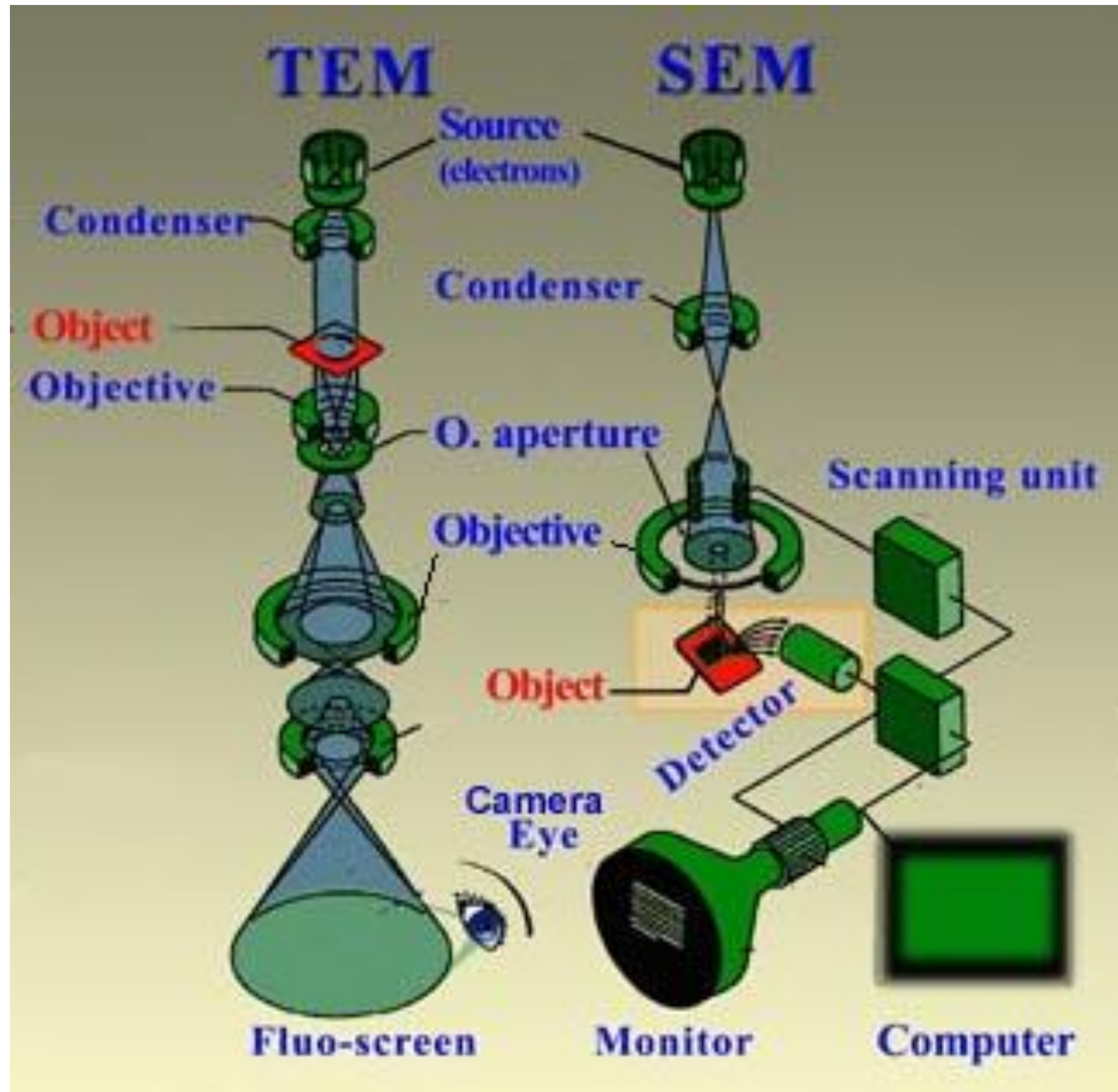

A cross-section through a modern 100 kV TEM

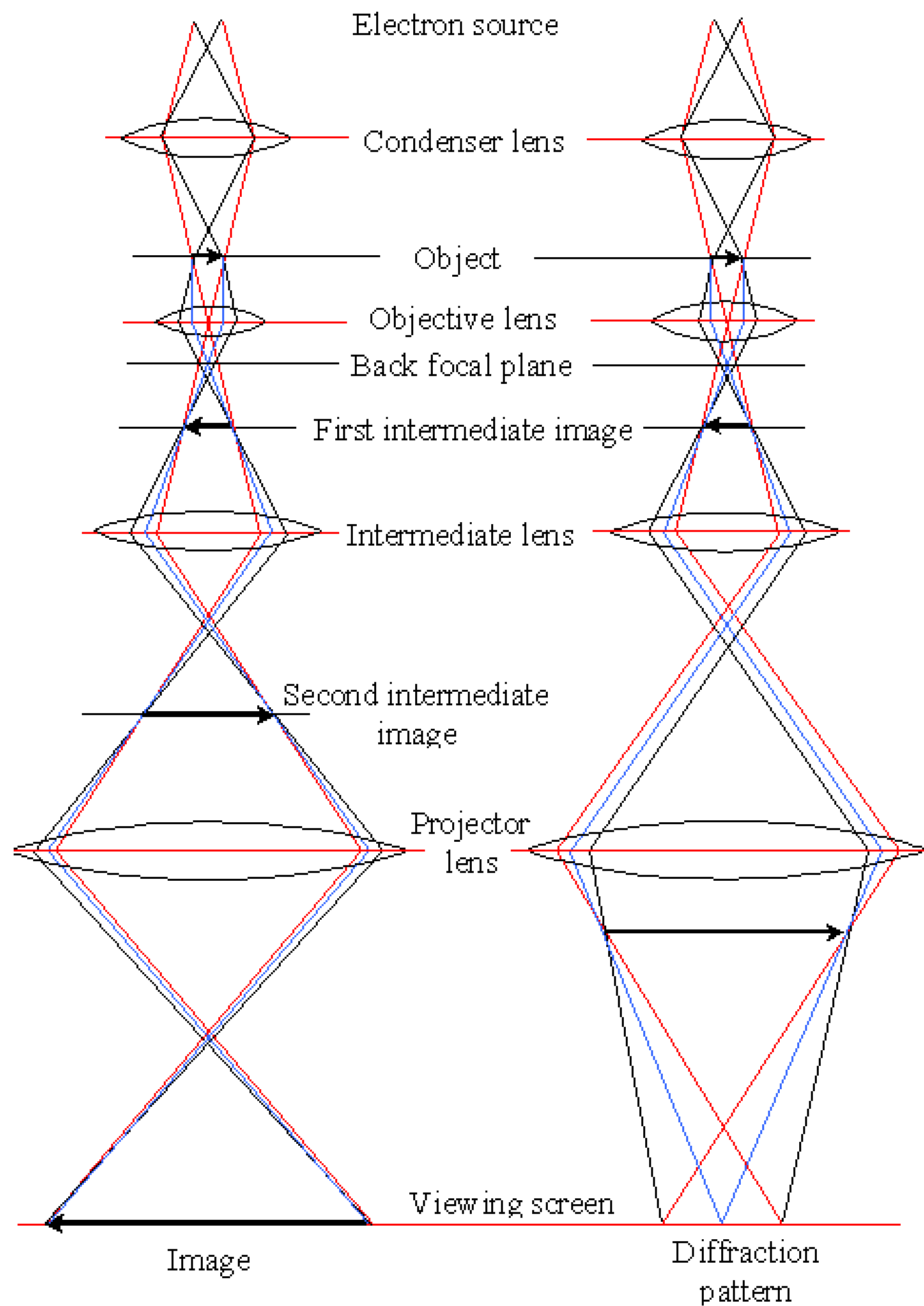
In a conventional transmission electron microscope, a thin specimen is irradiated with an electron beam of uniform current density. Electrons are emitted from the electron gun and illuminate the specimen through a two or three stage condenser lens system. Objective lens provides the formation of either image or diffraction pattern of the specimen. The electron intensity distribution behind the specimen is magnified with a three or four stage lens system and viewed on a fluorescent screen. The image can be recorded by direct exposure of a photographic emulsion or an image plate or digitally by a CCD camera.

The acceleration voltage of up to date routine instruments is 120 to 200 kV. Medium-voltage instruments work at 200-500 kV to provide a better transmission and resolution, and in high voltage electron microscopy (HVEM) the acceleration voltage is in the range 500 kV to 3 MV. Acceleration voltage determines the velocity, wavelength and hence the resolution (ability to distinguish the neighbouring microstructural features) of the microscope.
Depending on the aim of the investigation and configuration of the microscope, transmission electron microscopy can be categorized as :

Conventional Transmission Electron Microscopy
High Resolution Electron Microscopy
Analytical Electron Microscopy
Energy-Filtering Electron Microscopy
High Voltage Electron Microscopy
Dedicated Scanning Transmission Electron Microscopy

# (SEM) and TEM




Electron source
Condenser lens
Object
Objective lens
Back focal plane
First intermediate image
Intermediate lens
Second intermediate image
Projector lens
Viewing screen
Image
Diffraction pattern

## The TEM consists of the following major parts:

1. The illumination system

   Electron gun

   Condensers

2. The image forming system

   Objective lens

3. The projective system

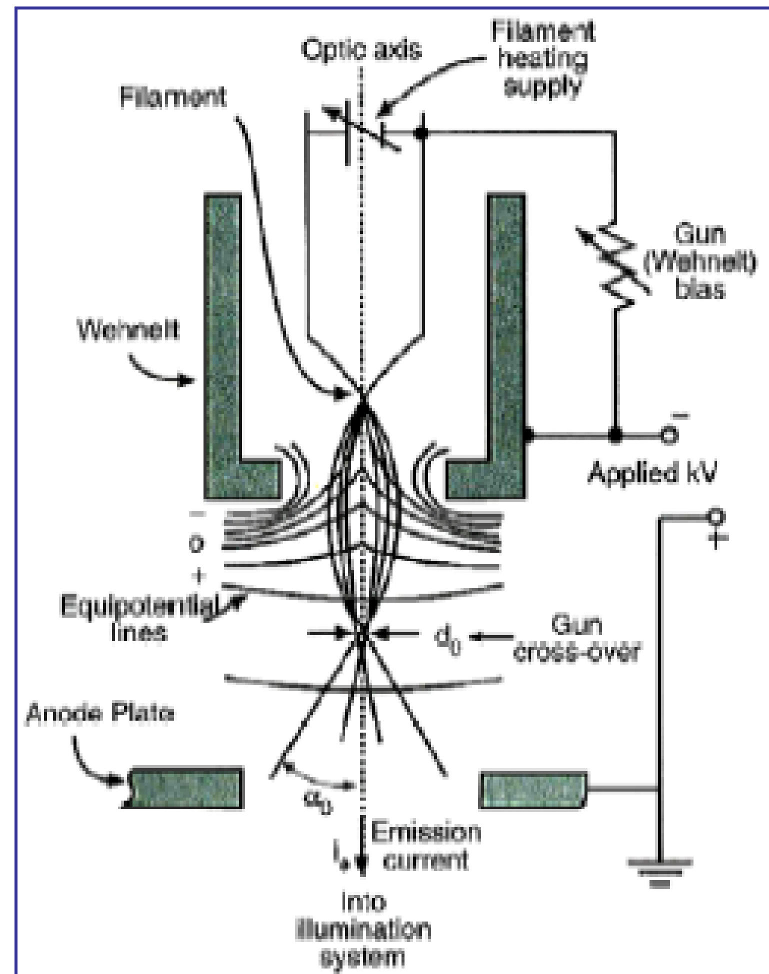
   Several projector lens

4. Apertures

   afftect the formation of images and diffraction patterns

# Electron gun

Schematic diagram of a thermionic electron gun. A high voltage is placed between the filament and the anode, modified by a potential on the Wehnelt which acts to focus the electrons into a crossover, with diameter $d_0$ and convernegce/divernence angle $\alpha_0$.



## Three types of electron source:

- Tungsten filament,
- Lanthanum hexboride ($LaB_6$) emitter
- Field emission emitter (FEG)

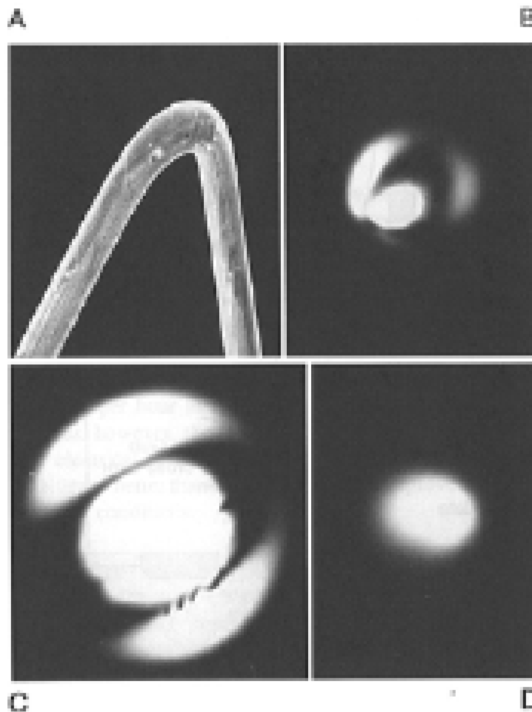



Figure 5.5. (A) The tip of a tungsten hairpin filament and the distribution of electrons when the filament is (B) undersaturated and misaligned, (C) undersaturated and aligned, and (D) saturated.

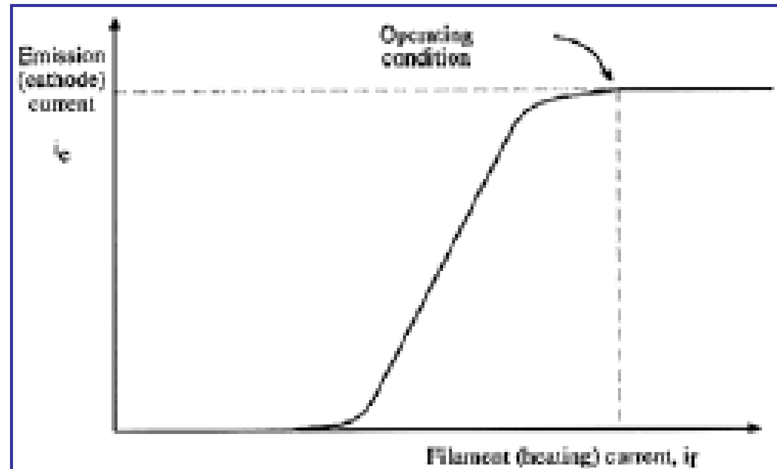



**Figure 5.3.** The relationship between the current emitted by the electron source ($i_c$) and the filament heating current ($i_f$) for a self-biasing gun. Increasing the filament current results in a maximum emission current termed saturation.

## The condenser system

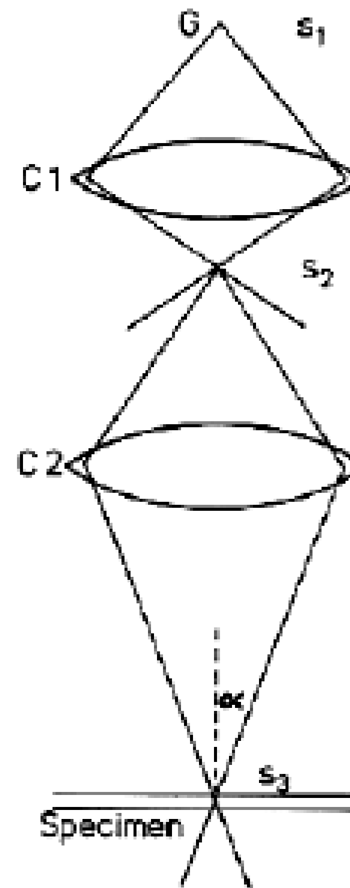
Two lenses:

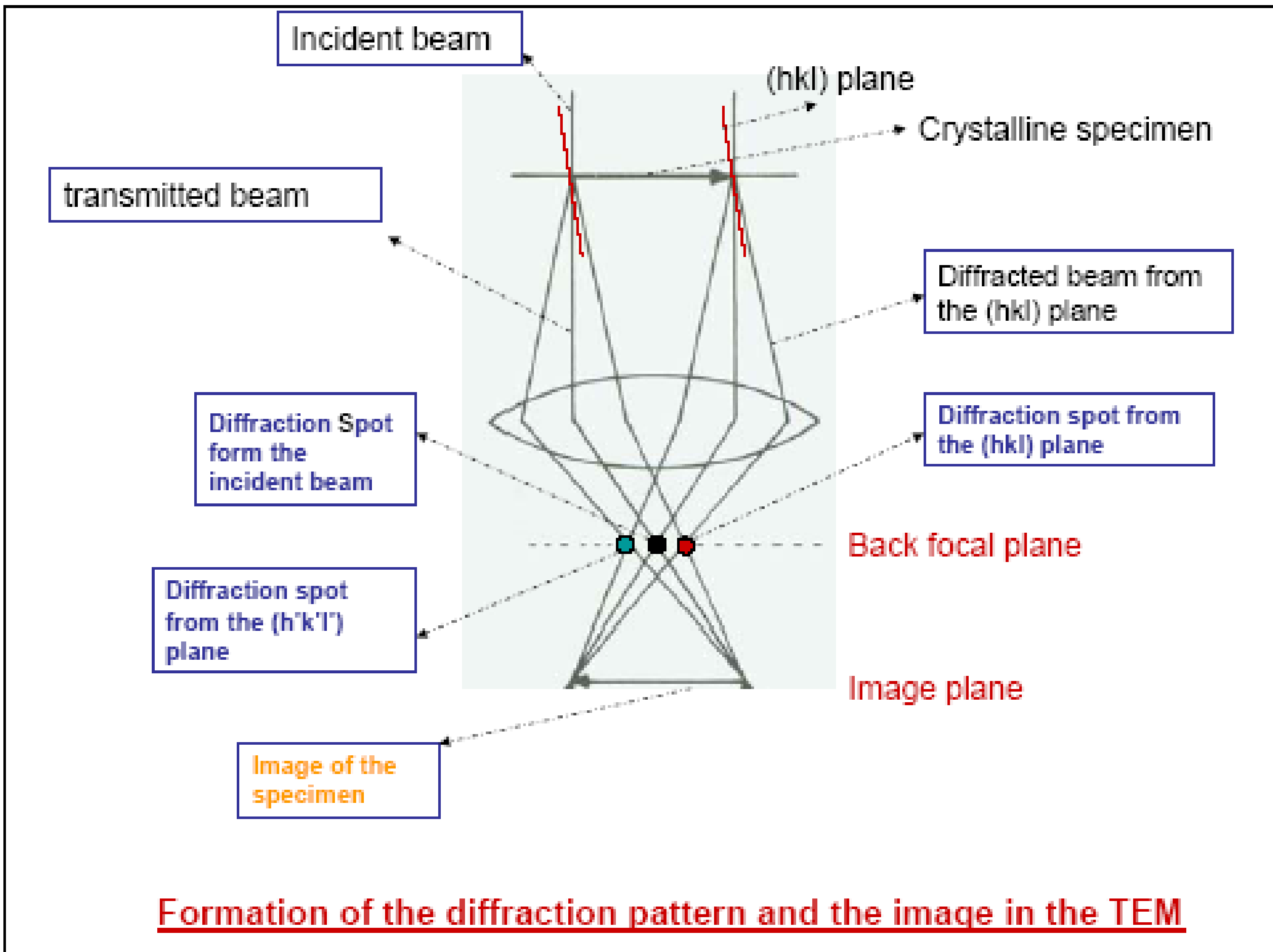
C1: strong M = 50x

produces a de-magnified image $s_2$ (~1µm) of cross-over $s_1$ (~50µm)

C2: weak lens,

produces a image $s_3$ (~2µm) onto the specimen






Formation of the diffraction pattern and the image in the TEM

## 2. The image forming system - The objective lens

The objective and first intermediate lenses. The objective lens (OL) is focused on the specimen and form an intermediate image as shown in (a).

*In imaging mord* the intermediate lens (IL) magnifies this image further and passes it to the projector lens for display.

In order to make the diffraction pattern visible, *in diffraction mord* the intermediate lens is refocused on the back focal plane of the objective lens (BFP) and the diffraction pattern is passed to the projector system (b).