Chapter 5: Electron Sources

Electron Microscopy
Summary for week 1
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Electron source provides the electrons that illuminate the sample and provide the image.

Various electron sources are available.

The best two sources: Thermionic and field-emission source.

Thermionic source:
- The most common.
- Requires a lot of interaction from the operator.

Field-emission source:
- More monochromatic electron beam.
- Can be highly automated.
- May become the most used in the future.

None of the available sources is the best in all of the aspects that need to be considered in electron microscopy.
Physics of Electron Sources
- Thermionic Source

- Any material will emit electrons when heated enough for the electrons to overcome a barrier called the work function ($\Phi$) of some eV.

- Current density ($J$) from the source is given by the Richardson’s law:

  $$J = A T^2 e^{-\frac{\Phi}{kT}}$$

  - $A$ = Richardson’s constant (determined separately for different source materials)
  - $T$ = temperature (in Kelvin)
  - $k$ = Boltzmann’s constant

- Most materials fail when $T$ is high enough for electrons to overcome $\Phi$
  - Source must have a high melting point (tungsten) or low $\Phi$ (lanthanum hexaboride LaB$_6$)

- Higher $T$ = higher $J$
  - High $T$ shortens the lifespan of the source, so it is reasonable to settle for lower
Physics of Electron Sources  
- Field-Emission Source

- Based on sharp needles electric field $E$ is enhanced as voltage $V$ is applied to a smaller radius $r$
  
  - $E = \frac{V}{r}$

- Tungsten can be used to make tips of <0.1 µm
  
  - Applying electric field to this tip will lower $\Phi$ allowing electrons to tunnel out
  
  - Stressful for the tip, tungsten and LaB$_6$ are found to be resistant enough

- The tip needs to be very pure for field-emission
  
  - Operation in high vacuum and low temperatures
  
  OR

  - Operation in low vacuum and high temperatures
Characteristics of the Electron Beam
Brightness $\beta$

- Should not be confused with intensity

**Definition of brightness:** The current density per unit solid angle of the source

- Sources are of different size and the amount of electrons is dependant on the angle

$$\beta = \frac{4i_e}{(\pi d_0 \alpha_0)^2}$$

- $i_e$ = cathode (the emission source) emission current
- $d_0$ = diameter
- $\alpha_0$ = divergence angle

- Not defined at the tip but at the gun cross-over

- Higher value of $\beta$
  - More information about the sample
  - More damage to the sample

- High $\beta$ allows recording images in shorter exposure times
  - Good for AEM and HREM
Temporal Coherency and Energy Spread

- Coherency is a definition of how well electron waves are in phase with each other
- White light is incoherent as it contains photons of all wavelengths
- Temporal coherency: All electrons have the same wavelength
  - Coherence length \( \lambda_c = \frac{\nu h}{\Delta E} \)
    - \( \nu \) = electron velocity
    - \( h \) = Planck’s constant
    - \( \Delta E \) = energy spread of the beam
- A stable high voltage supply of electrons is required to achieve low \( \Delta E \) and high \( \lambda_c \)
- Monochromators are used to select coherent electrons
- Modern electron beams are usually coherent enough as they hit the sample but the ones that go through it not so much
  - Energy loss of electrons within the sample
Spatial Coherency and Source Size

- All the electrons emit from a single spot in the source
  - Perfect spatial coherency
- Smaller sources are preferred
- Effective source size $d_c = \frac{\lambda}{2\alpha}$
  - $\lambda$ = electron wavelength
  - $\alpha$ = angle subtended by the source at the specimen
- $d_c$ can be maximized by
  - Using a smaller source
  - Using slits to minimize $\alpha$
  - Using lower voltage to maximize $\lambda$
- Spatial coherency is more important than temporal
  - Smaller sources are generally better
Stability

- The electron current from the source must be stable
  - Otherwise quantitative imaging cannot be done
- Thermionic sources are typically very stable
- Field-emission sources require additional components to improve stability
- Smaller sources provide less stable electron source
Electron Guns

The Electron Source and The Surrounding Focusing Components
Thermionic Guns

- LaB₆ is the most used electron source in modern TEMs
- Emitted electrons accelerate towards the anode plate
- Wehnelt cylinder is induced with a small negative field
  - Electrons are focused in the gun cross-over
- Emission current increases with heating until a maximum is reached
  - *Saturation condition*
- Thermionic sources should be operated at or just below this point to avoid unnecessary wearing of the source
- Operating at saturation also optimizes brightness
- Saturation can be determined by the image of the source cross-over
Field-Emission Guns

- In field-emission gun there are two anodes
  - First causes the electrons to tunnel out from the source tip
  - Second causes the electrons to accelerate further
- A magnetic lens is often used to achieve better control of the beam and larger brightness
- The tip gets contaminated even in high vacuum and needs to be cleaned
  - Contaminants decrease the emission current
  - Reversing the potential: Repel
  - Heating up: Burn away
Comparison of Guns

- **LaB$_6$**
  - Low work function (exponential effect)
  - Can be used to make very small tips
  - Good brightness and coherency
  - Requires very high vacuum

- **Tungsten**
  - Cheap

- **Field-emission gun**
  - Best for special applications that require coherent beam with large brightness
  - Not good for low resolution imaging as the tip is simply too small

- **Thermionic gun**
  - Not as good as field-emission for high resolution imaging
  - Faster and easier to use for common samples due to larger tip
Measuring Gun Characteristics
Beam Current and Convergence Angle

- **Beam current**
  - Can be measured directly using a Faraday cup
  - Whether beam current is constant or should be monitored depends on the electron source
    - Schottky field-emission gun (thermally enhanced field-emission) is constant
    - Cold field-emission gun loses beam current with time

- **Convergence angle**
  - Can be measured from the convergent-beam electron diffraction pattern
  - Important in brightness equation and some special applications of electron microscopy
Calculating the Beam Diameter

- Imprecise but easy to carry out
- No universal way to determine beam size
  - Manufacturers provide calculated values which may not be precise
    - Assume Gaussian electron-intensity distribution which is not true in most cases
- Total beam size \( d_t = \sqrt{d_g^2 + d_s^2 + d_d^2} \)
  - \( d_g \) = initial Gaussian diameter at the gun
  - \( d_s \) = spherical aberration in the beam-forming lens
  - \( d_d \) = diffraction at the final aperture
  - Only a first-order estimate
    - \( d_g \) is an estimate based on assumed value of brightness
    - \( d_s \) and \( d_d \) are dependant on divergence angle and may not always be made Gaussian as the beam cannot sometimes be correctly apertured
- All in all, the calculation is a reasonably justified but that does not make it accurate
Measuring the Beam Diameter

- Difficult to carry out and may be imprecise
- An image where the magnification can be calibrated must be formed
  - Not an easy feat to accomplish
  - The beam is photographed and the intensity distribution is measured
- In STEM the beam cannot be imaged directly
  - The beam must be moved over a sharp-edged sample and measure the difference in intensity
  - No sample is completely impenetrable to electrons and the method is not accurate
- All in all, measuring the beam diameter is no simple feat but it can be reasonably close to a calculated value
Energy Spread and Spatial Coherency

- Energy spread can be measured directly using an electron spectrometer
  - The spectrometer must have sufficiently high resolution
- Spatial coherency cannot be measured directly
  - Forming an out of focus image of a hole in the sample
  - Alternating dark and light fringes can be detected
    - Fresnel fringes
  - The number of fringes is a measure of beam coherency

Fresnel fringes
What kV should be used?

- The kV axiom: Maximum available kV should be used unless it should not
- Higher kV = better image
  - However, too strong beam will damage the sample
- 100 kV is usually safe
  - Less might be recommended for sensitive, crystalline and biological samples
- High kV provides
  - Better signal
  - Better resolution
  - Better spatial resolution
  - Heating effects may be smaller
  - Thicker samples can be used
  - The peak to background ratio in X-ray spectra is improved
Summary of Electron Sources

- Thermionic LaB$_6$ is the most common electron source in TEM
- Operating should be done just under saturation and (in most cases) using highest available kV
- Field-emission TEM is best for high-resolution imaging
- Beam size and convergence angle
  - should be measured to determine brightness
- Electron sources should be treated with care

LaB$_6$ crystal