**Techniques of Materials Characterization**
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**Lecture - 33**
**Optics of SEM**

Welcome everyone to this NPTEL online certification course on techniques of materials characterization. So, we are continuing with scanning electron microscopy. We are in module seven that is week seven and this week in the last two classes we were discussing about some basic components of scanning electron microscope where it is basically most of the components of SEM is pretty much same with transmission electron microscope, gun, electron gun, electron, electromagnetic lenses.

Most of these things are common so, we did not discuss about them. What we discussed mostly is about the detectors which is special in case of an SEM and detectors are because of the detector SEM is so diverse. And there are many different types of detectors we have discussed about the secondary electron detector and backscattered electron detector. We will try to discuss in the coming weeks we will try to discuss about at least another type of detector.

That is a characteristic X ray detector EDS or WDS kind of detectors we will discuss that. And then from this week in the next few classes we will be discussing about scan coil that is one very very short topic is left from last week so from last class. So, we will just finish that.

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And then we will discuss about the main part of this lecture that is optics in SEM. And then we will see about the pixel, pixel size its relation with the resolution and so on.

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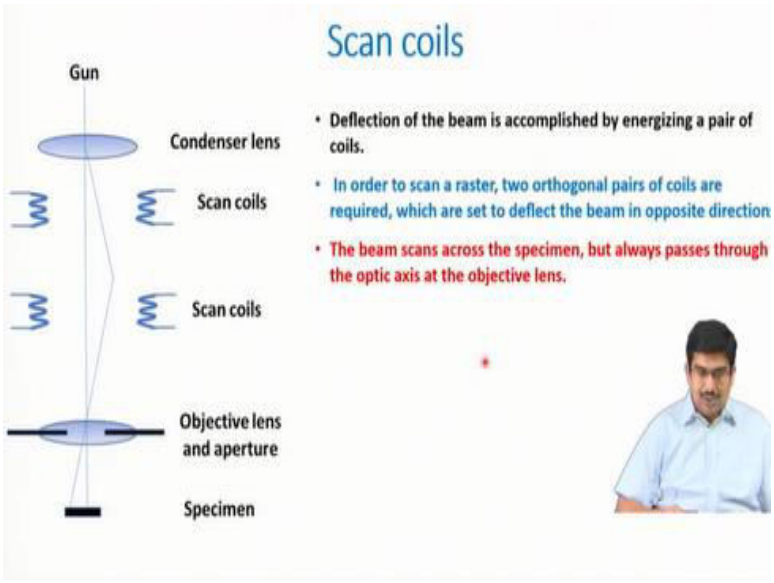


*So, scan coils this is another very special component of SEM scanning electron microscope and this gives basically the name itself the scanning the name itself comes from this technique that scan coils what the scan coils does. So, basically the scan coil deflects the beam as simple as this and we have discussed about scan coils previously also. And they are we have seen that scan coils are also kind of electromagnetic lenses but they are of very low strength.*

*So, that they do not alter the focus. They do not focus the beam which is already focused by the condenser lens or objective lens they do not interfere with that. What that does is that? They basically deflect the electron beam and this electron then they makes the beam to scan or to raster scan over a fixed raster on the specimen. So, that is what is done or that is what the purpose of the scan coils and they are kept between the condenser lens and objective lens.*

*In this case mostly in the real SEM that is where they are kept. So, basically, they are the beam that is produced by the condenser lens then it will be getting affected by the scanning coils and then the scan coils will make the beam to fall at different places on the specimen through the objective lens. Now, the point is there are two scan coils basically there are two orthogonal pairs of coils are required for this causing the deflection of entire basically to cover the entire 360 degree of the beam.*

*So, that it can deflect the entire beam can deflect. So, that is why we have two orthogonal pairs of coils and second thing they are kept above the objective lens. So, that when after the deflection the beam always passes through the optic axis at the objective lens. So, that is why the scan calls are kept in between the condenser above the objective lens that is one important aspect about the scanning electron microscope and that is where it is slightly different.*

*But not exactly different but they are in transmission electron microscopes STEM system at least they are also pretty much the same thing happens. That is, they are the differences that specimen remains above the objective lens here the specimen remains below the objective lens that is it. Otherwise, scan coils always remains above the objective lens and they deflect the beam and that beam then passes to the objective lens.*

*And then that beam remained passes through the optic axis* basically by the scan coils. So, that is why the scan coil is placed here. So, that is what the main another main component of scanning electron microscope.

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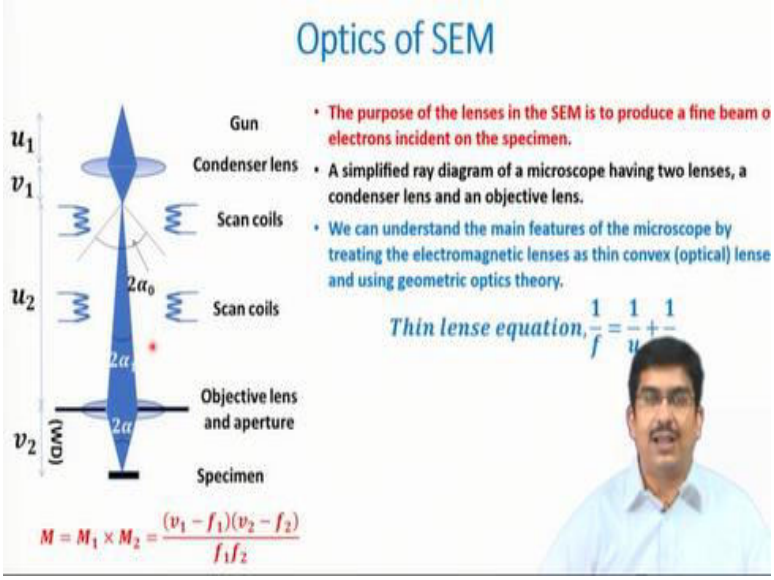


So, from here, now we will be moving towards this optics of SEM. So, virtually we can just consider this schematic this ray drive diagram that is what it is called the ray diagram of scanning electron microscopy. We remove most of the complex parts from here like gun and other things guns and anode plate all of these things are purchased, we remove it. And we simply keep certain important components.

So, that we understand that how exactly we achieve magnification, how exactly we can control the beam size and so on. So, the purpose of the lens in the SEM is basically to produce a fine beam of electrons which will then incident on the specimen and then because of the presence of the scan coils, this beam will travel on the surface of the specimen that is it. So, that is why what we can do in this simplified ray diagram we can omit all other components.

And just we can consider two different lenses, one is the condenser lens and one is the objective lens. So, condenser lens as the typically it is placed it will be after the electron gun which is somewhere over here and the objective lens will be just before the specimen that is it. And the entire from this ray diagram the entire functioning of the SEM can be understood. And for that what we need to imagine or need to make an assumption that these electromagnetic lenses.

The both the condenser lens and the objective lens they behave like a thin convex lenses. So, why this assumption? Why we need to assume that thin convex lenses are they were weak? So,

that are like why these electromagnetic lenses they are considered as thin lenses. And that is because to apply this geometric optics theory. Most importantly this thin lens equation which we have already discussed in module one if you remember.

So, where we have, we can write 1by f = 1 by u, u is object distance and 1 by v, v is the image distance. So, this equation we could develop for any kind of lens-based system and this equation can be applied in case of this simplified SEM. Now, what is the importance of this? If I do not consider this as a thin lens then this equation cannot be applied. We have to add an additional term here which is which represent the thickness of the lens.

And that will affect many other calculations. That will affect even the calculations of magnification, resolution, even aberrations and so on. But this is an assumption of course, because of the thickness there is a thickness effect on the aberration itself that we have already seen. That is because of the thickness we get different type of this astigmatism, different we get the distortion, all of different type of aberrations we get that is true.

But in order to just get a simplified some equations and some predictions to make we imagine that these electromagnetic lenses are can be considered as thin convex lenses and this equation is valid. In that case now, we can imagine that we have a two-lens system condenser lens and an objective lens and the final magnification is achieved by this equation $M_1 M_2 = \{( v_1 - f_1)( v_2 - f_2)\} / f_1 f_2$. This is not the magnification for any specimen that is a different that we already discussed.

The magnification that we get in scanning electron microscope is related to the pixel size of the specimen pixel and size difference between the specimen pixel and the pixel in the display device. So, that ratio basically gives you magnification in case of a scanning electron microscope that is how it is getting magnified. We can imagine this if I have to put it in this way that sometimes you can see in a digital camera often if you work with a digital camera or in your phone camera itself.

You will see that there are two different ways of zooming. So, one is called optical zooming and one is called digital zooming. So, optical zooming is where you really magnify by changing the focal length, object distance if it is remains constant by changing the focal length you basically do the magnification like here. This is for that optical zooming. Now this is valid for direct imaging when you have say for example, you have the optical microscope or you have the transmission electron microscope.

What do you do is it real optical zooming by changing the focal length and so on. But in case of scanning, what you do is very similar to that digital zooming, you basically magnify the digital images, you just magnify you just make the pixels bigger and bigger. That is why after a certain time the pixels become so bigger you things gets blurry. So, there you really do not get magnified by changing the focal length.

You just magnify by making the pixels bigger and bigger and that is exactly what you do in case of the scanning electron images. Here the specimen pixel, the beam size or the specimen pixel on the specimen surface is much smaller. And then you are seeing it in a digital display or capturing it in a image capturing device at much larger bigger size pixel. So, that means this smaller pixel you are zooming it at a much larger to a much larger size.

And that ratio will finally give you the magnification. So, in direct imaging you get something similar to what is in your phone or in your digital camera next time you use it just try to see, you do the optical zooming. And in scanning mode you do pretty much same as digital zooming that is the difference.

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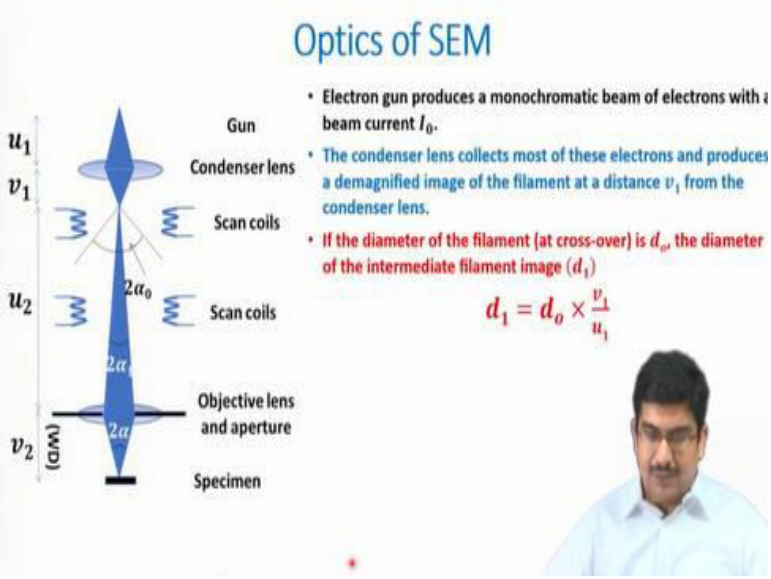


Now, we imagine that a gun is there and the gun is producing a monochromatic beam of electrons with a beam current $I_o$ and that beam current gives number of electrons. So, we have seen this is not the brightness of the current. This is the current the beam current that means the number of electrons present in the beam. Indirectly it is related to that number, number of electrons present in the electron beam that that is produced by this gun.

Now, what happens is when this beam passes through so, we are imagining from here basically this is the crossover. This point is the crossover this is not the gun we have already discussed about that. That in the gun after it passes through the wehnelt cap it this gets crossed over this beam beams are all converged at a small desk and that is virtually works for as a beam, I mean that is what virtually works as a source for this electron beam.

And that time we told that it is very important that size of the crossover is important. Because that is where that is what will decide the resolution for this entire microscope in a later stage and now, we will see why. So, let us imagine now that we have a monochromatic beam, the gun has produced a monochromatic beam with the current $I_o$ then the condenser lens will collect most of these electrons and it will be producing another spot of a smaller size.

That means it will basically do a demagnification of the image of this filament or basically the crossover. So, if you imagine the crossover the size whatever be the size here that will get

demagnified by this condenser lens. So, this demagnification we have to measure what is the amount of demagnification and that way we can find out the size of the beam here after they passes through the condenser lens.

So, now let us imagine that the distance physical distance between this crossover and this condenser lens $u_1$. Now, remember one thing that the position of the crossover can also be changed just by changing the current in the gun in bias in the Wehnelt cap we can change the position of this crossover. So, $u_1$ can also be altered but more or less for practical purpose we can imagine that $u_1$ is mostly it is constant.

The distance from the gun to the condenser lens is pretty much the constant. But that also can be changed but let us not go into that. So, now the diameter of the filament at crossover, so, this is the size of the beam here at the crossover. If this is the $d_o$ that is the size of the beam, we starting we are starting with the current $I_o$, the diameter of this beam after it passes through the condenser lens that is the intermediate filament image.

If we consider this as an image just if we consider that this is our object and this is the image here of the object and we have a lens in between. So, this lens is causing magnification, demagnification whatever you imagine this that will be basically $d_1 = d_o \times (v_1/ u_1)$. Again, using that thin lens equation using the relation between the magnification, magnification is simply the ratio between image distance versus object distance.

So, that is how we are getting it. We are calling it demagnified pretty much basically because the $v_1$ here is less than $u_1$. And that depends you can change the $v_1$ also just by changing the focal length of this condenser lens. We have discussed about that, that in a scanning electron microscope it is very easy to change the focal length and by changing the focal length you basically can change the image distance.

So, if you change the image distance you can basically control the size of this beam here. But more or less this is always demagnified this is smaller than the original beam size at the cross over.

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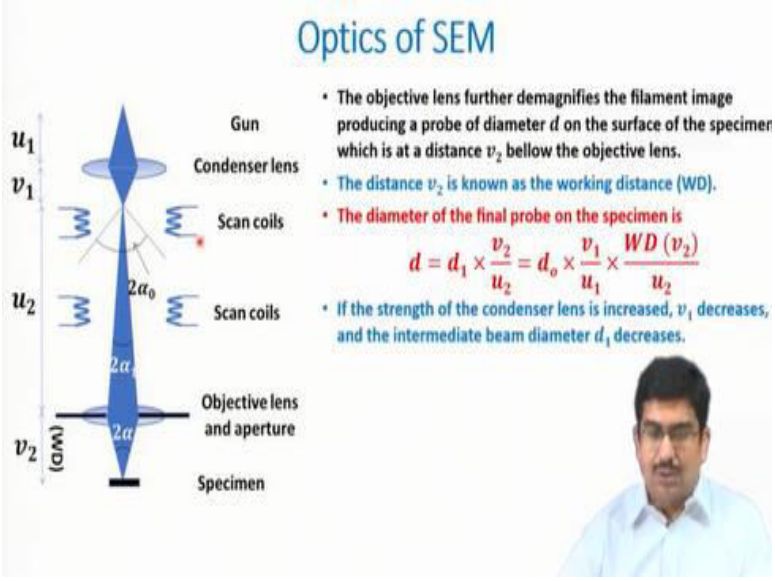


Now, after the condenser lens we forget about scan coils as I said they are not doing anything other than deflecting the beam. So, let us for now, at least let us not consider the effect of the scan coils. This beam then passes through the objective lens straight way. That objective lens will further magnify, demagnify whatever it is, but it will further focus this beam. So, after this point this beam gets converged again it is getting diverge.

And then this objective lens, will converged the beam further and make it a spot. Finally, that sport will fall on the specimen itself. Now, for the objective lens this is the image, the image that is produced. So, first image is this crossover, first object is the crossover for condenser lens then the condenser lens produce the image of this one that image is now working as an object for this objective lens.

So, if we imagine that this distance is $u_2$, the objective for the objective lens this object distance is $u_2$ here and the specimen to object distance that distance we imagined that $v_2$, this $v_2$, distance is called the working distance. So, this is basically the image distance for the objective lens this distance is called working distance generally. And this working distance is physically varied, you can vary this working distance.

The position of the objective lens is fixed, but you can take your specimen closer or further off from this objective lens that is the way you can change this object distance basically. So, if we now see the beam size or the spot size here after it passes through the objective lens, so that will be the diameter of that final probe d will be $d_1 \times (v_2/u_2)$, $u_2$ is the object distance here for objective lens.

This is the object distance $u_2$ and $v_2$ is the image distance for the object event which is the working distance as well. And for $d_1$ then we put $d_o \times (v_1/ u_1) \times (v_2 / u_2)$. So, the final diameter of the probe is related to the initial crossover size by this relationship. Now, what do we understand? What we get out of this entire relation fine? So, if the strength of the condenser lens is increased let us say.

So, strength of condenser lesson in lens is increased means now it is focal length is reduced that is what is basically means. Strength of condenser lens is increased means we are reducing the focal length that means the electrons are getting focused at a much closer distance from this condenser lens. That means, we are basically decreasing $v_1$ here this one and if we decrease $v_1$ now in this entire from this relationship what we understand that this $d_1$.

This one the first diameter of the beam after it passes through the condenser lens that one decreases. So, $d_o$ remains constant, $u_1$ remains constant, we are decreasing $v_1$ and that is how we are decreasing basically this $d_1$ that is the first thing.

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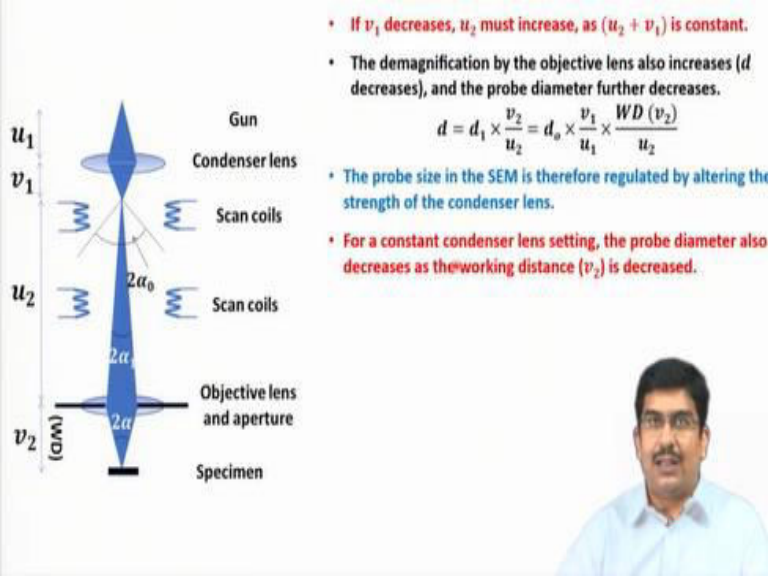


Now, if $v_1$ is decreased we are increasing the strength of the condenser lens, we are now reducing the focal length we are making the beam focused closer to the condenser lens that means, we are reducing $v_1$. The point is the distance between the condenser lens and objective lens in a microscope in that SEM is fixed, physically fixed this distance. We can change the focal length but we cannot change their physical positions.

So, this condenser lens and objective lens distance is constant. If we and as I said that this image that is formed by the condenser lens is working as an object for the objective lens. So, if $v_1$ is decreased by increasing the strength of the condenser lens if we decrease $v_1$, then $u_2$ has to increase, $u_2$ must increase because $(u_2 + v_1)$ is constant. This is a physical distance which is constant. So, let us now put that here.

Number one I have reduced $v_1$ and, in the process, I have increased $u_2$. Both of these will finally affect on this, the final probe diameter that means the final probe diameter will be decrease. We are not doing anything with the objective lens at all the objective lens strength working distance everything remains constant. Nothing is changing for the objective lens. What we are doing is just simply with this condenser lens and that itself will affect the final probe diameter here.

So, the probe size of the SEM can be regulated by altering the strength of the condenser lens in the first place. That is the importance of the condenser lens there. It can change the size of the

beam and as we have discussed previously and we will discuss in the next few slides that the size of the beam is related to the resolution achievable by this SEM. So, this beam size final spot size is now controlled by the condenser lens.

If we decrease the focal length of the condenser lens if you make the; if you increase the strength of the condenser lens, we can remake the beam or spot size finer. Now, if we do not do much of a change in the condenser lens, earlier we will not doing anything with the objective lens. Now, condenser lens settings remain the same. We are just working with the objective lens. What are our options? That means $u_2$, $v_1$ everything remains the same, we can change $v_2$.

How we can change $v_2$? Either we can play around with the objective lens basically we can change the focal length and so on and that is problematic then we will not get a focused beam on the specimen itself. So, this is physically constant as I said this is a physical distance. So, this distance I cannot change without changing the specimen in physically. Because the beam has to be always focused on the surface of the specimen that is the requirement for the objective lens.

Beam cannot defocus here. So, that means what we can do? We can change this working distance by moving this specimen. If I reduce now the working distance that is if I reduce $v_2$ what I can do is that I can simply decrease the probe diameter. So, if I take this specimen closer to the objective distance that means I am reducing working distance I am reducing $v_2$ and with keeping all other things constant $u_2$, $v_1$, $u_1$ everything remains constant.

Everything in this side remains constant, I am just changing the working distance I am taking the specimen closer to the objective lens then also the probe diameter will be smaller. So, this is the two way I can play around with the either the working distance or the strength of the condenser lens in order to get a fine spot size or in order to deduce the diameter of the beam on the specimen surface this is how it works.

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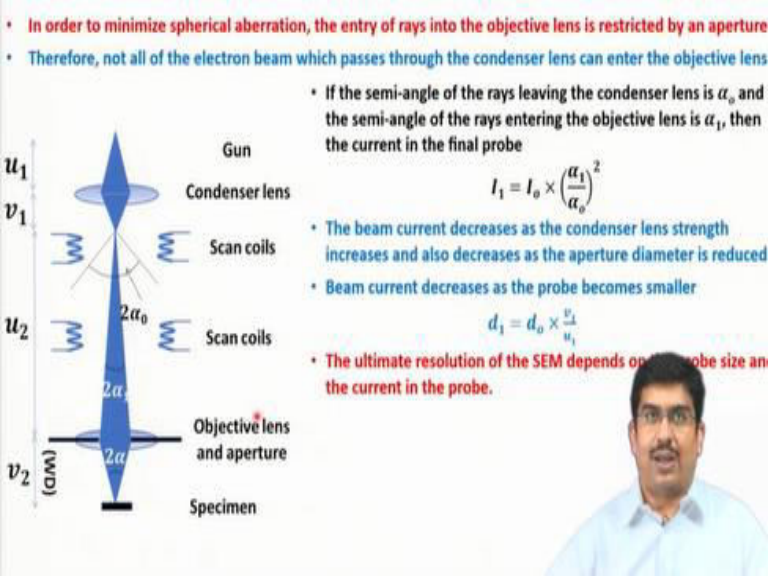


Now, there are a few other considerations that we need to make. Number one, in order to minimize the spherical aberration we use an aperture that is the first thing. So, spherical aberrations as we discussed the spherical aberration there the beam which are diverging from the optic axis are causing problems. So, we want to keep the only those part of the beam which are traveling parallel to the optic axis and we do that by using an aperture.

And mostly that is the aperture we use in the objective lens because that is where this spherical aberration mostly occurs. If the objective lens if we do not use an aperture and the objective lens then this diverging beam will pass through here and finally, they will be falling over different different positions on the specimen, so we do not want that. So, we use for reducing the spherical aberration we use an aperture with the objective lens that is fine.

Then what will happen? First thing is that whatever beam or whatever electrons are getting focused by the condenser lens. They will not be passing through not all of them will pass through the objective lens. So, they will diverge and only a part of that will be finally passing through the objective lens and that will depend on the semi angle of convergence on the condenser lens as well as in the objective lens.

So, if we see it here, from this focused beam, again the beams are diverging and only a part of the divergent beam is passing through the objective lens because I have now aperture here. So, if

this semi angle of rays which are leaving the condenser lens if that is $(alpha)_o$ that means the total angle of divergence is $2(alpha)_o$, this is a semi angle this is half of this angle. So, if this angle is $(alpha)_o$, the complete angle.

And if this angle; with which this aperture is allowing the beam to enter, the semi angle of the rays that is entering in the objective lens through the aperture. If that angle is $(alpha)_1$ that means out of part of this $(alpha)_o$ all the rays which are diverging at an angle of $(alpha)_o$ only $(alpha)_1$ within that angle whatever electrons are coming within that angle they are allowed to pass through. If that is the case then the current in the final probe is, $I_o$ in to $((alpha)_1/ (alpha)_o)$.

Remember $I_0$, is not changing by the condenser lens whatever electrons condenser lens we imagine that it does not have an aperture or even if it is having an aperture, it is quite large. So, all the beams, all the electrons which are coming from the gun electron gun, they are passing through the condenser lens and they are getting focused at one point de magnified but focused at one point. So, here the beam current does not change.

But beam current severely gets changed after it passes through the objective lens because of the presence of this aperture. And that beam current is now $I_1 = I_0$ in to $((alpha)_1/ (alpha)_o)$ square. So, what it gives? The beam current basically decreases; that means here this $I_1$ decreases as the condenser lens strength increases. Condenser lens strength means $(alpha)_o$ if $(alpha)_o$ decreases means condenser lens strength is increasing.

Condenser lens is causing more convergence towards the electron beam they are not allowed to diverge the beams. So, condenser lens is strength is increasing means its focal length is getting smaller and in the process all the beams the convergence angle also is reducing. So, if we reduce the convergence angle that is if $(alpha)_1$ is reduced then condenser lens is increase then the beam current will decrease here.

If the condenser lens strength increases sorry if the condenser lens strength increases, I am saying the other way around. If the condenser lens strength is increasing that means the beam divergence will be decreasing and in that process the beam divergence will increase and, in the

process, this beam current will decrease here. If this one increases the $(alpha)_1$ increases because condenser lens strength is increasing.

So, $(alpha)_0$ is increasing and in the process, it is decreasing this $I_1$ here that is first thing. Second thing is this $I_1$ also decreases as the aperture diameter is reduced that means, if $(alpha)_1$ is decreased than aperture diameter so, these two approaches are coming closer. The opening of the aperture is smaller, opening of the aperture is smaller means it is reducing this semi angle here. Less amount of beam less amount of angle is opens the solid angle over which the aperture collects electron.

That is now decreasing if the aperture is smaller and smaller and then also the beam current will decrease. So, these two effects will decrease the beam current. Number one if the condenser lens strength increases that means if $(alpha)_0$ increases, then also $I_1$, the beam current will decrease and if aperture is smaller and $(alpha)_1$ is decreased then also $I_1$ will decrease this is the thing. Now, what we get out of this is that probe becomes smaller.

Because if condenser lens strength increases then the probe also. Because it is what we have derived from here if the condenser lens strength increase that means this $v_1$ is decreased and that will finally decrease this d. So, if condenser lens strength increased then the probe will become smaller. If the probe gets smaller now, we find out the beam current also decreases. So, with a smaller beam, we are actually having less number of electrons to hit on the specimen.

So, beam size getting smaller beam current is also getting smaller. This is the kind of a trade-off. So, the ultimate resolution of the SEM will depend on both the probe size and the current in the probe. Why? We will discuss that but please remember the probe size means the sampling volume it is related to the sampling volume. So, from spatial resolution up to and the depth resolution up to which area the signal is coming that will be depending on the probe size.

Also, the current in the beam will be deciding that how many electrons are actually hitting the specimen and the signal production will be depending on this beam current. So, the signal strength will be very low if the beam is very small, the current will be very slow that means less

number of electrons will be hitting the specimen and the signal that is generated that strength will be also very very low. We will not get enough, signal to be able to detect. So, that is why there is a trade off in the beam size and the beam current.

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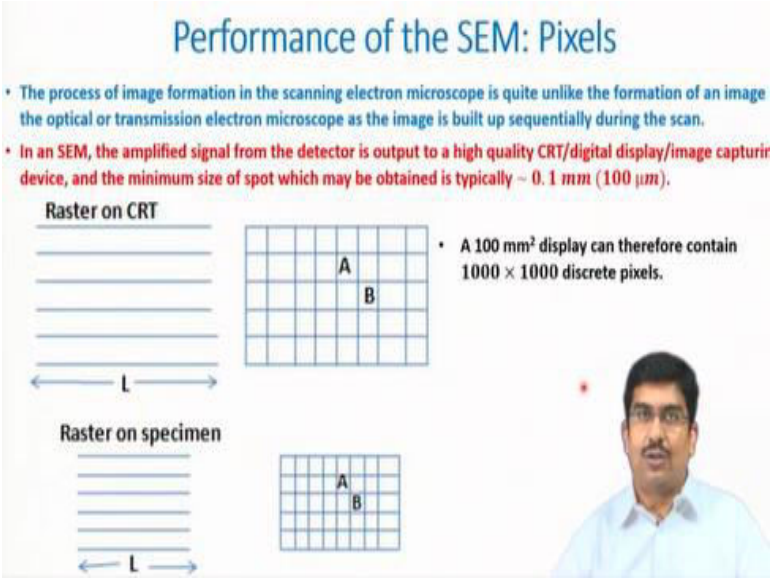


So, from this we have a discussion we will be having a discussion on the pixels and the final resolution of the SEM. But we will discuss in the next class. Good bye.