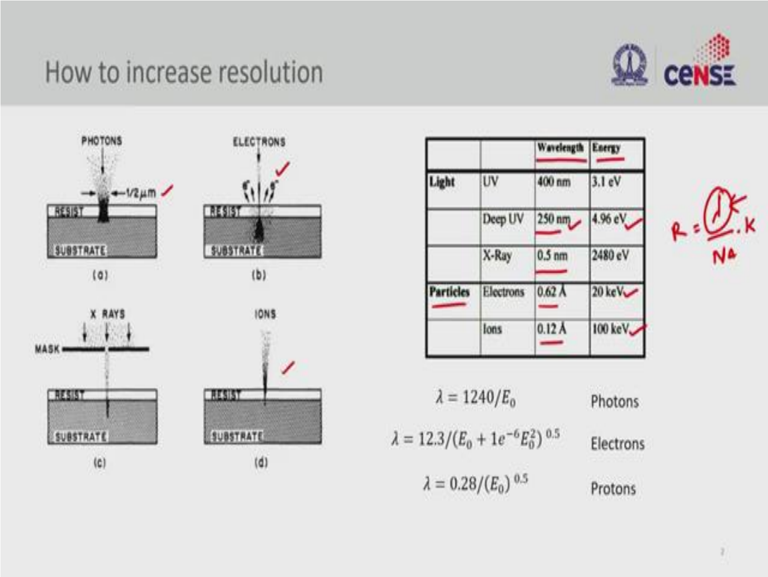
Fundamentals of Micro and Nanofabrication
Prof. Shankar Kumar Selvaraja
Center for Nano Science and Engineering
Indian Institute of Science, Bengaluru

Lecture – 39
Electron beam lithography: Basics

In the lithography lecture series, we are going to look at electron beam lithography. First of all let us look at why we need electron beam. So, far all our discussion was around optical lithography where we use light as the illuminating source for transferring pattern, but here we are going to use electron beam. So, it is not going to be photons, but electrons for pattern transfer. Let us just look at the idea behind electron beam lithography, but first of all let us look at the rationale behind going to electrons as opposed to photons.

(Refer Slide Time: 01:17)



How to increase resolution

		Wavelength	Energy
Light	UV	400 nm	3.1 eV
	Deep UV	250 nm	4.96 eV
	X-Ray	0.5 nm	2480 eV
Particles	Electrons	0.62 Å	20 keV
	Ions	0.12 Å	100 keV

$\lambda = 1240/E_0$ Photons

$\lambda = 12.3/(E_0 + 1e^{-6}E_0^2)^{0.5}$ Electrons

$\lambda = 0.28/(E_0)^{0.5}$ Protons

$R = \frac{\lambda}{NA}.K$

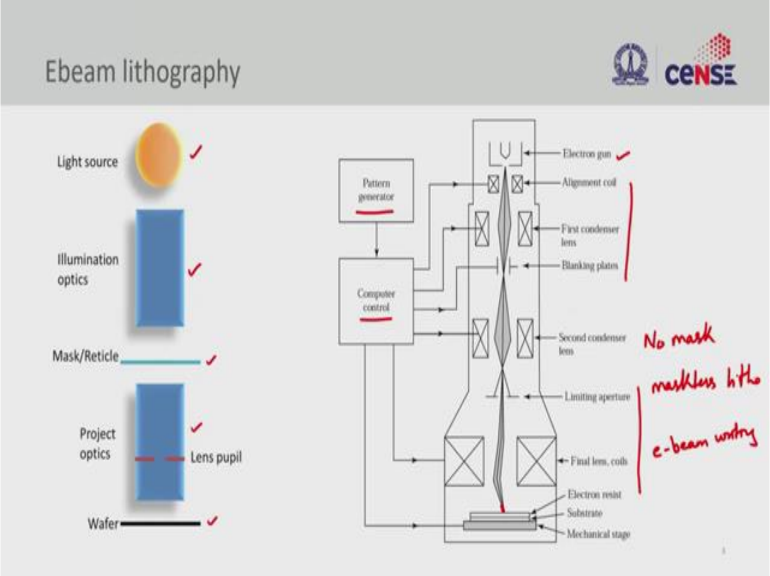
So, the whole idea of moving towards electron beam lithography or looking at alternate form of patterning than light is resolution. So, here in the table and also in the picture, you can see there is wavelength and then there is associated energy. So, the wavelength strongly depends on energy of the fundamental particle we are trying to use. So; so far we used light and this is what the wavelength was and the energy was about 5 eV, but wavelength is the one that is restricting.

If you remember our resolution depends on the kλ/NA. So, your wavelength was one of the restricting factor. So, how to reduce this wavelength was one of the resolution enhancement technique. So, you can use X-rays as well to improve the resolution, but then we will see later in alternate lithography that these x-rays are to handle and so on.

But if you look at the particles, electrons and ions energies are very high. So, 20 kV and 100 kV energy so, that brings down the wavelength so; that means, your waves are very small and with those you should be able to define very finer feature. So, this is the left side image that captures how small, you can define the pattern.

So, you can see here electrons and ions can finally, define or make a very pencil beam as opposed to photons that we use by focusing and so on. So, x-rays are a different class. So, we will discuss that later in alternate lithography techniques, but for now as we discussed the particles with very high energy that can be used for high resolution patterning.

(Refer Slide Time: 03:36)

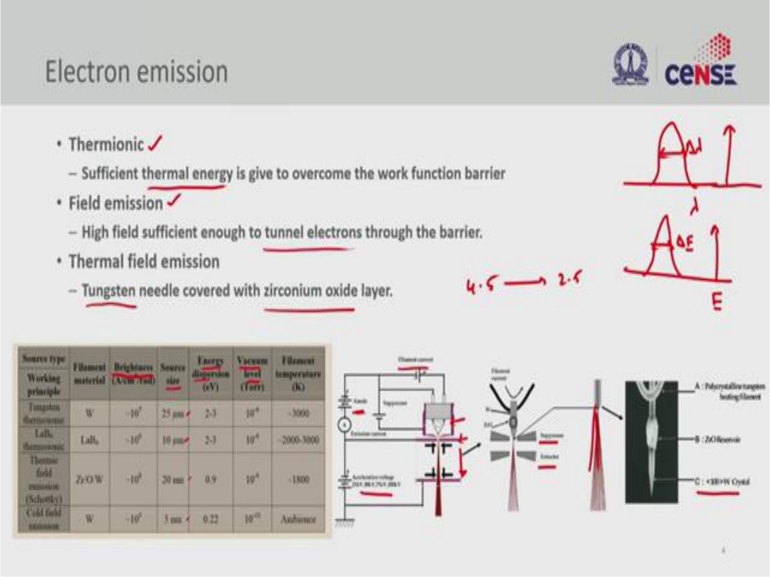


Ebeam lithography

So, this is a comparison between electron beam system and the projection system. On the left side you we have seen this in earlier lectures where you have this source, illuminating optics, the mask, the projection optics and the wafer. But if you look on the right-side ie., the electron beam system, it is much more complicated. But the elements remains the same. So, there is a electron gun that is the source, the condenser optics or illuminating optics, the aperture and the lens optics more or less acting as projection. But since there is no mask involved in electron beam lithography.

So, there is no mask and that is the reason why we call it as “mask-less process” So, how do we pattern structures then? So, the way we do that is by using this pattern generator and controlling the electron beam. Unlike optical lithography where we do printing here we do a writing. So, the right word to say is Ebeam writing. So, you use a pencil of beam here to write the patterns. So, we will look at this configuration little bit detail later in this lecture.

(Refer Slide Time: 05:17)



Electron emission

- Thermionic ✓
  - Sufficient thermal energy is give to overcome the work function barrier
- Field emission ✓
  - High field sufficient enough to tunnel electrons through the barrier.
- Thermal field emission
  - Tungsten needle covered with zirconium oxide layer.

4.5 → 2.5

Source type / Working principle	Filament material	Brightness (A/cm²·rad)	Source size	Energy dispersion (eV)	Vacuum level (Torr)	Filament temperature (K)
Tungsten thermionic	W	~$10^{[illegible]}$	25 µm	2-3	$10^{[illegible]}$	~3000
LaB₆ thermionic	LaB₆	~$10^{[illegible]}$	10 µm	2-3	$10^{[illegible]}$	~2000-3000
Thermic field emission (Schottky)	ZrO/W	~$10^{[illegible]}$	20 nm	0.9	$10^{[illegible]}$	~1800
Cold field emission	W	~$10^{[illegible]}$	5 nm	0.22	$10^{[illegible]}$	Ambience

But let us look at first element in the whole system so, that is the electron source itself. So, where do we generate the electrons from?. In optical sources, we use lasers, excimer laser or even lamps such as mercury vapor lamps were used. But let us see what are all the sources that we can have. Here, there are two predominantly two type of source; one is the thermionic source and the other one is field emission. The whole idea here is how to give enough energy to the electron sitting inside the material to take it out; that means, how do you take it over the work function and take it out of that material.

So, one way of doing that is by heating the material. So, when you heat it enough then you can overcome the work function barrier and then you can take the electron out. The other way to do that is by applying enough electric field. When you apply a very large electric field and the electrons tunnel through this barrier and then you should be able to get the electron out. So, you can also do combination of these two; so, the thermal and field emission together.

So, that is what predominantly done where you use tungsten as the source. When it is heated it will emit ions electrons and then that tungsten is covered by zirconium oxide which helps you in reducing the work function. So, the work function can be reduced somewhere between 4.5 eV to about 2.5 eV by this coating.

So, the lower the barrier that you need lesser the energy is needed to extract the electrons out. So, that is not only the reason why we like this the spot size. So, the brightness is nothing, but how much power you get out, how small is your source size and then the energy dispersion. Energy dispersion is again a very important parameter of your electron source. The reason for that is we saw this in partial coherence.

So, when you take a light source if this is λ so, you will have a certain width; you will not have a single line, but you will have some $\Delta\lambda$. Similarly, in electron beam ideally you want energy to be just E, but light sources are not ideal. So, you will have some ΔE. So, this is what energy dispersion is all about. So, what is the dispersion that we have and then the brightness is how much electrons you can extract out and the size is also important. The finer your beam, finer your structures are going to be and based on the type of sources this size could vary .

And the other important thing is the vacuum required. So, you cannot unlike optical lithography, you cannot use electron beam in atmospheric pressure. So, you need to go to low pressure. So, that is again a constraint. So, if you look at other sources, say lanthanum bromide, you have 10 µm as your source wavelength which is pretty good. You have a very sharp focus, but then the vacuum level needed here is very aggressive. So, you need to spend lot of energy in getting the vacuum here.

However, if you look at tungsten thermionic type emitters 25 µm wavelength a reasonable feature size, but 10^{-6} torr is the required vacuum level which is typically used in lot of vacuum processes.

So, it is not just about source size, it is also about the vacuum level one can reach and then the energy you want to spend on those as well. So, on the bottom right you have a typical configuration of an electron source. So, where you have the tungsten crystal that is sitting there and which is emitting your electrons and this emission is mediated through the extractor and then the suppressor to focus the beam and then you have the whole circuitry here.

So, you have the filament current which we have to give and then this is the emission current, this is the accelerator that is the potential difference between this plate and then your source is going to give you how much extraction current you can get and then you will have acceleration.

So, once you get it out, then you accelerate the beam and the accelerated beam can be achieved by varying the voltage difference between the extractor here and your accelerating voltage. So, this is how we do electron emission source configuration.

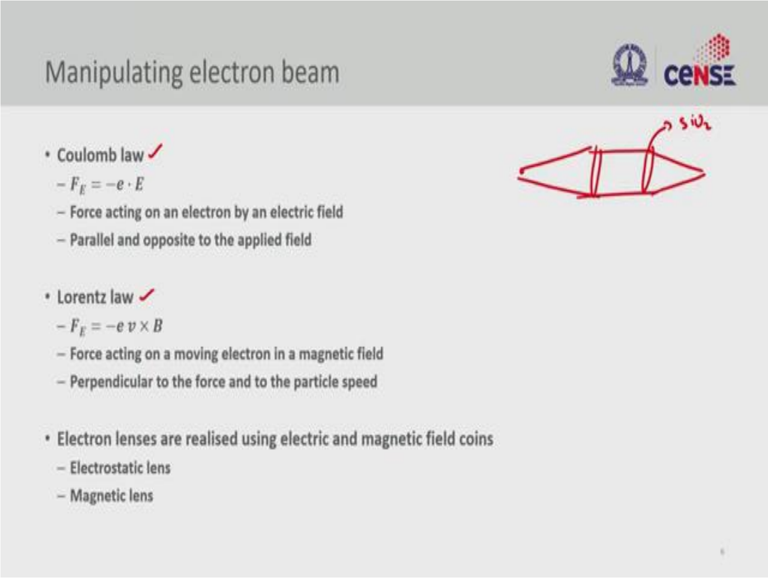
(Refer Slide Time: 10:45)

Vacuum column

- Three main components in the vacuum column
  - Electron Source ✓
  - Objective lens ✓
  - Beam deflection unit ✓

And next comes the vacuum tube itself or the column itself. So, there are three fundamental elements here; one is the electron source which we just saw and then there is objective lens and then the beam deflection unit. In addition to that you have lot of apertures and so on, but let us look at what are all the things that we have in this column.

(Refer Slide Time: 11:08)



Manipulating electron beam

- Coulomb law ✓
  - $F_E = -e \cdot E$
  - Force acting on an electron by an electric field
  - Parallel and opposite to the applied field

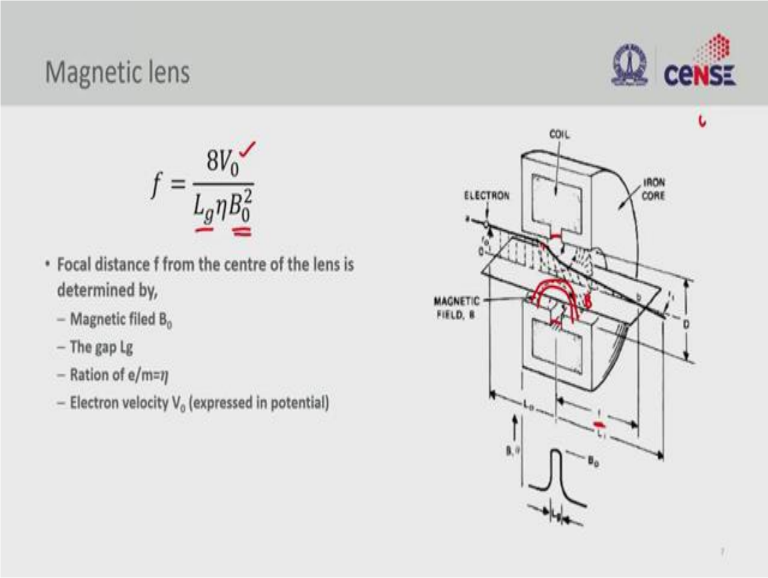
- Lorentz law ✓
  - $F_E = -e\, v \times B$
  - Force acting on a moving electron in a magnetic field
  - Perpendicular to the force and to the particle speed

- Electron lenses are realised using electric and magnetic field coins
  - Electrostatic lens
  - Magnetic lens

Primarily the whole idea of this electron beam column is to control the electron beam. So, like what we had in optical beams so, you have the condenser lens and then you want to focus and so on. So, there we use silica lenses if the material is transparent, but then how do we handle electrons? So, electrons cannot be handled by simple material . So, here we are using forces. So, one is a Coulomb and other is Lorentz force primarily coming from electric field and magnetic field.

We know the force extractors on to this particle strongly depends on the field that is applied. So, if you apply an electric field, you create a parallel and opposite force generated in this electron, while applying a magnetic field will create a perpendicular force with respect to the electron propagation direction. So, by using this magnetic and electric, we come up with electric and magnetic lenses. So, we use field coils whether it is electrostatic lenses or magnetic lenses, we use coils; in electrostatic lenses, we apply electric field; in magnetic lenses, we apply magnetic field. So, this is how we control the flow of electrons.

(Refer Slide Time: 12:51)



Magnetic lens

$$f = \frac{8V_0}{L_g \eta B_0^2}$$

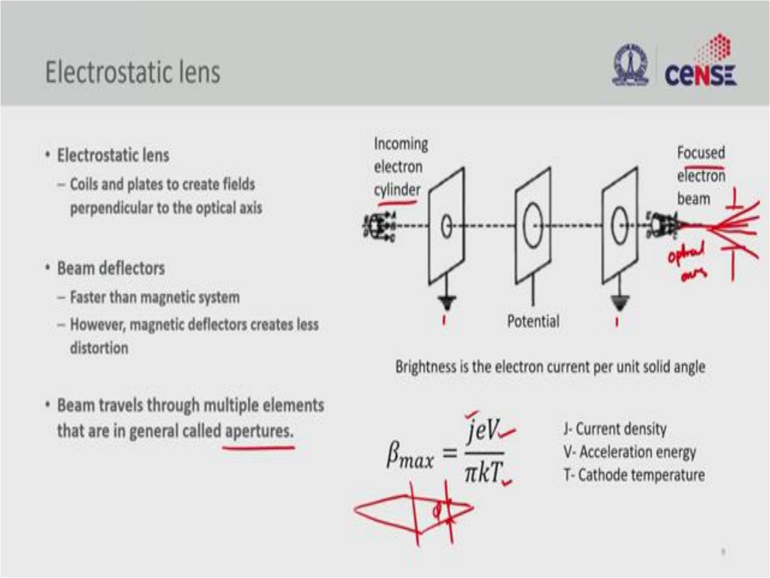
- Focal distance f from the centre of the lens is determined by,
  - Magnetic filed B_0
  - The gap Lg
  - Ration of e/m=η
  - Electron velocity V_0 (expressed in potential)

So, if you take a magnetic lens so, on the right side you can see a very simple cartoon of how we focus an electron beam. So, this is the gap that you see here where you start to make the field aligns and then this is the traversed path and then this is the focal length. So, from the lens to this; this is the focal length and L_g is the gap that creates the field of B , so B is the field that is generated. So focal length depends on V_0 . So, this is nothing, but electron velocity.

So, this is particle so, they move at certain velocity and if the velocity is very high and your field is low, your focal length is going to be long . If you want shorter focal length, you want to have this voltage lower. So, that the acceleration is smaller and you can use lower field in order to reduce your focal lengths and that also depends on the size of the lens . This gap is the one that creates this field that basically determines the interaction length and so on and of course, your field to particle to mass ratio is also very important. So, that is again a factor here, which remains constant to a large extent.

So, this is how we can make magnetic lens ; it is a simple coil like we have in our motors and everything, but then we are going to pass electron to this gap and we can control this flow through applied magnetic field which is attained by passing a current through this coil.

(Refer Slide Time: 14:51)



Electrostatic lens

- Electrostatic lens
  - Coils and plates to create fields perpendicular to the optical axis
- Beam deflectors
  - Faster than magnetic system
  - However, magnetic deflectors creates less distortion
- Beam travels through multiple elements that are in general called apertures.

Brightness is the electron current per unit solid angle

$$\beta_{max} = \frac{jeV}{\pi kT}$$

J- Current density
V- Acceleration energy
T- Cathode temperature

The next thing is a electrostatic lens; so we saw magnetic. So, electrostatic lenses are slightly simpler to implement; primarily done using coils and plates . So, when you have a cylindrical electron beam coming in, it will go through three plates normally ; most of the time these are all integrated where the middle plate is actually energized it is at a certain potential while the first plate and the third plate are grounded .

So, through this lens system by applying various voltages here, we should be able to convert a cylindrical beam to a focused electron beam and we use this same configuration for doing beam deflectors and so on. So, this electrostatic lens could also be used as a beam deflector where you apply certain amount of voltage to deflect the beam outside the optical axis.

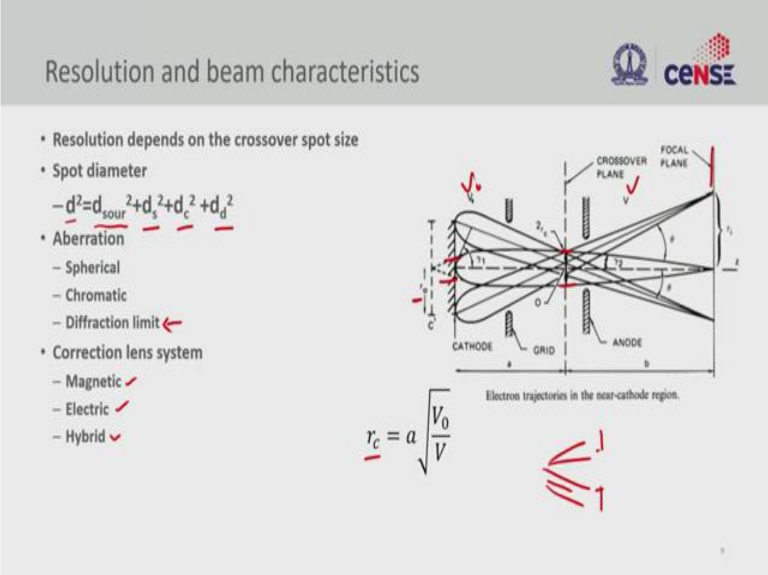
So, if the beam is within the optical axis, you will capture it and then if you put a deflector here . If I put a voltage here and then I can deflect the beam . So, if I deflect it then I will not see that beam . So, this deflectors can also be realized using this electrostatic plate, but you can also use a magnetic plate.

So, one of the interesting thing here is unlike electrostatic lenses, magnetic lenses create very less distortion because the field is pretty uniform and the other thing is they do not create unnecessary second order current inside the field itself. So, magnetic manipulation of the beams are primarily preferred for very good beam quality compared to electro static.

And irrespective of this lens and deflected system, there are multiple apertures we use to profile the beam, to change the size of the beam from one lens system to the other lens system. So, this is all integrated into the column and the brightness that you achieve depends on the current that you get per solid angle . So, if there is a beam being focused, it depends on how much beam is captured within this particular solid angle that the current generated from this.

So, we already saw earlier in projection lithography, there is something called a pupil lens . Similarly, you will have some blankers here to control the beam size and so on. So, based on that you will know what is the actual solid angle that you get and that current also depends on the cathode temperature, your current density and your accelerating energy as well. So, this is how one could control how much current you get onto the substrate .

(Refer Slide Time: 18:20)



Resolution and beam characteristics

- Resolution depends on the crossover spot size
- Spot diameter
  - $d^2 = d_{sour}^2 + d_s^2 + d_c^2 + d_d^2$
- Aberration
  - Spherical
  - Chromatic
  - Diffraction limit
- Correction lens system
  - Magnetic
  - Electric
  - Hybrid

$$r_c = a\sqrt{\frac{V_0}{V}}$$

Electron trajectories in the near-cathode region.

And the next thing is about the resolution of these beams . So, what actually determines the resolution . So, in optical lithography we said kλ/NA. So, here we discussed about NA, we discussed about λ and also we discussed about k; how the process determines the resolution here.

So, let us look at what determines the resolution here. First of all it is a pencil beam , it is a very sharp beam. What determines the spot size of this beam is the first question we should ask ; how sharp is my beam. So, that depends on various factor and that is listed here. So, it depends on the diameter of the source and this is the total diameter. So, what does this source diameter and what is the diameter because of spherical aberration.

So, aberration are undesirable distortion and the beam that you get. So, there is spherical aberration that you get and then you have chromatic aberration and then you have a diffraction limit. So, these are all the factors that determines your final spot diameter. So, we will look one by one.

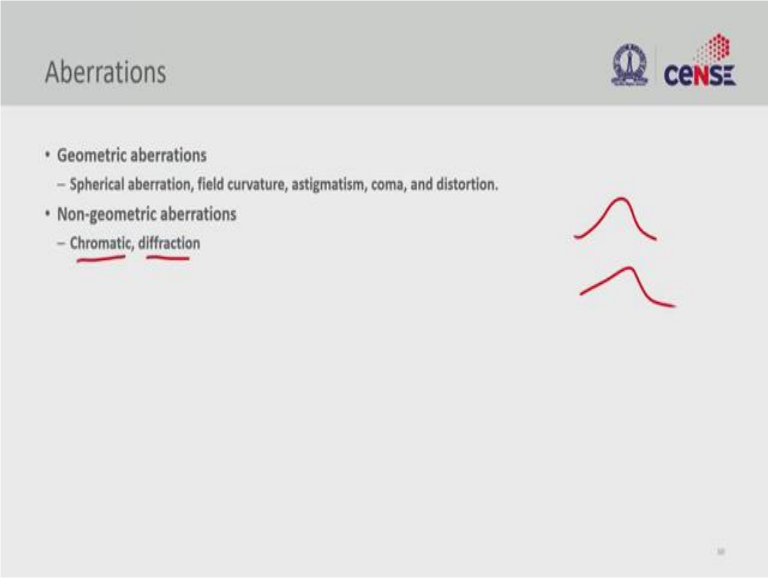
So, just quickly looking at this diffraction limit . So, diffraction limit is basically your blanker ; your size of your beam. So, if you have a large beam diffraction what you do is you put this blankers here . So, what is the size of this blankers and how much we can capture the diffracted beam is what we call the diffraction limit .

And in order to control these aberration , we need to use the lens system as we discuss their magnetic, electric or hybrid. Let us see how these things could be done on the right side, you see the effect of the source and your voltage that we use to take the electrons out and focus it .

So, to start with on the left side is the cathode that is giving you the electrons and then we captured it through this anode and then we are accelerating it and then here is our focal plane . So, what is the width that we have in this crossover plane is a very important factor , so that is rc. So, that if we just quickly look at it not very careful, you will see that maybe it depends on the size of the source itself . If this the if the source is very small, your crossover will be very small, but if the size is very large you might have large width.

But that is not the case. Actually what determines it is the voltage drop across. So, V_0/V across your anode is what is determining your width in the crossover point . So, not just the size of your a cathode itself, to a large extent it is determined by the voltage that we apply.

(Refer Slide Time: 21:54)



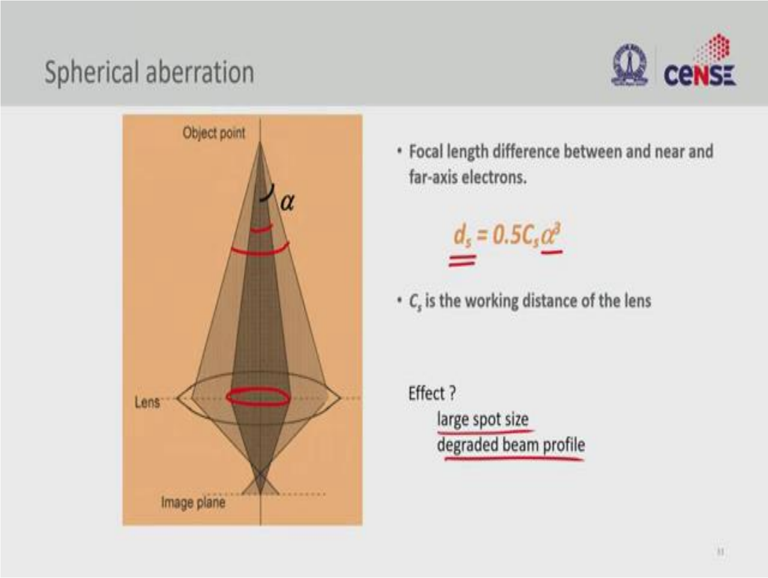
Aberrations

- Geometric aberrations
  - Spherical aberration, field curvature, astigmatism, coma, and distortion.
- Non-geometric aberrations
  - Chromatic, diffraction

So, let us look at the different type of aberration. So, there is geometric aberration and there is non geometric aberration. So, geometric aberrations include a spherical aberration . This is the beam that is getting distorted. You always want the field to be uniform, but if the field is just skewed, then you will have issues with the projection ; astigmatism, a coma and distortion.

So, this is all the term that one should have encountered in this simple optics. So, all those things apply here as well. So, that is what we call geometric aberration and there is non geometric aberration. So, that is chromatic dispersion and diffraction as well. So, these two are non geometric ; there is no physical structure that is creating this aberration on the top. The geometric aberrations are all from the physical structures.

(Refer Slide Time: 23:05)



Spherical aberration

- Focal length difference between and near and far-axis electrons.

$$d_s = 0.5C_s\alpha^3$$

- C_s is the working distance of the lens

Effect ?
large spot size
degraded beam profile

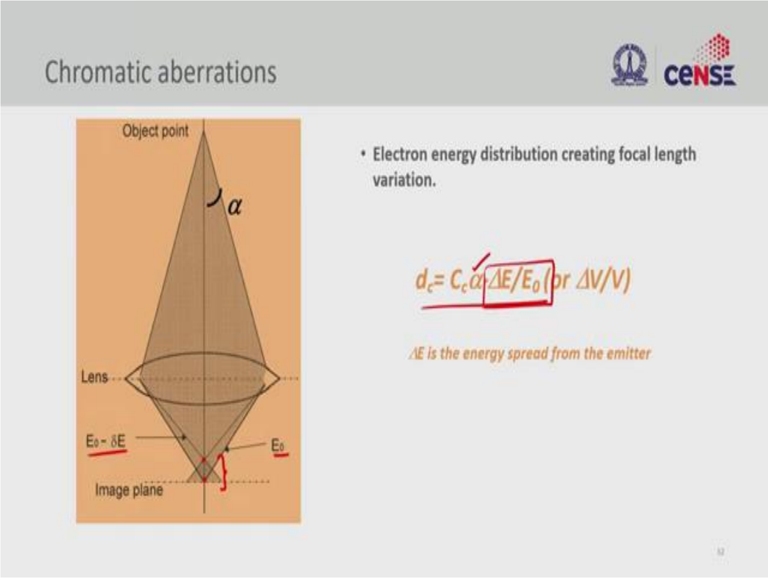
So, let us look at spherical aberration. Spherical aberration is nothing, but focal length difference between near and far axis of the electron . So, here you have the two beams here . So, one is focused and the other one is dispersed . So, if you look at the focal point , your focal point need to focus all the electrons within the distribution at a single point , but you will not be able to do that because your lens is also not uniform . So, you will have the lens dispersion there and that will come into picture and that is what is creating variation in the focal length as well.

The diameter due to spherical aberration (d_s) can be given by,

$$d_s = 0.5\, C_s \alpha^3$$

So, lens dispersion is determined by the focal working distance (C_s) and the solid angle(α) of diffraction. As you can see here it α^3. So, very quickly your spherical aberration can affect your focal spot size. So, if you do not take care of spherical aberration, you will have very large spot size where you will not be able to focus it well and then you will see a very degraded beam because the beam is not focused it is very broad and also your current will be low as well.

(Refer Slide Time: 24:50)


Chromatic aberrations

- Electron energy distribution creating focal length variation.

$d_c = C_c\alpha \boxed{\Delta E/E_0}$ (or $\Delta V/V$)

ΔE is the energy spread from the emitter

The next thing is chromatic aberration . So, chromatic aberration comes from the variation in the energy from the source itself. So, when you have a source you always expect the source to give out a certain energy particle, but unfortunately you will not be able to get all the time the same energy; there could be a small energy difference in the electrons that are coming out .

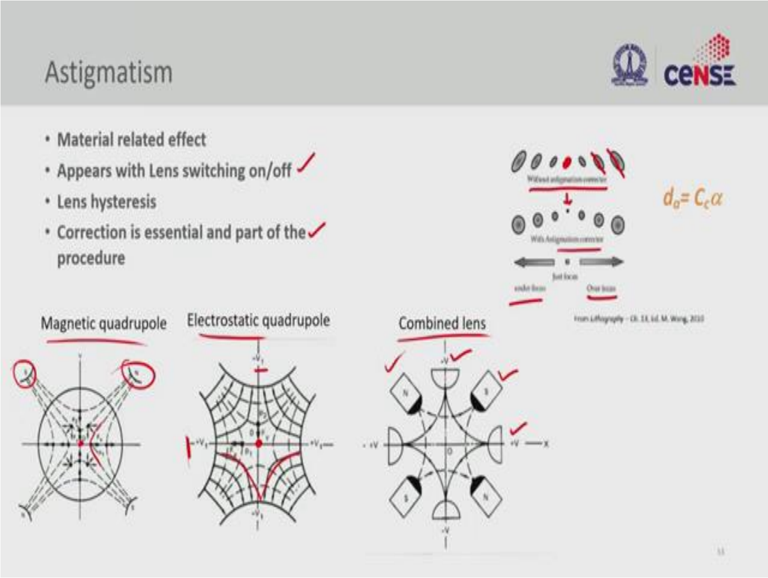
So, when there is small energy difference and that energy difference could result in a distribution and that distribution will create a variation in the in the focal. So, there is a focal difference. The diameter due to chromatic aberration (d_c) can be given by,

$$d_c = C_s \alpha\, \Delta E/E_0$$

So, if you have just E it will focus here. If there is a change in the energy, then you are going to focus it somewhere . So, this is what we call chromatic aberration.

So, chromatic comes from variation in the energy of the electrons that you covered similar to the chromatic dispersion in optical lenses. So, all the wavelengths cannot be focused at the same location . So, there will be slight variation in the focal point between different wavelengths. So, that is characterized by this the dispersion angle and it plays a role here as well, but primarily the energy difference between the central energy and the distribution plays a huge role here.

(Refer Slide Time: 26:28)



Astigmatism

- Material related effect
- Appears with Lens switching on/off ✓
- Lens hysteresis
- Correction is essential and part of the ✓ procedure

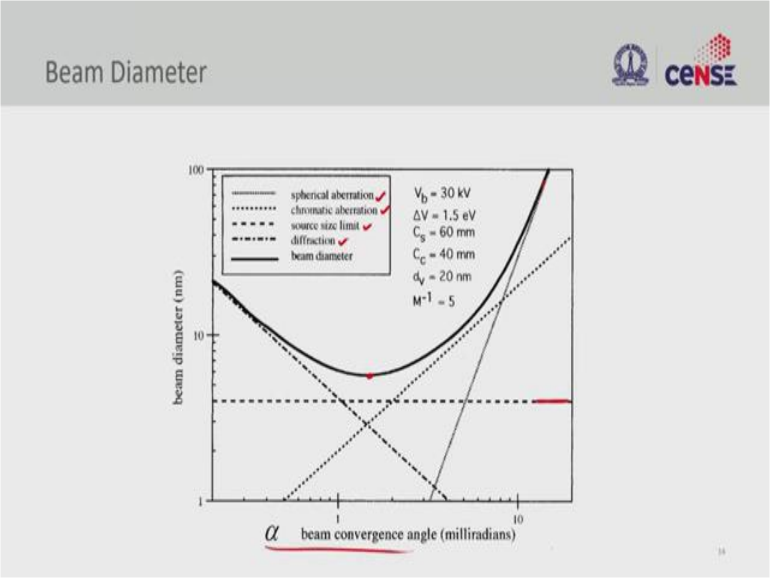
And how do we control the astigmatism? Primarily this is material related as well. When I say material related to the lens system; we switch on and off the system sometimes and there will be some hysteresis in the lens that will add up and create this astigmatism and we need to constantly correct it. There is no fixed solution to this unlike optical lithography where you fix the lens and then it should do its job unless the alignment goes off, but here you have to constantly correct it.

So, on the right-top what you see is the effect of astigmatism. Without astigmatism correction, you have best focus. If the spot size itself is pretty large unlike the one with width correction, but then when you do defocus. So, you do over focus, you do under focus. When you do that instead of the beam becoming larger and blurred, you will have some sort of orientation here this tells you that the lens is not aligned properly. So, there is a preferential elongation in one direction, magnification in one direction, the other direction you do not see it. So, this is a classic example of how astigmatism affects your beam quality.

But when you do the correction; if you do focus and out of focus, you will still maintain this spot nature. So, it will be always circular . So, when you do focus, the diameter reduces and when you do out of focus, the diameter increases. And then how do we control this? As I mentioned, we use a magnetic and electrostatic lens.

So, in a magnetic lens you use magnets. So, you have the field lines going through and then the electron beam will feel the force and then accordingly you can focus on the other hand, you do electrostatic where you apply alternate voltage that will again create this very nice fringe fields that will make the beam focus in this part. But more often you use combination of lens, where you have both electric lens and also you have magnetic lens together. So, it gives you a lot of freedom to control the beam quality.

(Refer Slide Time: 29:15)

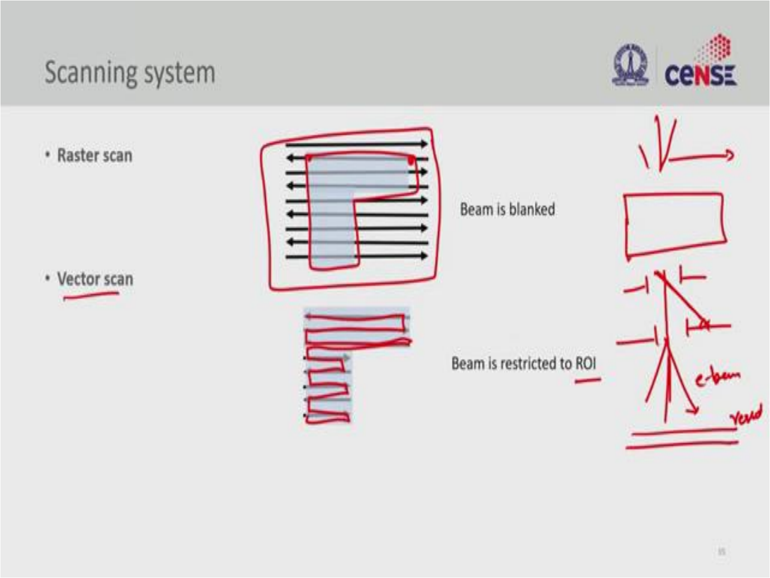


Beam Diameter

And next thing is the beam diameter. What is the minimum diameter that you can define. This depends on all the non-idealities we discussed. The source size, chromatic aberration spherical aberration and the diffraction of the beam so, all of this put together determines your beam diameter. So, these are all various trends one can look at and if you combine all of it, you will see the minimum spot size that one can achieve.

And in order to achieve best beam diameter, one need to address all this. If you just say I will control my source size, I should be able to get it; but if you look at source size, it is fixed you are not going to change the source size, but the other things like the diffraction your chromatic aberration and spherical aberration or within your control by using the lenses you should be able to control it. So, by controlling the beam divergence you control your beam diameter.

(Refer Slide Time: 30:26)



Scanning system

- Raster scan
- Vector scan

Beam is blanked

Beam is restricted to ROI

And the next thing is writing. How do we write? So, now, I have a pencil of beam now . So, I have a sharp beam and then I want to write a pattern. So, there are two ways to do that . So, one is called raster scanning, the other one is called vector scanning.

In raster scan, the beam if this is the area the beam scans the whole area and then this is the structure, I want to write and then whenever I want to write the beam actually comes into the spot and once it goes outside the beam is deflected out. So, when you put this beam blanked; you will deflect the beam within this part and then what you will do is when you are outside the pattern region, you will deflect the beam outside and it will not pass through the deflector. So, that you arrest a beam from exposing the electron beam resist.

So, this is the resist that you have and this is your electron beam. So, this is raster scan. So, the beam is always there and it will be blanked wherever you do not want to write, but the beam is scanning all the time. But in vector scan it is a little different its a much more sophisticated writing where you deflect the beam only in the region that you want. So, the beam will not go outside your region at all. So, only the place that you want will write and what we will call as region of interest and the other parts will not be exposed at all. So, you need to have the better algorithm here compared to raster scan which is pretty easy to control by one deflector, but here you need to control much better.

(Refer Slide Time: 32:36)

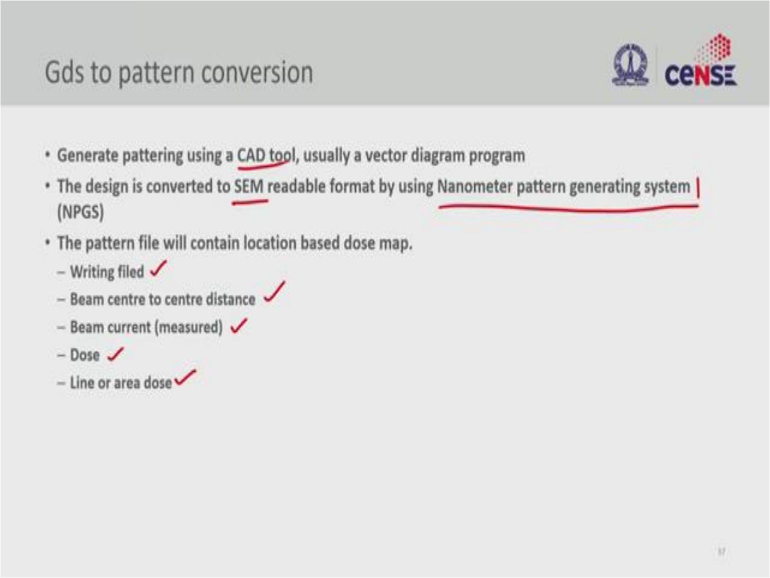
Line Vs Area

- Line
  - Small feature scale for fine details ✓
  - Centre to Centre is closely spaced ✓
  - Low energy ✓
- Area
  - Large scale fill ✓
  - Centre to Centre is closely spaced ✓
  - High energy ✓

And there are two ways of scanning as well. There is line scan and area scan. Line scan writes very fine lines, area scan writes large areas . It will normally write very large areas with large currents. So, if we want very fine features, you use line scan and the center to center spot is kept very close. So, that you have fine features and you normally operate it at low energy because high energy will always have larger exposure and if you have lower energy, you will have lower exposure . So, your exposure is much larger if your energy is higher and this is for energy is lower. So, your spot size is going to be much finer.

And in the area scan you will have large areas to fill instead of writing in line; if you have large patterns, you can use this large pattern for writing and then here the center to center distance is also closely packed, but you use high energy for large area fill.

(Refer Slide Time: 33:56)



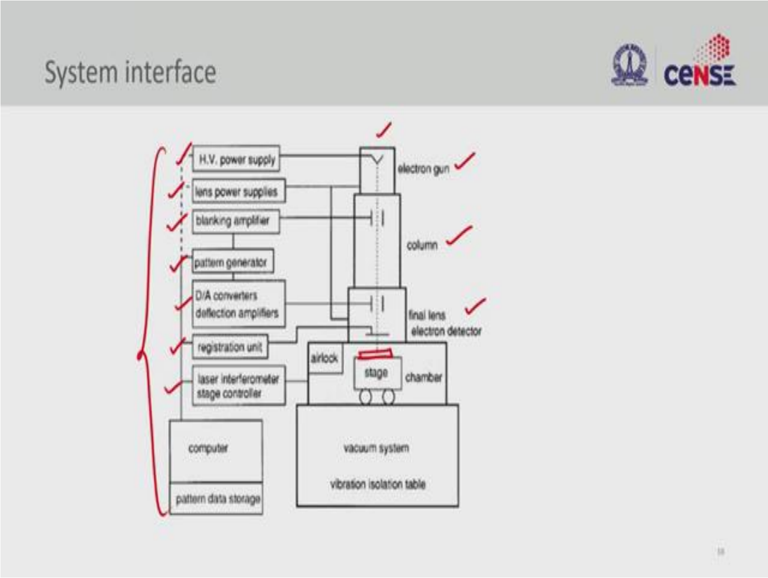
Gds to pattern conversion

- Generate patterning using a CAD tool, usually a vector diagram program
- The design is converted to SEM readable format by using Nanometer pattern generating system (NPGS)
- The pattern file will contain location based dose map.
  - Writing filed ✓
  - Beam centre to centre distance ✓
  - Beam current (measured) ✓
  - Dose ✓
  - Line or area dose ✓

The way we do it is by generating patterns from the pattern generator which we already saw. So, CAD tools can be used to generate these patterns, but this nanometer pattern generator is something that you can buy offline and then add it to your scanning electron microscope and you can use your scanning electron microscope as a electron beam writer.

So, what this one does? It will create the writing field that you want: what is the center to center beam distance and what is the beam current, what is the dose required whereas, it is a line or area. So, all the information will be put into this pattern file. Once it is there, then you take it to the system and then you can write it.

(Refer Slide Time: 34:42)



System interface

And this is the system that one can use. So, on the right-side, you see the interface system. So, you have the gun, the column, the final lens system and then you have your wafer sitting here on the stage. All of this is in vacuum and you need high voltage to generate your electrons, the lens supply to control all the lenses, your blanking amplifier (blanking your electron beam when not required).

So, if you do not blank when you move your sample on top of the beam it is going to expose all the resist. So, pattern generator is going to tell the system where to write and where not to write and that would require a digital to analog converter that is fed to the deflection amplifier. So, here you have the amplifier that is going to tell the pattern deflected where and how much to deflect, register is for location specific writing and laser interferometric stage is to keep the stage constant.

So, you can see here, it is not just the column, it is a supporting system here with the computer that should be high performing in order to control the beams dynamically. So, this is what a system looks like for a e-beam lithography. So, unlike an optical lithography where you do not have dynamic control of lenses it is all fixed here in electron beam system, you want to have highly dynamic control of the system through these electrostatic and magnetic lenses so, that you get good quality imaging.