Fundamental of optical and scanning electron microscopy

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Module – 03
Unit-6 Introduction to scanning electron microscopy
Lecture – 11
Fundamentals of electron optics
Electrostatic lenses
Electromagnetic lenses
Electron gun

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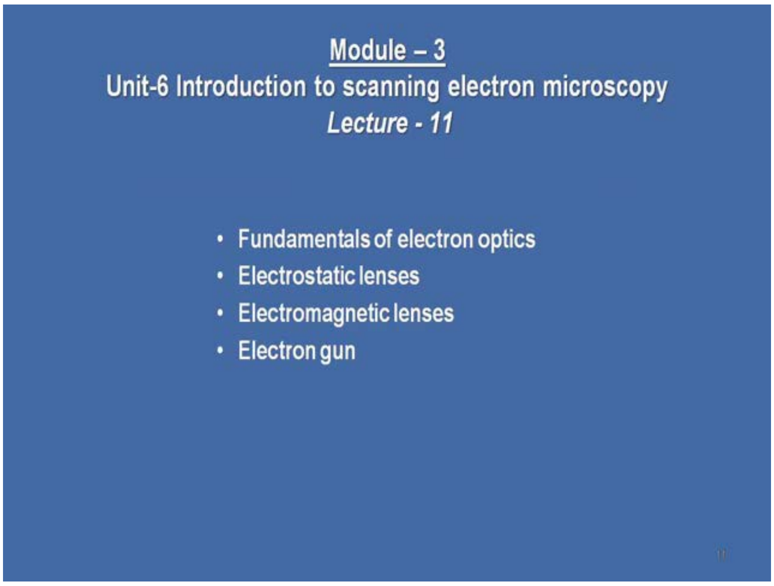

Module – 3
Unit-6 Introduction to scanning electron microscopy
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- Fundamentals of electron optics
- Electrostatic lenses
- Electromagnetic lenses
- Electron gun

Hello, welcome back to this Material Characterization Course. In the last few classes we have just reviewed all this Optical Microscopy variants and it is working principles and live demonstrations so on. Now, we will move on to the next domain of Electron Microscopes. Like I did it in optical microscopy first let us review some of the Fundamentals of Electron Optics which will be useful to understand the electron optical system as well as electron lenses design and its operation methods.

So far we have just looked at the light optical rules and then we will see how these light optical rules will be applicable to the electron optical system. In this few lectures of Fundamentals of Electron Optics, we will try to build a background to appreciate the electron lenses and their application to electron optical system, and then we will also review the aberrations which are encountered in this electron lenses and then how to correct them in order to obtain a better resolution of the microscope. So, with these intentions in mind let us begin our Fundamentals of Electron Optics lecture with few remarks.

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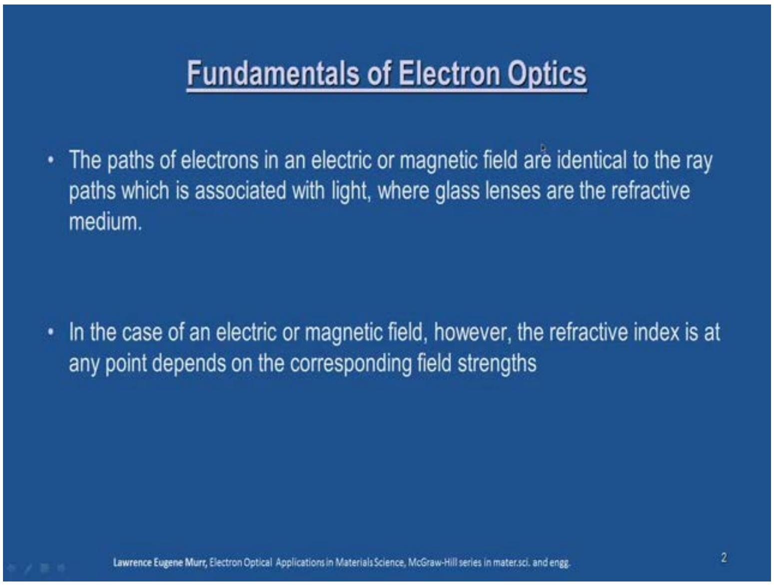

Fundamentals of Electron Optics

- The paths of electrons in an electric or magnetic field are identical to the ray paths which is associated with light, where glass lenses are the refractive medium.
- In the case of an electric or magnetic field, however, the refractive index is at any point depends on the corresponding field strengths

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In fact, the paths of electrons in an electric or magnetic field are identical to the ray paths which is associated with light, where glass lenses are the refractive medium. In fact, this approach was first made by some of the German scientists who applied this analogy of the light optical system to the dynamics of electron in the electron optical system. In the case of an electric or magnetic field, however, the refractive index is at any point depends on the corresponding field strengths. We will see how this is valid for the actual electron optical system.

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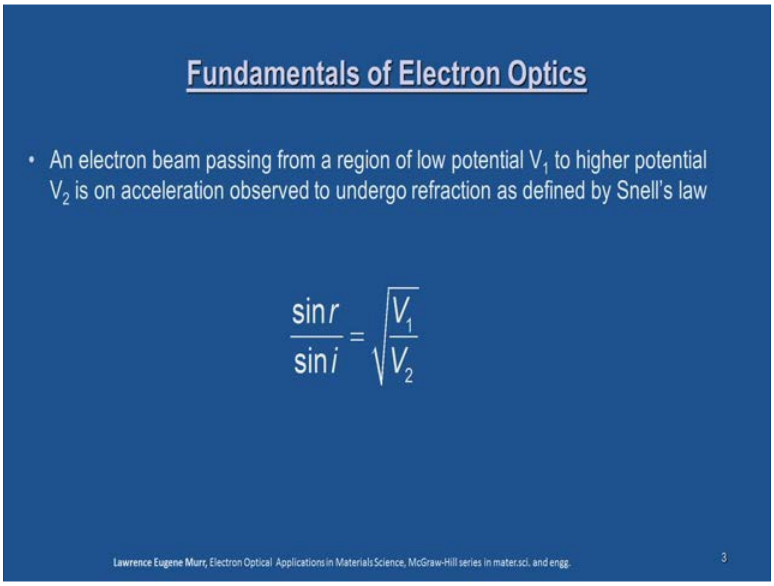

Fundamentals of Electron Optics

- An electron beam passing from a region of low potential V_1 to higher potential V_2 is on acceleration observed to undergo refraction as defined by Snell's law

$$\frac{\sin r}{\sin i} = \sqrt{\frac{V_1}{V_2}}$$

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We will first discuss Electrostatic Lenses, because the electrostatic lenses where the first used in the electron microscope and then their design and behavior were studies then only this was adapted to electromagnetic lenses. So let us review some of the primary features are the theoretical concepts underlying this electrostatic lenses. An electron beam passing from a region of low potential V 1 to higher potential V 2 is on acceleration observed to undergo refraction as defined by Snell's law. Sin r by sin i equal to square root of V 1 by V 2. We know that the Snell's law which we have reviewed in the fundamentals of optical a microscopic system, so similar thing is obeyed by this electron optical system as well. This equation clearly mentions that; this clearly demonstrate that your electron beam also undergo a refraction according to Snell's law.

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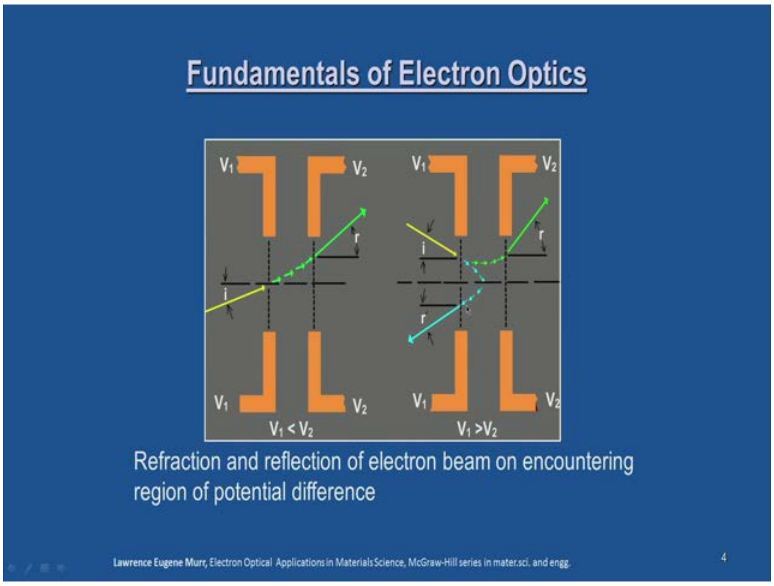

Fundamentals of Electron Optics

Refraction and reflection of electron beam on encountering region of potential difference

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Look at this schematic where we are demonstrating the refraction and reflection of electron beam on encountering the region of potential difference. You see these two diagrams, first we will describe this. First one, look at this electron beam is encountering the potential difference by this electrostatic lens where V 1 is less than V 2 and then it undergoes refraction, so where i is the angle of incidence, r is the angle of refraction. On the other hand, if you see that this is a electron beam encountering the two electrostatic lenses where the potential is reversed, where V 1 is greater than V 2 then your electron beam undergo a reflection like this and then you have the refraction also taking place in this manner. We will see under what condition these two are happening.

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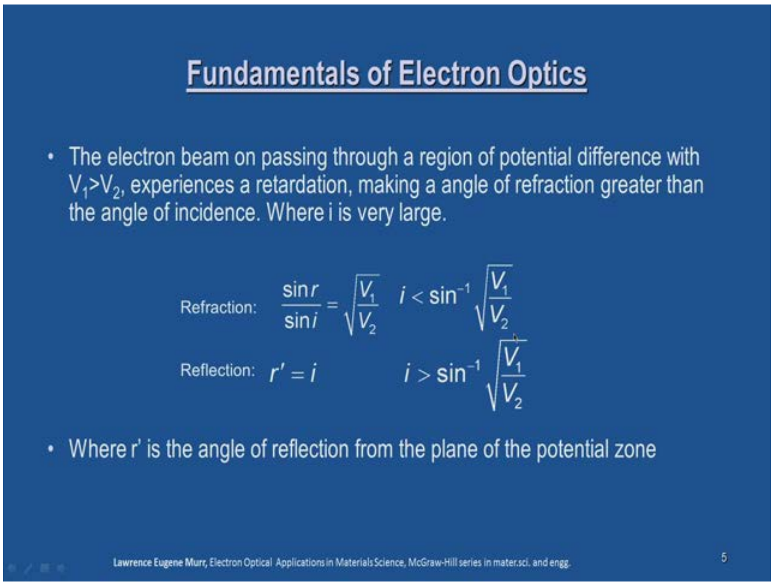

Fundamentals of Electron Optics

- The electron beam on passing through a region of potential difference with $V_1 > V_2$, experiences a retardation, making a angle of refraction greater than the angle of incidence. Where i is very large.

Refraction: $\frac{\sin r}{\sin i} = \sqrt{\frac{V_1}{V_2}}$ $\quad i < \sin^{-1}\sqrt{\frac{V_1}{V_2}}$

Reflection: $r' = i$ $\quad i > \sin^{-1}\sqrt{\frac{V_1}{V_2}}$

- Where r' is the angle of reflection from the plane of the potential zone

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The electron beam on passing through a region of potential difference with V 1 is greater than V 2 experiences a retardation making angle of refraction greater than angle of incidence.

This is what we have just seen. So, where i is very large then these two conditions are valid. So for the refraction sin r by sin i equal to square root of V 1 by V 2, where i is smaller than sin inverse times, square root of V 1 by V 2. For the reflection where r prime is equal to i, where i is greater than sign inverse times, square root of V 1 by V 2, where r is the angle of reflection from the plane of potential zone. We will go back and then see. So the plane of potential zone which we referring somewhere here, and then you see that i is equal to r i when the reflection is considered. So, with this we simply see that the electron beam exactly follows the rules of a light optical system and we will see what the additional points are, we need to consider.

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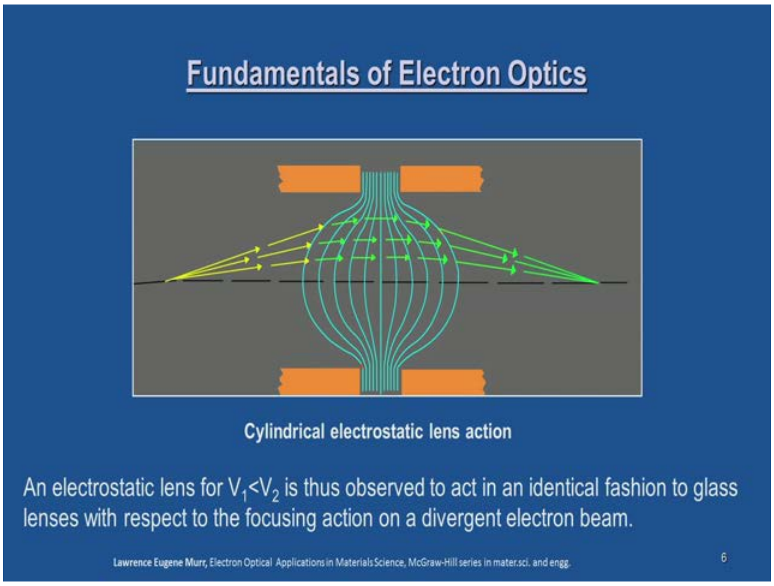

Fundamentals of Electron Optics

Cylindrical electrostatic lens action

An electrostatic lens for $V_1<V_2$ is thus observed to act in an identical fashion to glass lenses with respect to the focusing action on a divergent electron beam.

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This schematic clearly shows that the cylindrical electrostatic lens action, what you see is? You see this electron beam coming and then the diverged beam is going through this the electrostatic field and then it is getting converged. So, the converging action of this electrostatic lens very clearly demonstrated in this schematic. So, an electrostatic lens for V 1 is less than V 2 is thus observed to act in an identical fashion to glass lenses with respect to the focusing action on a divergent electron beam. So this is what is clearly demonstrated in this schematic.

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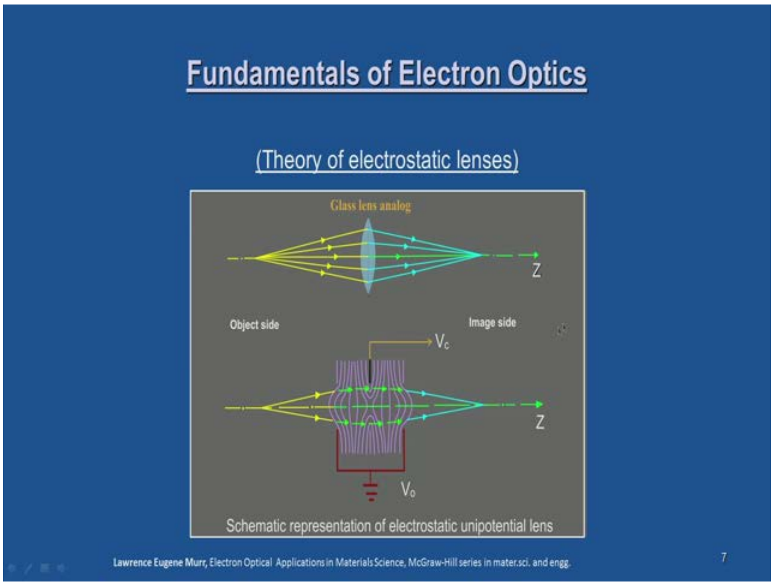

Fundamentals of Electron Optics

(Theory of electrostatic lenses)

Schematic representation of electrostatic unipotential lens

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Now, as I just mentioned before, the electrostatic lenses where the one first developed for the electron microscope and you can see in this schematic that it is exactly analogous to a glass lens system. So you see where a light is coming and falling on this glass and then it is converged in the right hand side, and here you have this electrostatic lenses here again the converging action is demonstrated. In fact, the focal length the front and back focal length of this two lenses I mean in this each system are equal. Hence, we will see that that lens equation is exactly valid in this electron optical system as well.

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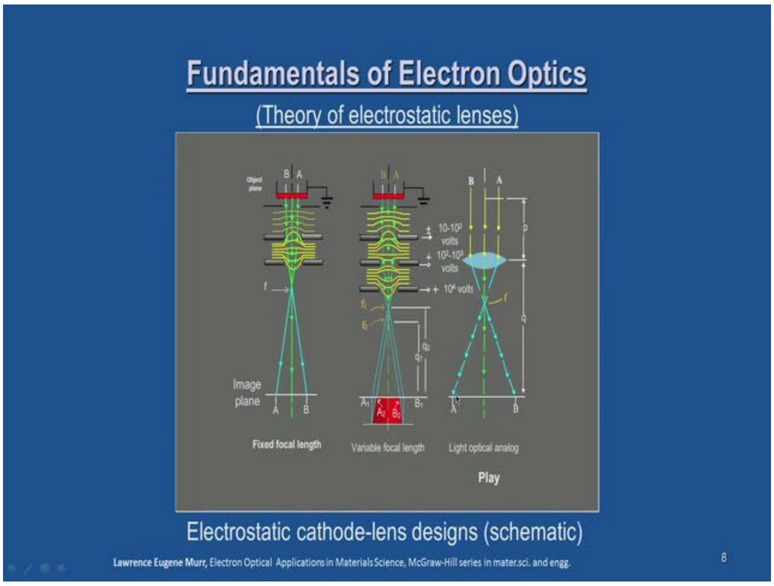

Fundamentals of Electron Optics

(Theory of electrostatic lenses)

Electrostatic cathode-lens designs (schematic)

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What I am going to show in this schematic is, you see these are all some of the electrostatic lens design for the Cathode-lens microscope, and what you are seeing is a unipotential electrostatic lenses for a fixed focal length. In this schematic it is clearly shown this is for a fixed focal length. I can play this schematic for you just to have a better capture of the concept you see that electrostatic lens and then the electron beam is forming entering into this electrostatic field, and you see that f focal length is fixed in this situation.

In the second case, it is a variable focal length where you have the combination of electrostatic lenses for different field strength you can also vary this focal length f 1 and f 2. You can see that the first one coming through f 1 point is lying are meeting at A 1 and B 1 in the image plane and then the beam passing through f 2 is falling on the image plane in the point A 2 and B 2. So, you have the variable focal length electron optical system is demonstrated and what you see in the right hand side is a simple right optical analog. I just want to make sure that the electron optical system is exactly what we have in a light optical analog. You should not get confused just because we are replacing this light I mean light optical system where we use a glass lens as the refractive medium instead of this refractive medium in an electron optical system you have electrostatic lenses.

I hope this schematic gives you a nice comparison between these light optical system as well as the electron optical system, where the electrostatic lenses are used or the cathode-lens designs are adopted.

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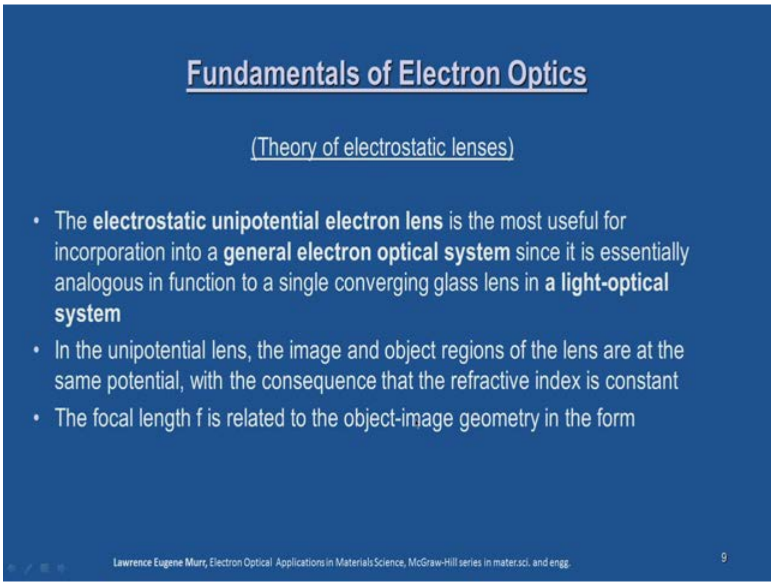

Fundamentals of Electron Optics

(Theory of electrostatic lenses)

- The **electrostatic unipotential electron lens** is the most useful for incorporation into a **general electron optical system** since it is essentially analogous in function to a single converging glass lens in **a light-optical system**
- In the unipotential lens, the image and object regions of the lens are at the same potential, with the consequence that the refractive index is constant
- The focal length f is related to the object-image geometry in the form

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The electrostatic lenses we just discussed about where, the electrostatic unipotential electrons lenses the most useful for the incorporation into a general electron optical system since it is essentially analogous in function to a single converging glass lens in a light-optical system. This is what just we have seen. What is unipotential lens? In unipotential lens, the image and the object regions of the lens are at the same potential with the consequence that the refractive index is constant. So, as I just mentioned that the front and back focal length or I would say that the focal length in the front and back focal plane are same.

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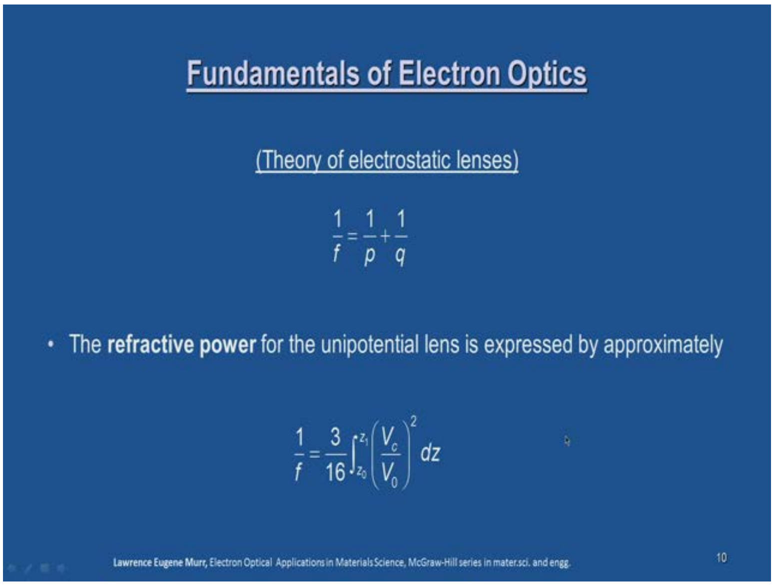

Fundamentals of Electron Optics

(Theory of electrostatic lenses)

$$\frac{1}{f}=\frac{1}{p}+\frac{1}{q}$$

- The **refractive power** for the unipotential lens is expressed by approximately

$$\frac{1}{f}=\frac{3}{16}\int_{z_0}^{z_1}\left(\frac{V_c}{V_0}\right)^2 dz$$

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So, the focal length f is related to the object image geometry in the form 1 by f is equal to 1 by p plus 1 by q. The refractive power of the unipotential lenses expressed by approximately 1 by f equals 3 by 16 times the integral from z naught to z 1 times V c by v naught whole square dz, which is function of the field strength.

I think with this few introductions to the electrostatic lenses, we will now look at how the electromagnetic lenses are being developed into the modern electron microscopes. Since, electrostatic lenses are analogous to the optical system the same electrostatic lenses also or I would say the electrostatic lens design is adapted to electromagnetic lens. Let us see how it goes.

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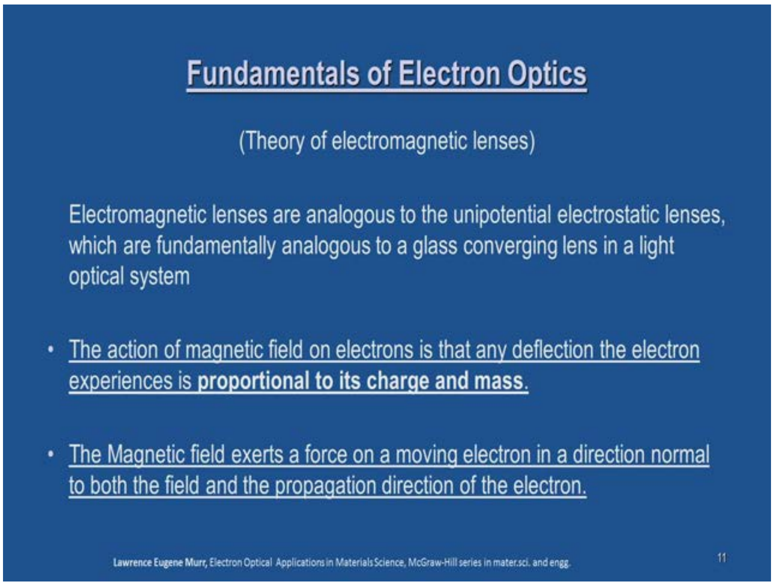

Fundamentals of Electron Optics

(Theory of electromagnetic lenses)

Electromagnetic lenses are analogous to the unipotential electrostatic lenses, which are fundamentally analogous to a glass converging lens in a light optical system

- The action of magnetic field on electrons is that any deflection the electron experiences is **proportional to its charge and mass.**
- The Magnetic field exerts a force on a moving electron in a direction normal to both the field and the propagation direction of the electron.

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The electromagnetic lenses are analogous to the unipotential electrostatic lenses, which are fundamentally analogous to a glass converging lens in a light optical system. So, what that we have to now understand is what this additional magnetic field does to the electron path or beam of electrons? Let us see, the action of magnetic field on electrons is that any deflection the electron experiences is proportional to it is charge and mass. The magnetic field exerts a force on a moving electron in a direction normal to both the field and the propagation direction of the electron. So what you have to understand here is, the magnetic field is going to produce an additional force in a direction normal to both the propagation and field direction of the electron. So, it is perpendicular to both.

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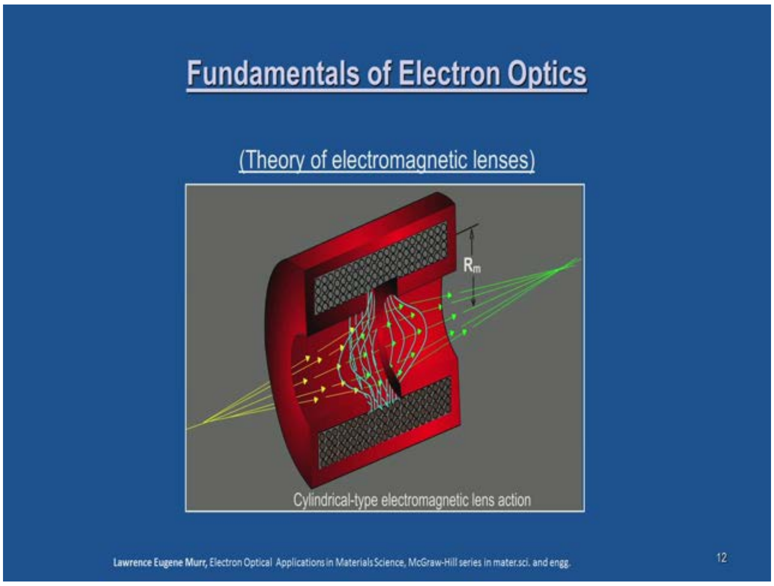

Fundamentals of Electron Optics

(Theory of electromagnetic lenses)

Cylindrical-type electromagnetic lens action

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This is demonstrated in this a schematic, you see this is the typical cylindrical type electromagnetic lens action it is a cross section where you have all the circular slots where a soft iron coil is being bound like this, and this is the electron beam getting into this a core of the lens and then you see the field which is being generated, and then you see all the electron beam is converging. The magnetic field produces a force normal to this field direction as well as the propagation of the electron, so that means perpendicular to this direction. So that produces a field like this and which will have a kind of a cylindrical shape with the radius R. We will see how this is perceived.

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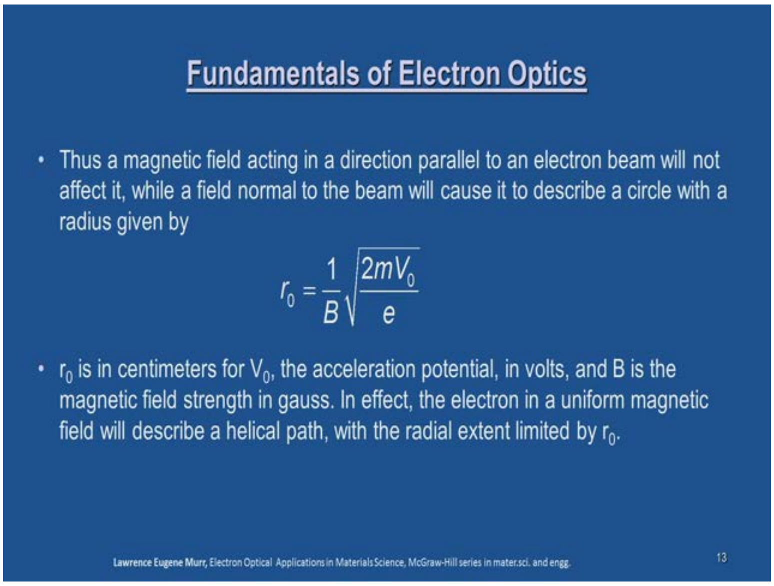

Fundamentals of Electron Optics

- Thus a magnetic field acting in a direction parallel to an electron beam will not affect it, while a field normal to the beam will cause it to describe a circle with a radius given by

$$r_0 = \frac{1}{B}\sqrt{\frac{2mV_0}{e}}$$

- r_0 is in centimeters for V_0, the acceleration potential, in volts, and B is the magnetic field strength in gauss. In effect, the electron in a uniform magnetic field will describe a helical path, with the radial extent limited by r_0.

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Thus a magnetic field acting in a direction parallel to an electron beam will not affect it, while a field normal to the beam will cause it to describe a circle with the radius given by r naught is equal to 1 by B square root of 2 m V naught divided by e. Where, r naught is in centimeters for V naught, the acceleration potential in volts, and B is the magnetic field strength in gauss. In effect, the electron in a uniform magnetic field will describe a helical path, please make a note of this. In a uniform magnetic field describe a helical path, with a radial extent limited by r naught. So what you have to remember is this, this is r where you have the circular beam are field is represented around this region.

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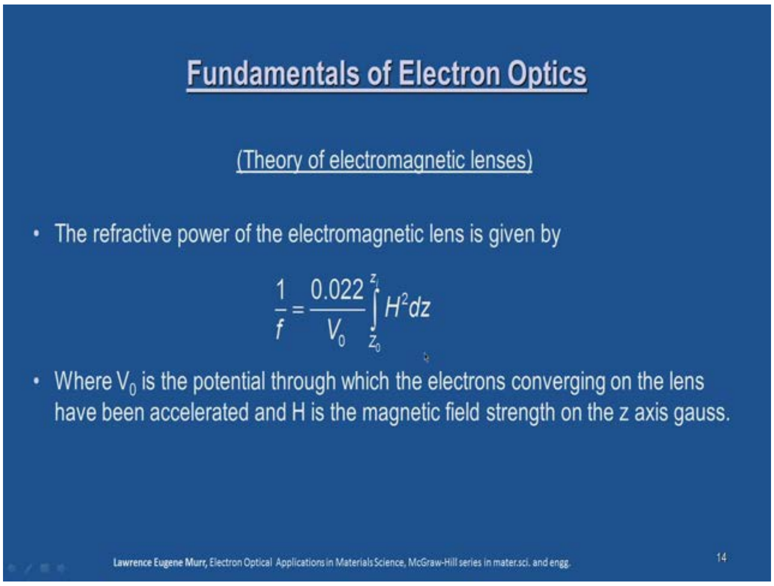

Fundamentals of Electron Optics

(Theory of electromagnetic lenses)

- The refractive power of the electromagnetic lens is given by

$$\frac{1}{f} = \frac{0.022}{V_0}\int_{z_0}^{z_i} H^2 dz$$

- Where V_0 is the potential through which the electrons converging on the lens have been accelerated and H is the magnetic field strength on the z axis gauss.

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Now we will see how the other parameters are getting affected? The refractive power of the electromagnetic lens is given by 1 by f is equal to 0.022 by V naught times the integral of from z naught to z i H square dz. Where, V naught is the potential through which the electrons converging on the lens have been accelerated and H is the magnetic field strength on the z axis in gauss.

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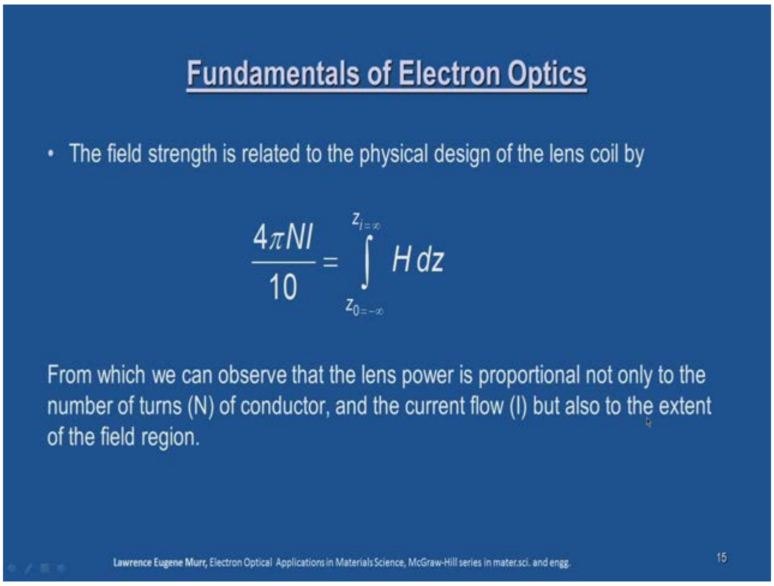

Fundamentals of Electron Optics

- The field strength is related to the physical design of the lens coil by

$$\frac{4\pi NI}{10} = \int_{z_{0=-\infty}}^{z_{i=\infty}} H\,dz$$

From which we can observe that the lens power is proportional not only to the number of turns (N) of conductor, and the current flow (I) but also to the extent of the field region.

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The field strength is related to the physical design of the lens coil by 4 pi NI by 10 is equal to integral of z naught equal to minus infinity to z i equal to infinity H dz. From which we can observe that the lens power is proportional not only to the number of turns N of the conductor, and the current flow I but also to the extent of the field region. Now, it is very clear from this expression you can understand this, I will go back to this you can understand the typical electromagnetic lens and the number of coils which is being used to produce this magnetic field in this kind of a slotting system is going to be also a function of your the magnetic field strength. From hence forth in electron microscope you are going to use only these kind of lenses, electromagnetic lenses instead of what we have seen already the optical analog.

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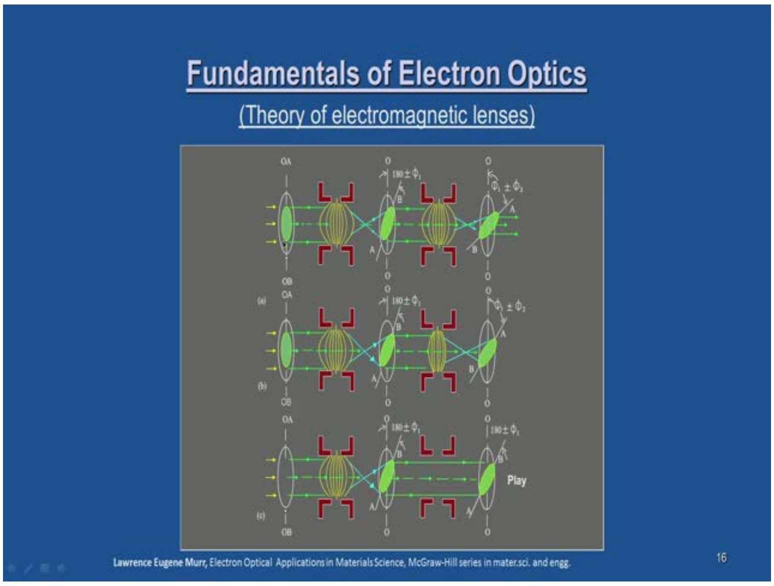

Fundamentals of Electron Optics

(Theory of electromagnetic lenses)

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Now, I will just play some of the schematic where we will demonstrate the electromagnetic system. I want you to go through this carefully and then see what you observe then I will explain one by one. You see that this is object OA. I hope what all of you would have seen this schematic once, I will replay this you observe it again. What I am going to describe from this slide is, here the primary difference between the glass lens optical system or electrostatics system to the electromagnetic system.

In a light optical system, you see that you are image inversion takes place, here also you can see that OA the object is inverted and it is not just inverted, inversion takes place at 180 plus or minus phi 1 you have the additional rotation takes place here, and if you have the double lenses then it is further rotated back to A B, but then you see that in the additional rotation is added that is phi 1 plus or minus phi 2. So this is the primary difference between the light optical systems or electrostatic system with electromagnetic system, you have image rotation takes place.

We will see the consequence and importance of this image rotation when we deal with transmission electron microscopy which I will deal with later. So, carefully if you see the next schematic the animation clearly showed that, you see that the first lens has same strength as the previous one so it has undergone inversion plus rotation. But the second lens there is a difference I hope you will be able to appreciate this, you see that the number of lines has come down that indicates the field strength has come down. So you see the similar reaction takes place here that means this rotation also will come down. If you look at the third schematic you see that inversion plus rotation takes place and I have the second lens completing the field is absent and you see that there is no additional rotation that is the phi 2 is 0 the phi 1 which is generated by the first lens remains in the image plane.

So, this particular schematic and with the animation a clearly demonstrates the primary difference between electron optical system or electromagnetic lens system with the light optical system. This is the only difference you can if all you want to make a between these two systems otherwise rest all the same.

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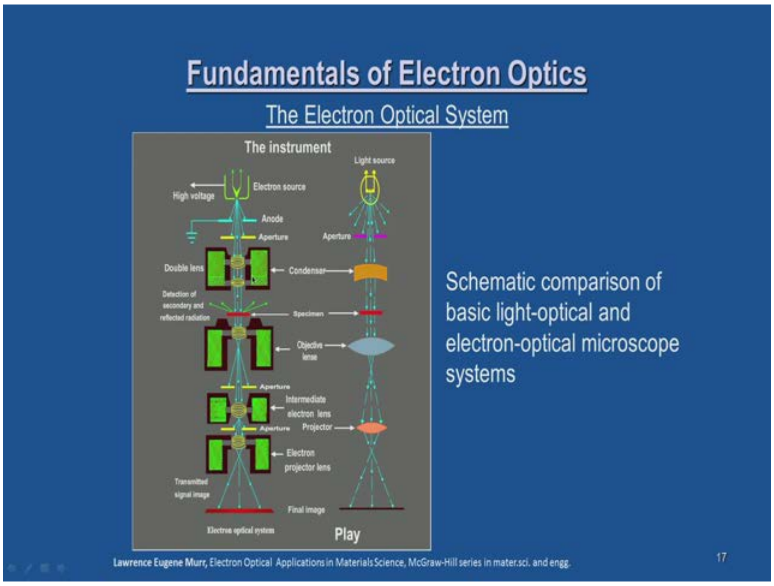

Fundamentals of Electron Optics

The Electron Optical System

Schematic comparison of basic light-optical and electron-optical microscope systems

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Now, we will also look at the another schematic where you see the clear animation shows that electron optical system, where you have the electron source usually it is a filament, and then you have the condenser lens, and then you have a specimen, and you have objective lens, and then some of the additional intermediate lenses, and then projector lenses and finally the image. You see that similar analogue of optical system is also shown you can see that animation very nicely shown. Except the lens electromagnetic lens action or you can see all this corresponding components of the electron sorry, optical system corresponding to the light optical system. You can see the condenser lens which here it is used to regulate the light and here also it is being used to regulate the electron beam and convert them onto specimen that is a primary action. Here also the objective lens will focus the light to the image plane, the same action is done here the objective lens, and then these two additional apertures also help.

We will look at the details when we deal with this especially the transmission electron microscope. For the introduction I just want you to have a feel of these two systems in comparison so that you do not have to feel anything confusing they are all the same whatever we have just looked at in the light optical system as far as the instrument details are concerned or the ray diagram is concerned.

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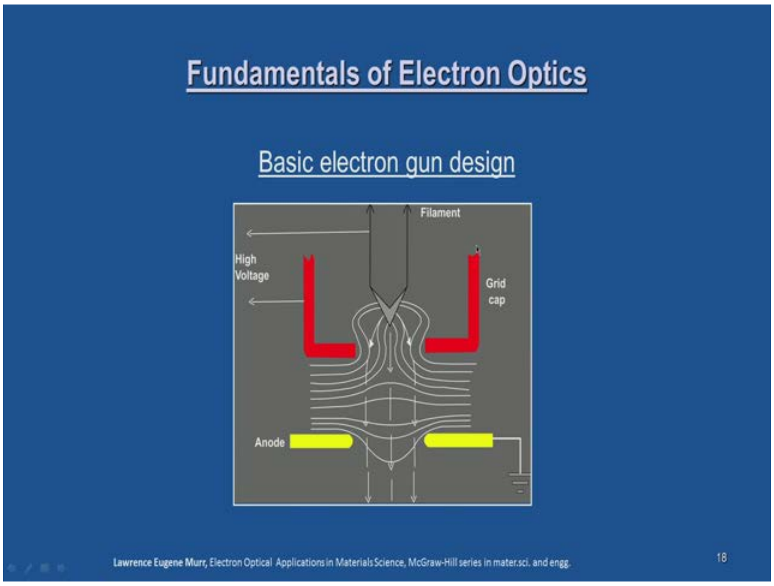

Fundamentals of Electron Optics

Basic electron gun design

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First we will look at the electron gun. You see that this is a typical schematic of electron gun design, you have the filament, and then you have the cylinder is called (Refer Time: 27:48) cylinder. The grid cap is, I mean the filament itself a cathode and then you have the anode. Then you see that field strength is a kind of a convergent, this is done by a negative bias given to this between a filament and this anode which will not only accelerate the beam and also concentrate the beam to this region. We will see the importance of this in due course. I just want to introduce this in the beginning like this.

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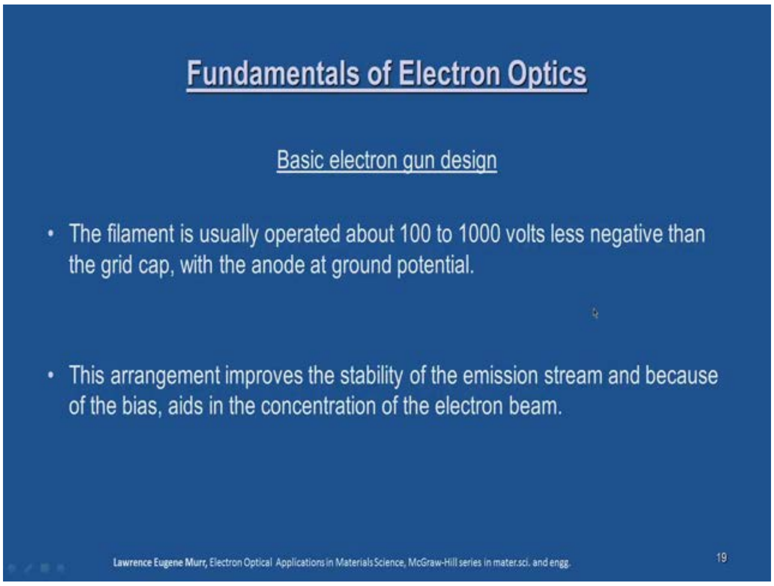

Fundamentals of Electron Optics

Basic electron gun design

- The filament is usually operated about 100 to 1000 volts less negative than the grid cap, with the anode at ground potential.
- This arrangement improves the stability of the emission stream and because of the bias, aids in the concentration of the electron beam.

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The filament is usually operated about 100 to 1000 volts less negative than the grid cap, with the anode and the ground potential. This is the bias which I talked about. So, filament is operated at 100 to 1000 volts less negative than the grid cap. This arrangement improves the stability of the emission stream and because of the bias aids in concentration of the electron beam.

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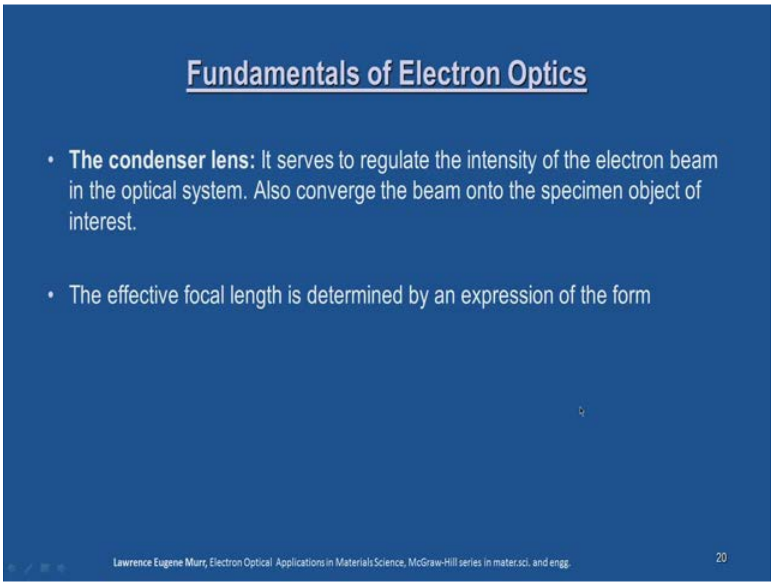

Fundamentals of Electron Optics

- **The condenser lens:** It serves to regulate the intensity of the electron beam in the optical system. Also converge the beam onto the specimen object of interest.
- The effective focal length is determined by an expression of the form

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If you look at the function of the condenser lenses, it serves to regulate the intensity of the electron beam in an optical system. Also converge the beam onto the specimen object of particular interest. The effective focal length is determined by the expression of the form.

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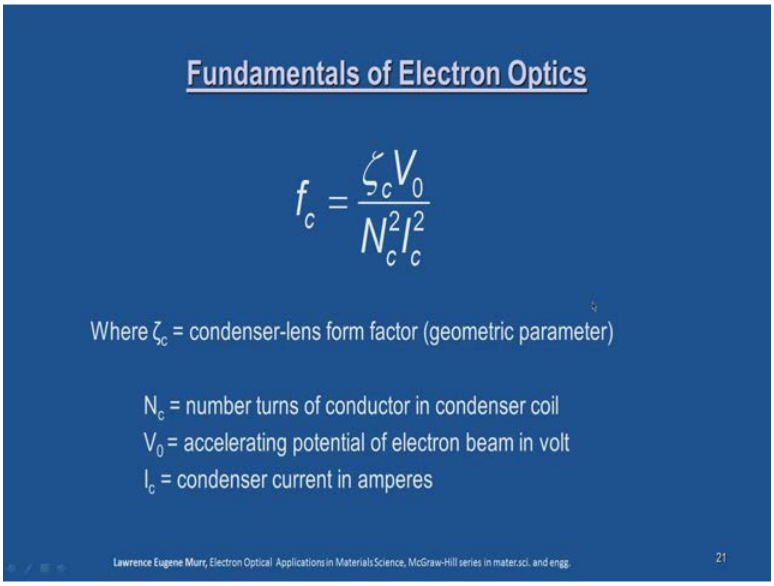

Fundamentals of Electron Optics

$$f_c = \frac{\zeta_c V_0}{N_c^2 I_c^2}$$

Where ζ_c = condenser-lens form factor (geometric parameter)

N_c = number turns of conductor in condenser coil
V_0 = accelerating potential of electron beam in volt
I_c = condenser current in amperes

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F c equal to zeta c, c stand for condenser and then V naught is a potential, divided by N c square and I c square. All c stands for the a condenser, this is a focal length of the condenser lens where zeta z the condenser lens form factor it is a geometric parameter and N c equal to number of turns of conductor in the condenser coil system. Now, you will understand what I mean by the condenser coil, you have seen that the cross section of the electron optical electromagnetic lenses so you will be able to relate it very quickly. So, V naught is the acceleration potential of electron beam in volts, I c is a condenser current in amperes. So, it is clearly understand by this expression this focal length of this electromagnetic lens is related to these many parameters.

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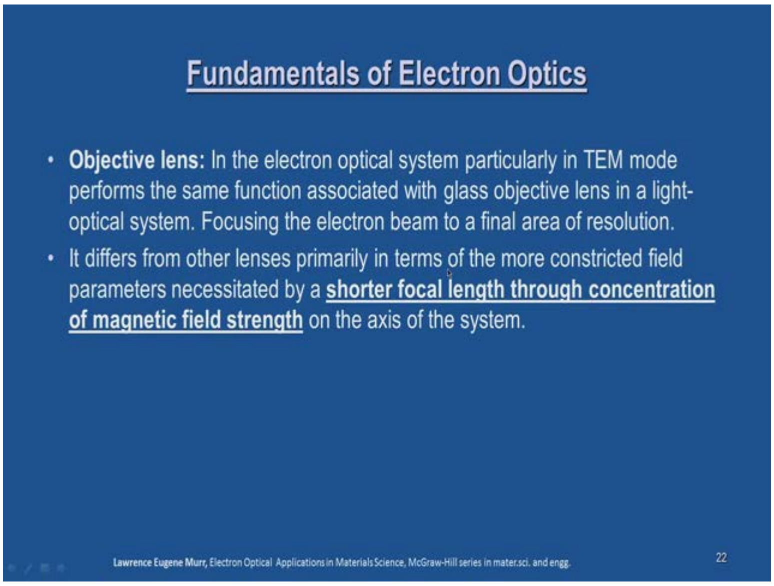

Fundamentals of Electron Optics

- **Objective lens:** In the electron optical system particularly in TEM mode performs the same function associated with glass objective lens in a light-optical system. Focusing the electron beam to a final area of resolution.
- It differs from other lenses primarily in terms of the more constricted field parameters necessitated by a **shorter focal length through concentration of magnetic field strength** on the axis of the system.

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Then if you look at the function of objective lens, in an electron optical system especially in a Transmission mode performs the same function associate with glass objective lens in a light-optical system. Focusing the electron beam to a final area of resolution. Objective lens is a very different from the other lenses primarily in terms of the more constricted field parameters necessitated by a shorter focal length through the concentration of magnetic field strength on the axis of the system. So, the objective lens has a slightly different role in order to bring the shorter focal length.

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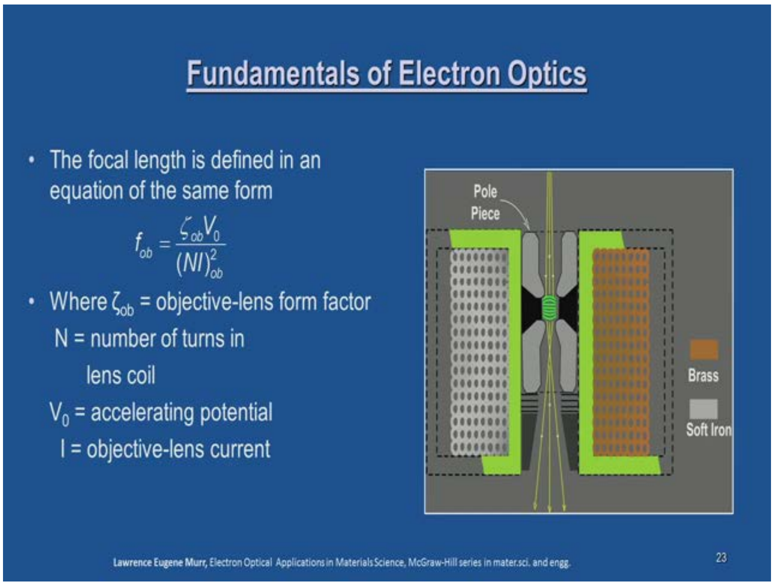

Fundamentals of Electron Optics

- The focal length is defined in an equation of the same form

$$f_{ob} = \frac{\zeta_{ob} V_0}{(NI)^2_{ob}}$$

- Where ζ_{ob} = objective-lens form factor
  N = number of turns in lens coil
  V_0 = accelerating potential
  I = objective-lens current

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Obviously, the design will be slightly different; you can see that it is slightly bigger. Even if you go back to the schematic diagram we have shown always the objective lenses shown much bigger than the condenser and other intermediate lenses because of the special action of this objective lens. So, we will see that the focal length is defined in an equation of the same form f objective is equal to zeta objective V naught divided by NI whole square. Where, zeta objective is objective lens form factor, N is number of turns in lens coil, V naught is acceleration activating potential, I is objective lens current.

So, you can see that nicely a drawn the schematic. You can see that there is an additional a hardware which is used called Pole Piece. This is used to focus all this electron beam in the column and this pole pieces completely magnetized during the operation and you see that the electron field or a the electromagnetic field strength is a focused using this two pole pieces like. These pole pieces are used in all the lenses whether it is condenser as well as objective and other lenses.

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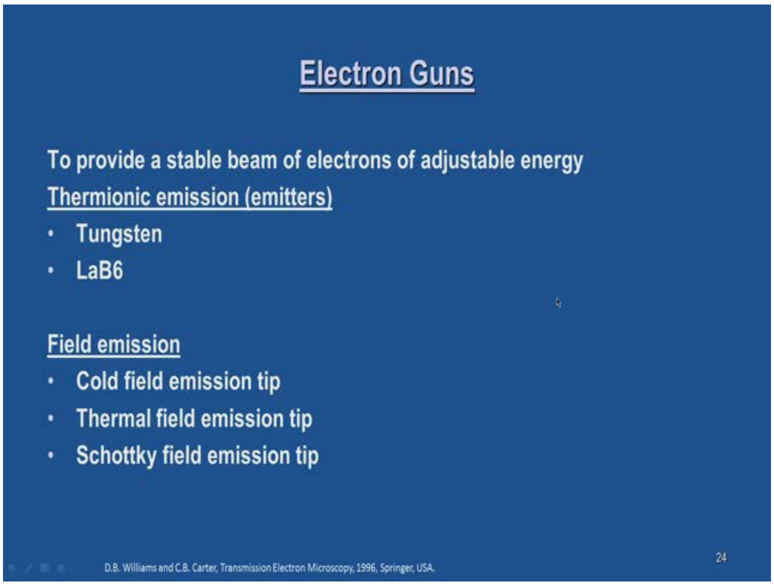

Electron Guns

To provide a stable beam of electrons of adjustable energy

Thermionic emission (emitters)

- Tungsten
- LaB6

Field emission

- Cold field emission tip
- Thermal field emission tip
- Schottky field emission tip

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

Now, we will just see what are the types of electron guns it is just an introduction, we will see the details of a functions much more all the details we will see when we actually look at the system, but I just want to introduce this types of electron guns. So to provide a stable beam of electrons of adjustable energy to have thermionic emission they are also called emitters; example Tungsten and Lanthanum Hexaboride. It is being also called a LaB6 or Lanthanum Hexaboride. These two are thermionic emitters. Then you have another type called Field emission guns, which has got three variants; Cold field emission tip, Thermal field emission tip, Schottky field emission tip.

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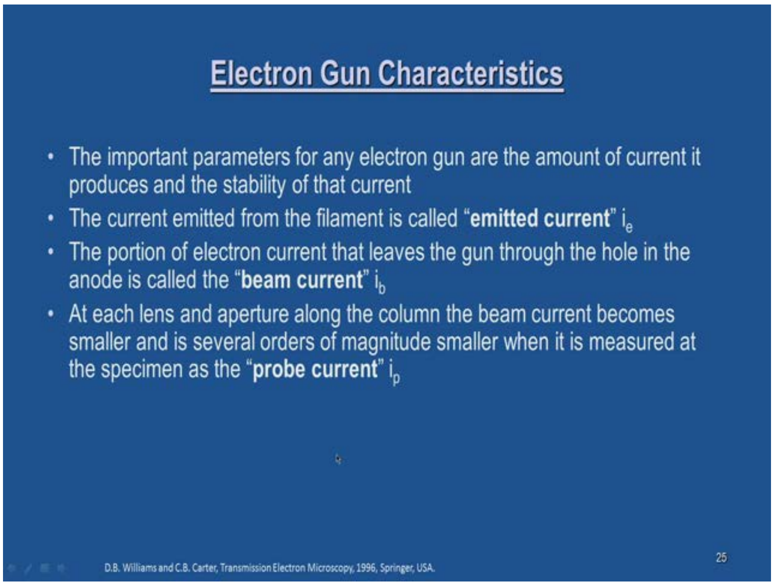

Electron Gun Characteristics

- The important parameters for any electron gun are the amount of current it produces and the stability of that current
- The current emitted from the filament is called “**emitted current**” i_e
- The portion of electron current that leaves the gun through the hole in the anode is called the “**beam current**” i_b
- At each lens and aperture along the column the beam current becomes smaller and is several orders of magnitude smaller when it is measured at the specimen as the “**probe current**” i_p

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

So, what are the general characteristics of electron gun? The important parameters for any electron gun are the amount of current it produces and the stability of that current. The current emitted from the filament is called "emitted current" i e. The portion of electron current that leaves that gun through the hole in anode is called a "beam current" i b. At each lens and the aperture along the column the beam current becomes smaller and it is several orders of magnitude smaller when it is measured at the specimen as the "probe current" i p.

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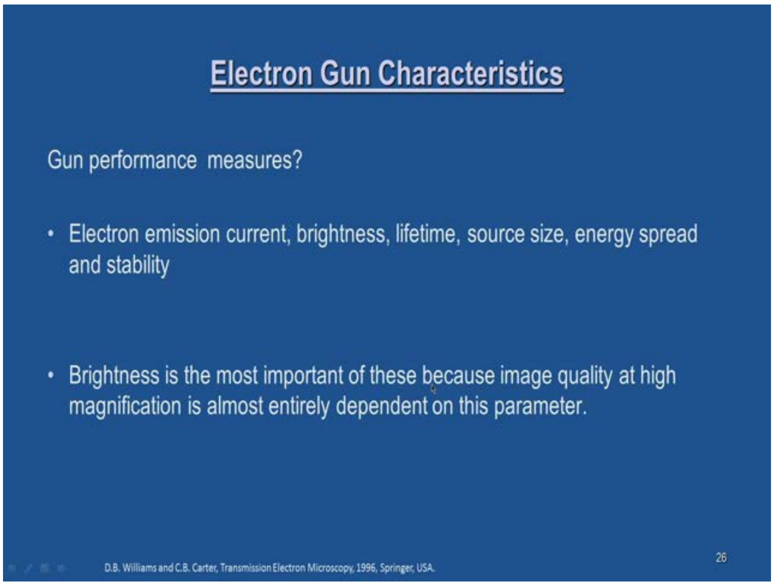

Electron Gun Characteristics

Gun performance measures?

- Electron emission current, brightness, lifetime, source size, energy spread and stability
- Brightness is the most important of these because image quality at high magnification is almost entirely dependent on this parameter.

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

So, how this gun performance is estimated? Electron emission current, brightness, lifetime, source size, energy spread and stability. You will appreciate all this parameters when we actually look at the operation of the electron microscope and the some of the application we will take up and then will explain the each parameter how it affects the resolution and the brightness and so on. Another important parameter is, brightness is the most important of all this because image quality at high magnification is almost entirely dependent on this parameter.

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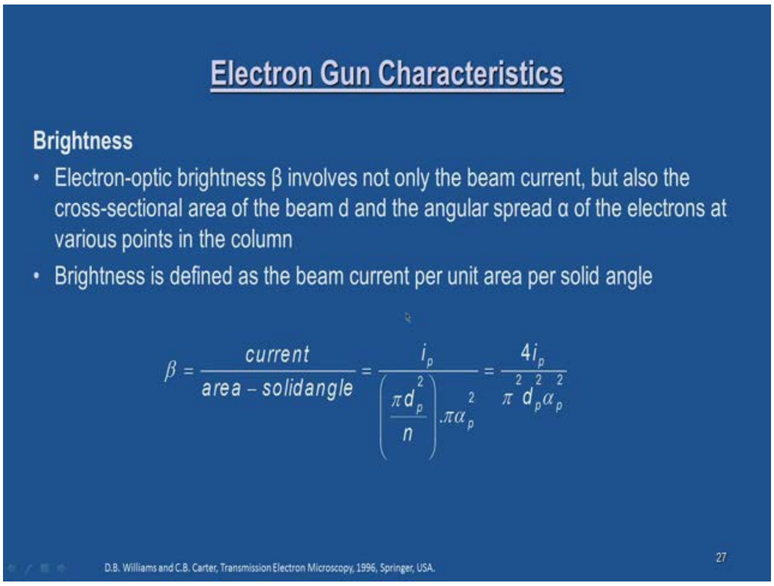

Electron Gun Characteristics

Brightness

- Electron-optic brightness β involves not only the beam current, but also the cross-sectional area of the beam d and the angular spread α of the electrons at various points in the column
- Brightness is defined as the beam current per unit area per solid angle

$$\beta = \frac{current}{area - solidangle} = \frac{i_p}{\left(\frac{\pi d_p^2}{n}\right) .\pi\alpha_p^2} = \frac{4i_p}{\pi^2 d_p^2 \alpha_p^2}$$

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

We have a definition for this brightness. Electron optic brightness beta involves not only the beam current, but also the cross-sectional area of the beam d and the angular spread alpha of the electrons at various points in the column. Brightness is defined as the beam current per unit area per solid angle, which is represented by this equation beta equal to current divided by area solid angle which is nothing but i p divided by pi d p square by n times pi alpha p square which can be written like 4 i p divided by pi square d p square and alpha p square. Where, the p stands for probe current. We will see the importance of all this parameters as and when we relate to the microscopic operation as well as the image quality and aberrations and so on. So these are all very important parameters to remember.

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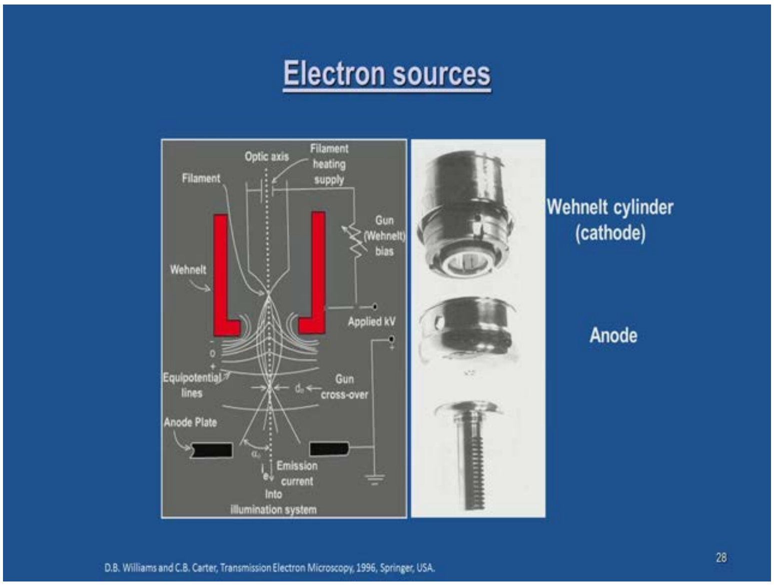

Electron sources

Wehnelt cylinder (cathode)

Anode

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

This is another schematic. This is from another text book we have taken you can see the similar filament and gun design, and we have already seen the action of the gun and so on.

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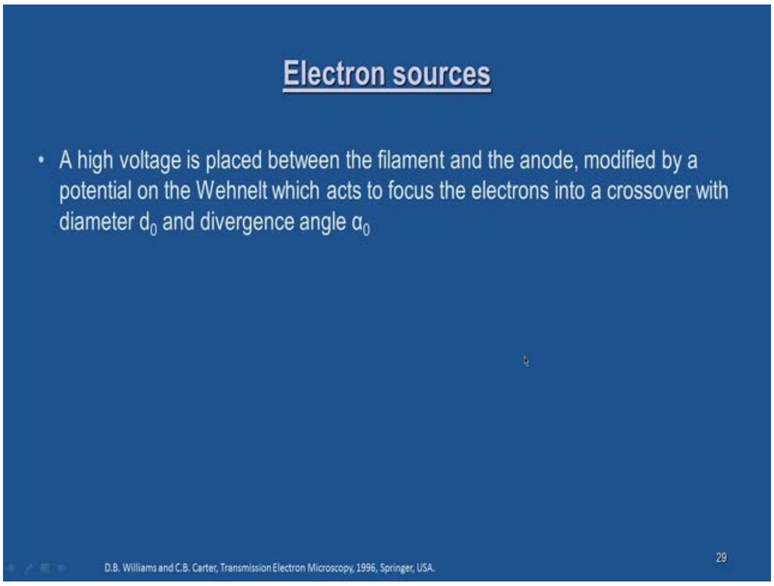

Electron sources

- 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 divergence angle α_0

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

A high voltage is placed between the filament and anode, modified by the potential on the Wehnelt which acts to focus the electrons into the crossover with diameter d naught and divergence angle alpha naught. So these two, just I want to show d naught and the alpha. These two are controlled by this lens design in order to focus the electron b.

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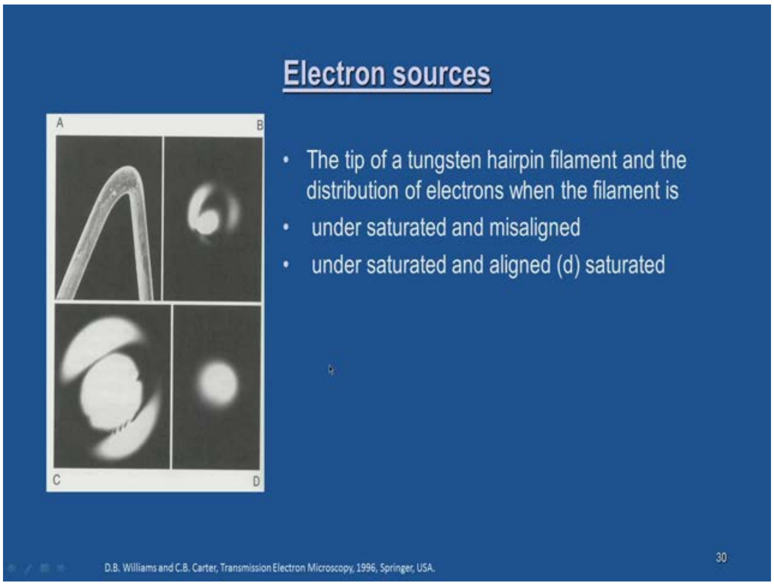

Electron sources

- The tip of a tungsten hairpin filament and the distribution of electrons when the filament is
- under saturated and misaligned
- under saturated and aligned (d) saturated

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

This is the image of the Tungsten Hairpin, the tip of Tungsten Hairpin filament and the distribution of electron is when the filament is under saturated and misaligned. Under saturated and aligned and saturated. So, this is one of the thermionic source, and these images or at different conditions and this is under saturated and misaligned and you have under saturated and aligned and you have completely saturated, so you will understand all this when we go to the operation of the microscope especially in a transmission mode. This is just for an introduction.

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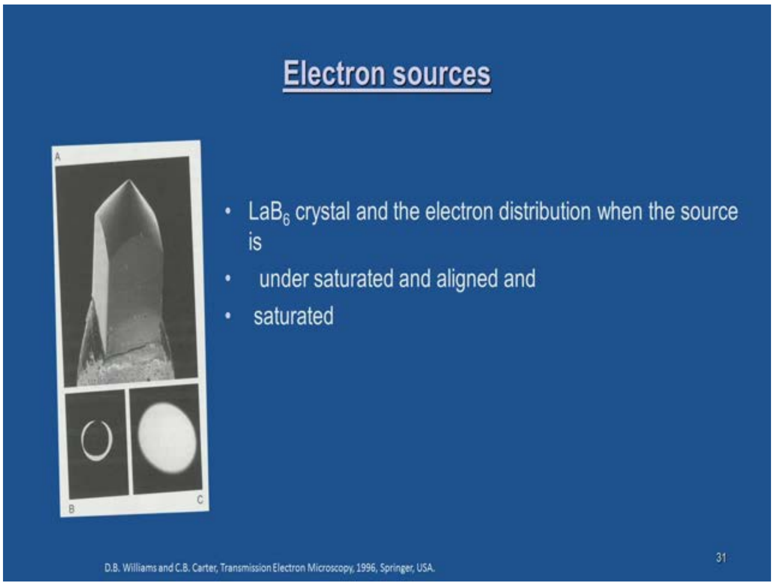

Electron sources

- LaB_6 crystal and the electron distribution when the source is
- under saturated and aligned and
- saturated

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

Another thermionic emission filament is, Lanthanum Hexaboride crystal and the electron distribution when the sources under saturated and aligned and the one, is saturated. This is just for your introduction of the electron gun source.

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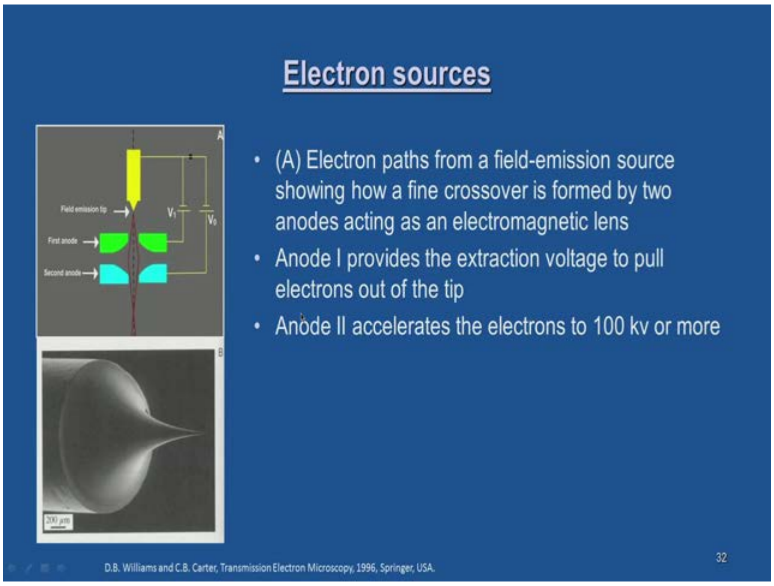

Electron sources

- (A) Electron paths from a field-emission source showing how a fine crossover is formed by two anodes acting as an electromagnetic lens
- Anode I provides the extraction voltage to pull electrons out of the tip
- Anode II accelerates the electrons to 100 kv or more

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

The next superior electron gun sources as I mentioned it is a field-emission source. So, where you can see that the field-emission tip and you have this subsequent anode design. Electron path from the field-emission source showing how a fine crossover is formed by two anodes acting as an electromagnetic lenses, so you see that this is very fine and you can also see this a photo graph, how sharp the tip is so that is why you are able to produce a very, very fine crossover of the electron beam. The action of the anode one is to provide the extraction voltage to pull the electrons out of the tip. Anode two accelerates the electrons to 100 kv or more. So, we will look at the parameters are much more details about this field emission gun as we go along.

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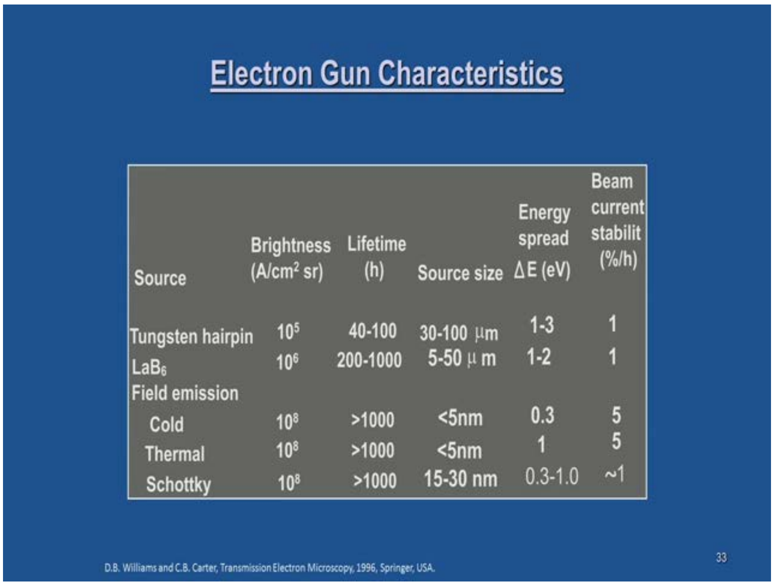

Electron Gun Characteristics

Source	Brightness (A/cm^2 sr)	Lifetime (h)	Source size	Energy spread ΔE (eV)	Beam current stabilit (%/h)
Tungsten hairpin	10^5	40-100	30-100 μm	1-3	1
LaB_6	10^6	200-1000	5-50 μ m	1-2	1
Field emission					
Cold	10^8	>1000	<5nm	0.3	5
Thermal	10^8	>1000	<5nm	1	5
Schottky	10^8	>1000	15-30 nm	0.3-1.0	~1

D.B. Williams and C.B. Carter, Transmission Electron Microscopy, 1996, Springer, USA.

These are some of the gun characteristics you can look at it. Please remember the microscope performance is a related to this electron gun source and we will also see how it is, but for the introduction I just want you to have some basic knowledge about this electron gun characteristic. You see the source your Tungsten hairpin, LaB6, Field emission, Cold, Thermal, Schottky and in terms of brightness as I mentioned it is one of the primary requirement of the electron gun and it is, lifetime, source size, energy spread, and then beam current stability. You can see that the field emission gun have superiority over this thermionic emitters in terms of brightness as well as life time also in the probe size.

This is very important you see that thermionic sources you can go up to 30 to 100 microns, LaB6 can go up to 5 to 50 microns and here we are talking about less than 5 nanometers. You will all appreciate the importance of the probe diameter when we discuss the operation as well as image forming capability of a different microscopes we will discuss and this is how the field emission than a superior, because it is able to form a very fine crossover or less than 5 nanometers. Then also you see that energy spread is also very a small compared to the thermionic sources. You see the stability is also much higher. So, with this I would like to conclude this lecture and when we come to the next lecture, we will discuss another important aspect of this Electron Lenses or Electromagnetic Lenses namely The Aberrations. The aberrations and it is Effect on Resolution or Limiting Resolution. These aspects we will see in the next class.

Thank you.