Nanostructures and Nano Materials: Characterization and Properties
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Lecture - 38
Transmission Electron Microscopy

In this lecture, we will continue on what we learnt on the transmission electron microscopy. As we had realized that our we are making electrons being transparent to the particular material that is how the term comes out.

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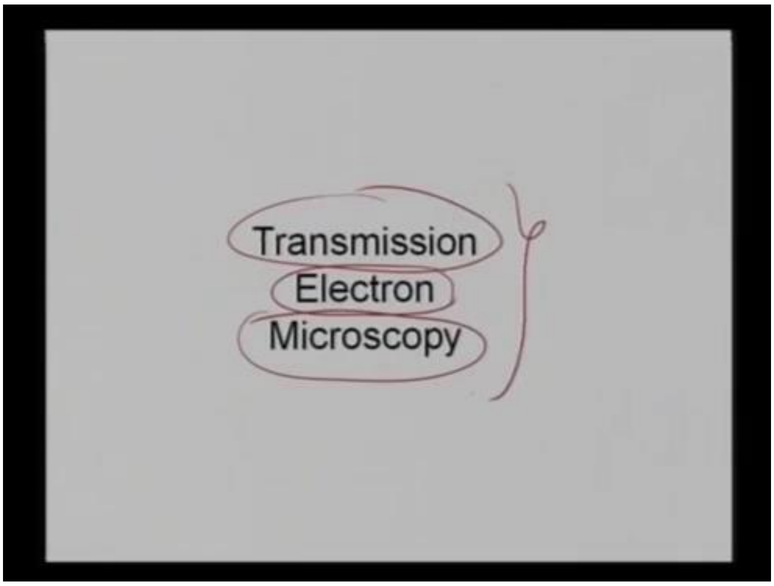

That it is a transmission electron microscopy because we are utilizing electrons to transmit them through the material to my specimen. And then understanding, what is happening and much more at the microscopic or the nano scope level that is, the term transmission electron microscopy. So, in earlier class we had already in the earlier lecture, we had learnt how we can utilize electrons in terms of how we can form an image or how we can really achieve a diffraction pattern.

By focusing them particular either at intermediate image plane or at back focal plane. If we are forming diffraction pattern at the back focal plane, what we get finally, is nothing but an image and if you are forming we are keeping our aperture at the image plane what we get is finally, a dark fashion pattern. So, thus essentially the couple of features which are required for imaging.

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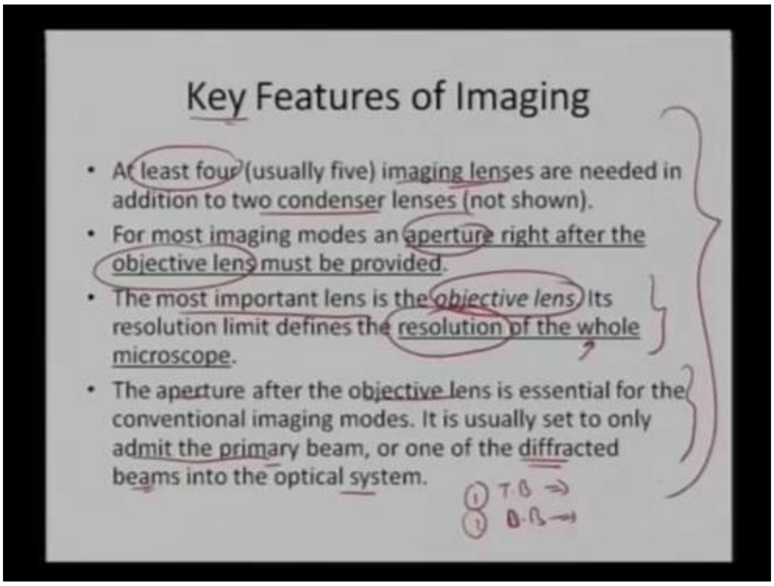

So, we can see that there are certain key features which are required for imaging. That we require at least 3 4 or 5 imaging lenses that are needed in addition to the 2 condenser lenses. And for most imaging systems we keep aperture just after the objective lens because we are forming our image plane as well as, the back focal plane behind it beneath that particular level. So, that is the reason we want to keep an aperture just after the objective lens.

So, that we can form we can selectively choose what we want to really form whether a diffraction pattern or an image. So, we need to have an aperture, so we can selectively place whether incident beam or the transparent beam is passing through or whether we are able to whether we want to get a bright field image or dark filled image. And this part has not to be under stated, but objective lens is the most important lens because this is the one, which defines the resolution because whatever we are forming all the information from a specimen is now being collected by the objective lens.

So, that is the reason objective lens is the one which will decide the overall resolution of the particular imaging system. And more than it is where it is collecting all the information from the specimen and the clarity of that particular image at the objective lens. That will essentially decide how the diffraction pattern will form or how the particular image will form and that becomes very critical in defining the resolution. So, objective lens we have objective lens, after that we keep our aperture.

So, whatever image which was passing through the objective lens that gets accumulated at a particular plane that can be back focal plane or the image plane. And once we keep our aperture there, the information which is being collected by the objective lens that are only can pass through forward to produce the next image. So, that is the reason we keep that objective lens is the most critical component of the whole electromagnetic lenses and that defines the resolution of the whole microscope itself.

And again, the aperture which is being placed after the objective lens it is also very essential because it is not only admitting the primary beam, but also allowing the diffracted beam also into the optical system. So, what we are getting, we are getting 2 sets one thing is the direct transmitted beam itself we are allowing it to pass through. So, for that we admit the primary beam to pass through the particular aperture. At the same time we can also use the diffracted beam to also pass through the aperture in case, we want to produce a dark field image.

So, that is the key feature of imaging, first of all if you are allowing a transmitted beam to pass through we can form something called a bright field. And if you allow a diffraction, diffracted ray to pass through we can form something called a dark field. So, interplay of all those things we can play around and can form the particular image. So, in this thing we directly know that we require certain lenses, certain magnetic lenses, which will allow the formation of a nice electron beam, a collimated electron beam and of well accelerated electrons which can now become transparent to the specimen.

Once, it passes through the specimen collects the information and then goes to the objective lens. So, the image or the diffraction pattern which is being formed by the objective lens that decides the overall resolution of the transmission electron microscope. So, that becomes the most critical component in the TEM because that is one which decides the resolution. So, once we have that we allow the beam to pass through forward and now we pass it through certain apertures. It can be either the back focal plane or at the image plane to yield the final diffraction pattern or the image itself.

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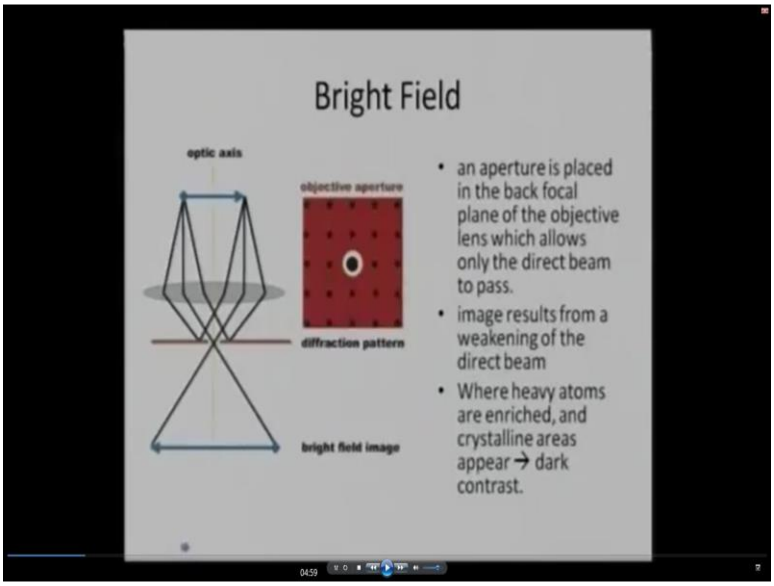

So, this is how we can form a bright field image, we allow the transmitted beam to pass through and once it strikes the particular sample. Then we have the objective lens out here, once it is passing through objective lens we have the aperture as we stated earlier. So, we allow this is a back focal plane, at the back focal plane we allow only the transmitted beam to pass through. And then finally, what we achieve is nothing but a bright field image.

So, in this particular place where we have the back focal plane it is the intermediate plane where we get the diffraction pattern. So, in this case we are allowing, we are keeping the aperture, so that we can allow only the transmitted beam to pass through. So, let me highlight it with some other colour so that we can show it. So, we allow only this particular portion to pass through everything else is nothing but it is basically cross stopped and we do not allow to pass through at all. So, the aperture has to be of particular diameter or of particular size that it allows only the transmitted beam to pass through.

We can also allow a certain region to pass through, we can allow central beam plus some other parts to pass through the aperture, but in case once you want to form a bright field image. We allow only this particular portion where the only transmitted beam is let through the aperture. So, we have this aperture and this is our transmitted beam after interacting with the sample, it passes through the objective lens. And then we are allowing only the aperture which allows only the direct beam to pass through.

So, in this case what we are saying is that, so we keep the aperture in the back focal plane this is nothing but the back focal plane, where we are forming our diffraction pattern, intermediate diffraction pattern. So, we keep the aperture in this particular location at the back focal plane and now our objective lens and which is the plane, which is passed through the objective lens in this aperture we allow only the transmitted beam to pass through. So, this is my transmitted beam and we allow only transmitted beam to pass through.

And, so the image which is being resulted some of the beam is now getting blocked. The diffracted beam which was diffracted that is getting blocked. So, there is a weakening of the direct beam itself, but not this weak beam only results my final image. So, in this case what happens is we see the heavy atoms, those are enriched and the crystalline area areas they appear dark because what is happening is the crystalline area which have diffracted they appear dark. And the other heavy atoms they also tend to absorb the electron beam so they also appear much darker. So, brighter regions appear much more the thinner regions much more brighter.

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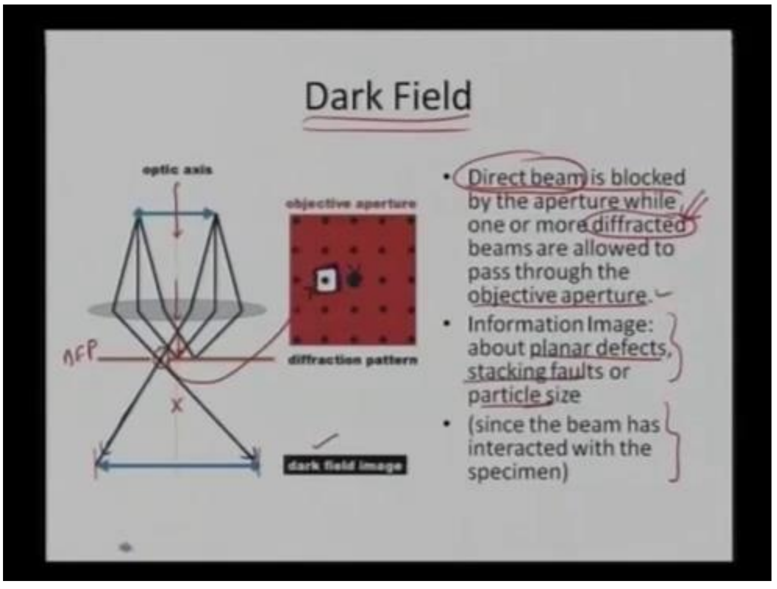

So, coming to a contrast of it in the previous case, when we use when we utilizing the bright field our field the overall area round a particular feature appears very bright. And only it is those features which tend to diffract the electron beam. So, my features will appear dark, but my field appears bright that is how we get the name of bright field that my field is bright whereas, my features are darker.

Now, coming to the contrast of it I have something called dark field imaging. In this case the direct beam is blocked by the aperture, whereas one of the diffracted beam, the diffracted beam is allowed to pass through the objective aperture. So, what we have now here is we have our transmitted beam where we see once it passes through the objective lens. The information which is being carried from the specimen it is now getting blocked.

So, I do not allow my transmitted beam to pass through at all rather I take one of the diffracted beams. In this case, I have some diffraction so this particular spot which corresponds to the won out here. So, I let only one of the diffracted spots to pass through and from that I allow only the transmitted only one of the diffracted spots to create the image. So, once I am letting only the one of the diffracted beams to form an image I get because my direct beam is now being stopped, I cannot the features the field around it becomes very, very dark because I only have a very weak beam which giving me the overall image.

So, what happens here is that the information which is coming here, is coming only from the particular plane or any from particular crystallites, which have given rise to this diffracted spot. So, only those features will tend to appear bright because we are able to capture that diffracted beam. So, that is what is happening here and the dark field imaging our field is totally dark my features appear very, very bright because in this particular case, in the dark field imaging I catch the beam which has diffracted, which has been diffracted from a particular feature.

So, that is the reason my feature will tend to appear brighter whereas, my field will appear dark that is the reason we call it a dark field imaging. In this case, we are blocking the transmitted beam and we are allowing only the diffracted beam to pass through. That is, what we are seeing here that we are allowing this diffracted beam to pass through and form an image. So, that is what is giving rise to the dark field imaging.

And in this particular case, we can get information it can be from the planner defects, it can be stacking faults or even we can get some particle sizes. And this happens because the beam has already interacted with the specimen and that is how what we get is a dark field image. So, we had a particular aperture which was at the one of the diffracted beams spots and we allow this particular diffracted beam spot to pass the information further in terms of forming the image.

So, in this case we are blocking the direct beam and we are allowing only a diffracted beam to pass through the objective aperture. And this is again the back focal plane where we are forming the back focal plane, where we are forming the intermediate diffraction pattern. And now, this goes on to form the final image and that gives me the information specifically from the region which has diffracted this particular spot. And that come out in the form of planner defects, it can come out from stacking faults or it can even from the particles as well. So, this is the information what I can get from the dark field.

This case I have an advantage that I can specifically pin point that this diffraction spot is coming from which particular location. So, all those crystalline regions which were diffracting this transmitted beam all those which were responsible for the diffraction will tend to appear very bright in this particular imaging. So, I can exactly pin point what is the overall orientation of the particular grains just by using my seeing my or analysing my diffraction pattern.

So, I can select a particular spot and I can say this grain belongs to so and so category what will be the orientation of those particular planes, just by indexing the diffraction pattern. That is the beauty of this dark field imaging that we can find out the orientation of these particular grains, which are leading to the diffraction of a particular beam.

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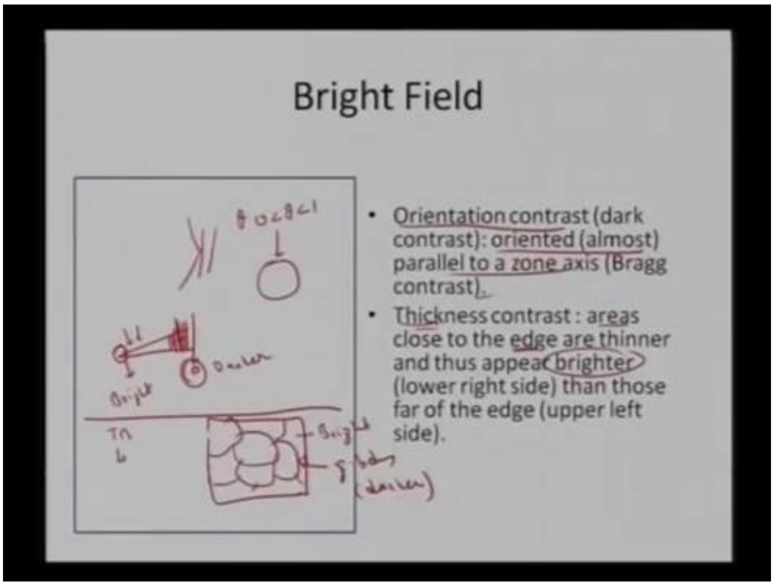

So, in bright field image what I can get is some orientation contrast because depending on if I have particularly align, I have some align crystals they will tend to diffract the light. So, in this case if anything is oriented almost parallel to the incident beam they will tend to diffract. So, I have a particular crystal which tends to diffract the beam and in this case we know that theta is approximately 0 to 1 degree which is very, very low.

So, even when they are almost parallel to the zone axis, so my incident beam itself becomes the zone axis. So, if I have any particular grains which have oriented in this particular direction, they will tend to appear much more darker. So, I get some dark contrast because of the orientation additionally, I can also get some thickness contrast. It happens that the areas which are closer to the edge they appear much more brighter.

It happens because if I have some region which is much more thinner, less electrons are being absorbed in this particular region. So, I get very bright image when the specimen is very thin. Whereas, most of the electron they get absorbed by the thicker regions because they are interacting with the material it is harder for them to get completely transmitted. So, those regions which are far from the edge they tend to appear much more darker.

So, in overall we can see that for a bright field image we are allowing only the transmitted beam to pass through and all my region, all my field appears very, very bright. So, I have certain grain boundaries they will appear dark whereas, most of the regions they will appear bright so I have bright background. Whereas, my features will be dark such as grain boundaries will appear darker or any particular inclusion they might appear darker because they are diffracting the light, my dislocations will appear very dark because they are diffracting the light, diffracting the beam.

So, in this case in the bright field imaging we can get orientation contrast that can arise from just by the orientation of a particular grain, the oriented approximately parallel. Then they will tend to diffract the beam because they will satisfy the Bragg’s law and the incident beam itself becomes the zone axis for those particular crystals. And secondly, I can get some thickness contrast which arises, because when I have a very thin edge, very thin material electrons can pass through very easily. So, they can generate very high intensity of the signal, whereas if I have a particular material which is very, very thick then electrons find it hard to interact and pass through the material. So, information what we are getting after the electron beam has passed through the material I tend to get a very dark image. So, that is how it can also arise, the thickness contrast can arise like that. And secondly, in the bright field imaging all my features tend to appear very dark because they tend to diffract the light.

So, my dislocations, grain boundary they tend to appear very they appear very dark whereas, my overall field appears very bright because I let the transmitted beam to pass through. That is the idea about the bright field image I can get the overall field of how the sample is, what is approximately grain size and all such things I can find out from the bright field imaging. How the distribution of say dislocations or may be precipitates in a particular matrix. So, that gives the overall idea using the bright field imaging how the distribution of phases is or how the dislocations are there, what is the overall grain size and all such things.

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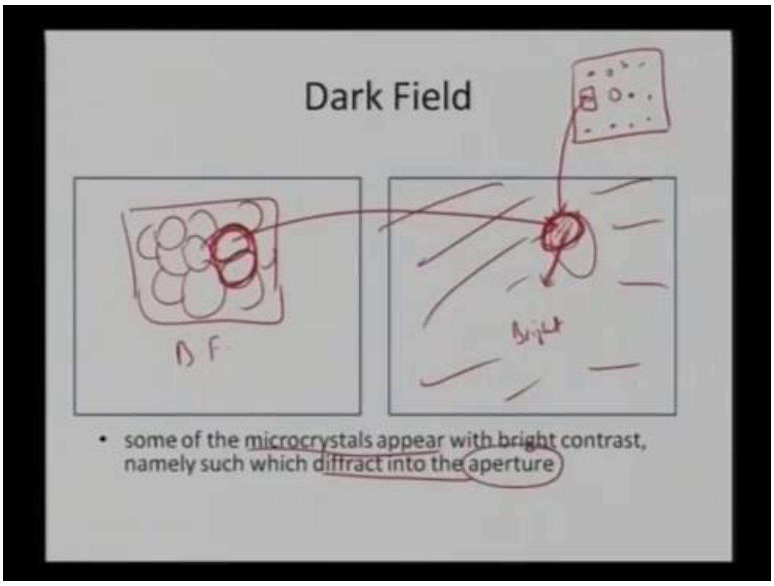

Now, coming to the dark field imaging it happens that in the bright field image I get certain features which may not be so distinctly observed. So, in case I might have some features like this the grain boundaries and all those things can be like this in a bright field, but once I come to dark field I might realise that, one of the grains that was appearing to be single grain might have some different orientations.

So, might be one grain was oriented differently and then that feature is coming out to be very bright because that one is responsible for the particular diffraction. So, if I choose a particular diffraction spot, my diffraction pattern was appearing more like this with the central beam this is the central beam. So, I had probably one of the spots which is giving me everything else will appear dark whereas, only one of the portions will appear bright.

So, this one is the dark field imaging, but from that I can clearly distinguish that this particular crystallite is oriented in a very preferably in a manner that it is satisfying the Bragg's law. So, only this particular grain this particular diffraction spot is arising only from this particular crystallite, because it is oriented favourably to the transmitted beam. So, as soon as my transmitted beam is coming it gets diffracted by this particular regime to give me a diffraction spot.

So, I can clearly say that this is not, that this particular region is not a complete grain, it is probably sub divided into 2 sub grains and this sub grain is giving me the particular diffraction spot because it is oriented to certain direction. So, and those microcrystals which are appearing brighter and those are the ones which are diffracting beam into the aperture which has an opening. So, if you go back and we can see that we are allowing all the beams transmitted beam diffracted beam.

So, we are stopping the transmitted beam and we are allowing one of the diffracting beams to pass through. And this brightening is result of the portion of that particular beam which is now being diffracted into the aperture because that diffracted beam once it falls in to the aperture that results in the formation of the final image. So, this particular crystallite is responsible for creating that final image. So, that is the reason this particular crystallite starts appearing brighter.

This causes one more thing that initially we are seeing two crystals. In this case, we were seeing single crystal, but now in the bright in the dark field now, we are seeing those as two different crystals only a portion of that has is appearing bright. It means, it only that particular portion is a crystallite which has a perfect orientation of a particular plate. So, that clearly distinguish that this particular grain is not a single grain, but it is a it has more than one grain present in it.

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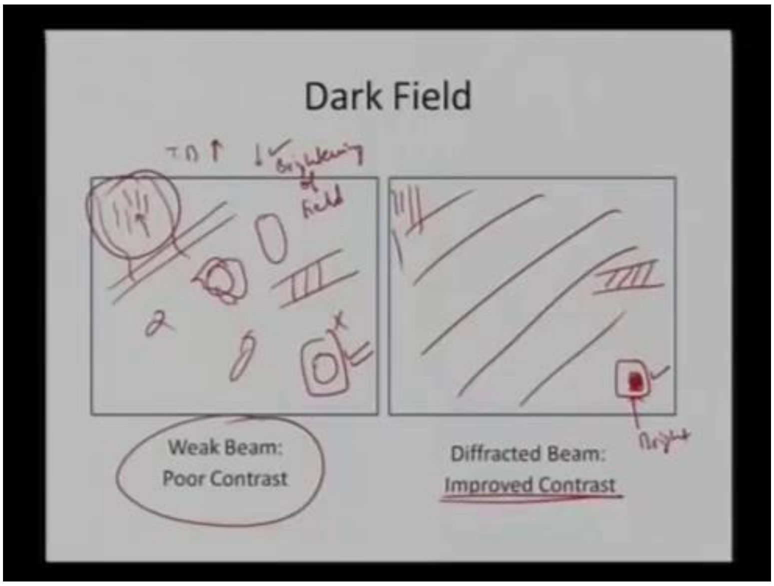

And again, in the dark field like ones we have weak beam sometime what happens, we allow only the transmitted beam to pass through. So, what happens because of that certain features they tend to get dissolved into the background which is very, very whiter? So, I had I might have very features which are very bright here some features out here, but it might happen that certain pattern of dislocations are the certain features, they get dissolved into the background just because that it is very poor contrast because my central beam has passed through.

So, it will result a very, very bright, brightening of the overall field, brightening of the field. So, in that particular case some of the grains which should have been appeared very brightly now because my overall background is so whiter. So, this particular features basically hides away, but in the dark field I can exactly pin point this region. By choosing that particular diffraction spot which is responsible for creating this particular portion, this particular feature. Then I can select I can just highlight only this particular part.

So, once I can highlight from this part I can get much more clarity because my background is totally dark and now this feature only is bright. So, the contrast I am getting from a bright feature and the dark field it can provide me very nice information about this particular feature, I might even see how this particular dislocation, how they are nicely oriented. So, I can get some information from that as well in case I had a stacking fault is there any substructure in the stacking fault, that part I can also see clearly in the dark field images.

So, that is the beauty of dark field imaging I can create a better contrast because I allow only a very weak portion which was a very, which was forming one the diffraction beams. It means, that the contribution from that particular feature was very, very low that it is resulting only a small diffraction spot. So, now I can trap that particular feature through a particular diffracted beam and I can learn more about that particular feature.

It can be a dislocation, it can be a small feature it can be a nicely oriented grain, it can also be a twin boundary or it can it can be a stacking fault. So, that is the beauty of the dark field imaging that I can get a very nice or improved contrast through the dark field imaging. Whereas, it might result a poor contrast because of the weak beam in the bright field.

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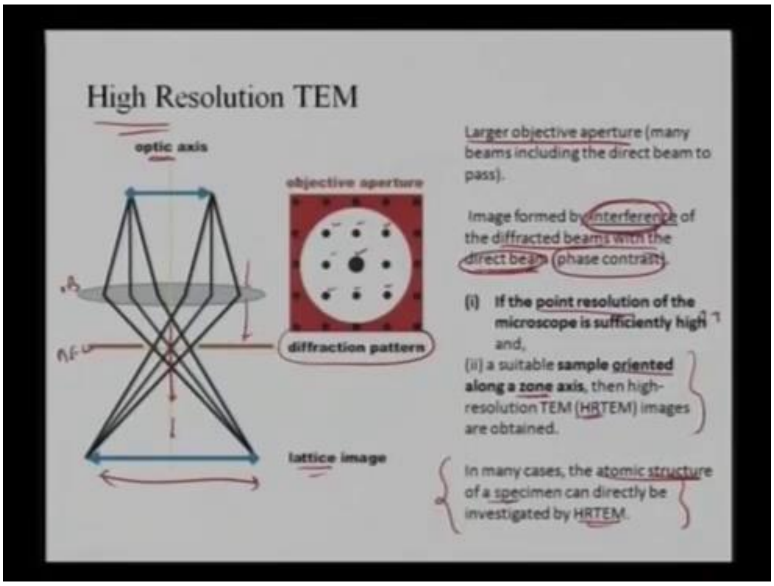

And coming to the high resolution TEM I can form lattice fringes, I can even result something called a lattice fringing, I can image each and every the parallel fringe which are responsible forming a particular plane. In this case, I use a larger objective aperture. So, what I allow? I allow a transmitted beam I had my sample somewhere here and then that thing has taken the information to the objective lens. This one is the objective lens and then we have the plane, the back focal plane which allows not only the directed beams, but also couple of the diffracted beams.

So, in this case I allow many of the diffracted portions as well as the transmitted beams to pass through and form a lattice image, these results because of the interference of the diffracted beam with the direct beam. So, I can get some phase contrast as well so what is happening here is, we are getting creating the interference of the diffracted beam with the direct beam to result a phase contrast. In this case, what I am what we are doing, we are allowing the central beam to pass through we are also letting the diffracted beams to pass through the aperture.

So, in this case our aperture size is much bigger, but it is allowing both the diffracted beam as well as the transmitted beam to pass through the aperture. So, this is a diffraction pattern and we are allowing more than one spots to pass through. And the interference between those two beams will result the lattice fringe imaging. At the same time for creating a high resolution I need to have a particular TEM which is a resolution sufficiently high enough.

So, point resolution of the microscope has to be very, very high. So, that it can really image, at the same time we need to have a proper orientation of a zone axis. If my zone axis is not properly oriented I might not get all the fringes, all the lattice fringes. So, I need to have the sample properly oriented so that I have a particular orientation and that can be imaged through the high resolution TEM. So, again if my resolution is sufficiently high enough I can see individual row of atoms.

So, in that case I can even analyse the atomic structure for a particular specimen just by seeing it under the high resolution TEM, that is what a HRTEM is high resolution TEM. So, I can form an image I can see individual row of atoms just by this particular imaging pattern. So, once I want to get a high resolution TEM, I am more interested in lattice fringe imaging. So, in this particular case I would let the transmitted beams to pass through as well as the diffracted beams to pass through.

And the interference of both will result a lattice fringe and this lattice fringe is nothing but the array of or the row of atoms which are parallel to one another. Those are forming certain the planes of particular crystal and all those rows of atoms, I can really see individual kind of I can see individual rows of atoms ,which are perpendicular to the plane.

As well, row of atoms which are spread by a certain distance through the lattice fringing which are being formed using this particular technique. And in this case, I need to have a very high resolution TEM, so that I can separate out the lattice fringes, but contrary to that it is not always necessary that I always need to have a high resolution to get a lattice fringe imaging, I can even get the lattice fringe imaging even when I do not have a very high resolution.

So, high resolution does not always mean that I need to have a lattice fringe imaging, I can even see grain boundaries which are a couple of angstroms in width through the high resolution TEM. So, high resolution TEM I should be able to resolve couple of angstroms will be less than an angstrom by this particular technique that is called high resolution. And the term of lattice fringing is something different as compared to the high resolution TEM.

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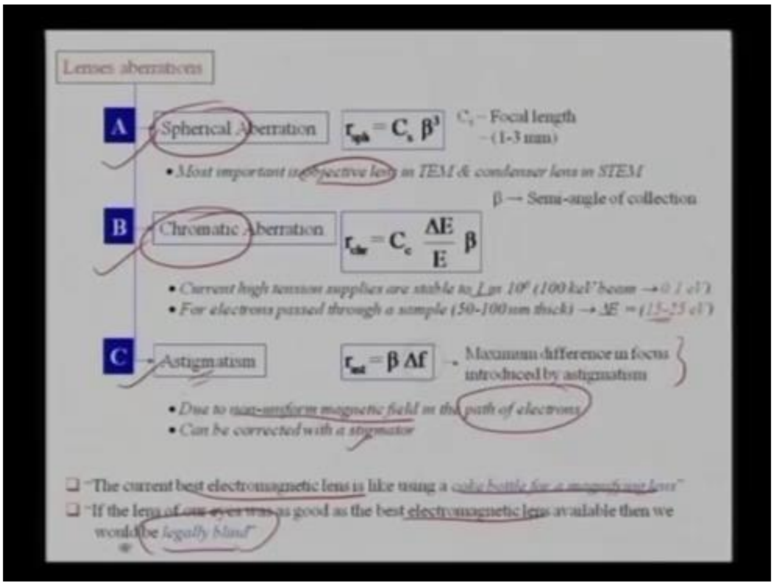

But again, the TEM is not free from the aberration, so in this case particular case we have something called spherical aberration, chromatic aberration and again astigmatism. So, what is happening here is in the spherical aberration, I am getting more of a barrelling again this is the most important of the objective lens in TEM, is the objective lens in the TEM because that is one which is responsible for collecting the information and forming an image.

So, once I have something sphericity being introduced into the particular imaging it is again not good. So, in deed to avoid the spherical aberrations because the lenses they have to focusing everything at a particular location. In case, I do not focus the image at one particular point plane, then it will tend to make the image look more spherical that part I want to avoid.

And second thing is the chromatic aberration because though we have that high tension supplies more stable like 1 into 10 to the power 6 volts will be variation in 1 into 10 to the power 6 volts. So, that is the high tension supplies are generally much more stable, but once the electron is passing through a particular material it will tend to have some variation in energy. And that is the one which causes much more chromatic aberration.

It means that energies of different wavelengths will tend to focus at different regimes. They would not focus all at one single point, so that causes that the lower wavelengths may tend to focus much earlier, longer wavelengths focus at much larger distances. So, that will not focus everything at one single spot and that causes the chromatic aberration. And again we have astigmatism that means, that the beam which is basically travelling on the horizontally and the one which is travelling vertically.

They again would not tend to focus at a single point it is because the way the lenses are designed. So, it might happen that lenses are much stronger at certain points and they will tend to focus at different lens. So, that thing is called astigmatism that my vertical and my horizontal scales do not match up properly. That happens because of the non-uniform magnetic field which is present in the path of the electrons. And we can again correct it using a sting meter, but again with all these aberrations it is more like using a coke bottle as a magnifying lens.

So, the best electromagnetic lenses can be thought of that much manner. So, it means that so much aberration is already existent at that particular scale and if we can translate it to what we see it means, we can be called legally blind. So, if our lenses are as good as our eyes and we then have the best electromagnetic lenses which are available still which will be legally blind, we would not be able to see anything.

That is the overall, feature of this particular TEM that they have spherical aberrations, chromatic aberrations astigmatism. And these create so much problem that we cannot if we can scale it up to our eyes, we will be totally blind, but these cannot be, some of them cannot be avoided they can be corrected. So, we have certain features of some corrected lenses which have come recently to the market.

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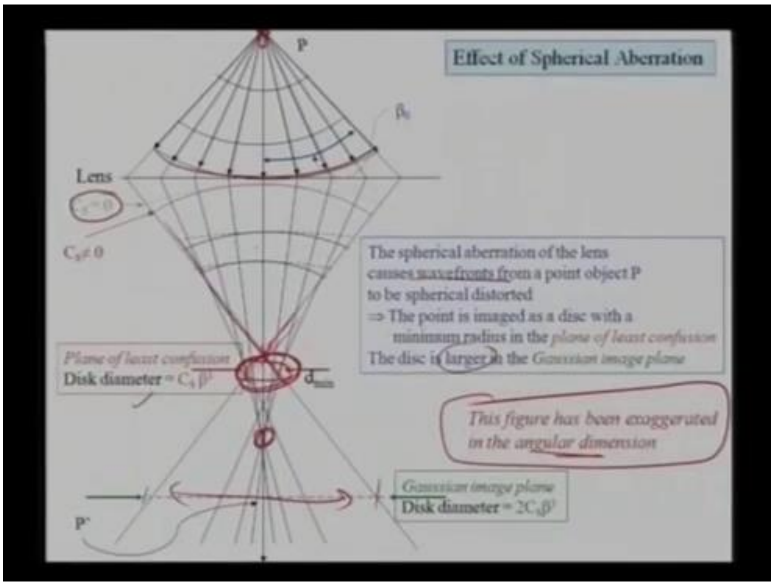

So, this is what is happening in the case of spherical aberration that we have a point source that starts forming an image. So, at this particular point was for the same exact kind of circularity or the length how much they have travelled for a particular plane. We have total spherical aberration of 0, so we will form the same image at this particular plane, but at any other location say at the particular red line must spherical aberration may not be 0.

So, because you want the wave fronts, all the wave fronts which are arising from a particular point to be spherically distorted we do not want that to happen. So, the point has to be image as there will be basically imaging as a disk. And we will have certain regime because some things are getting focused much earlier, some things they get focused much later. So, we have a ring which is showing the plane of least confusion and again once, we come to the Gaussian image plane around here the image is completely distorted and it is showing very large feature.

Again, these all features are much more elongated in this particular direction angular wise, but again we can see that, this region is causing minimum confusion. So, this is the one where we want to keep our particular aperture to finally, image it further. And this disk diameter comes out to be C s B cube where, B is the half semi angle and C s is a constant.

Again, we are do saying that we are exaggerating this image in the angular dimension because these angles are limited to couple of degrees less than 0 to 1 degree. So, still we are exaggerating to that particular level to show, what is happening exactly because we want the wave fronts to travel exactly the same distance. So, in order to avoid the distortion of a particular image.

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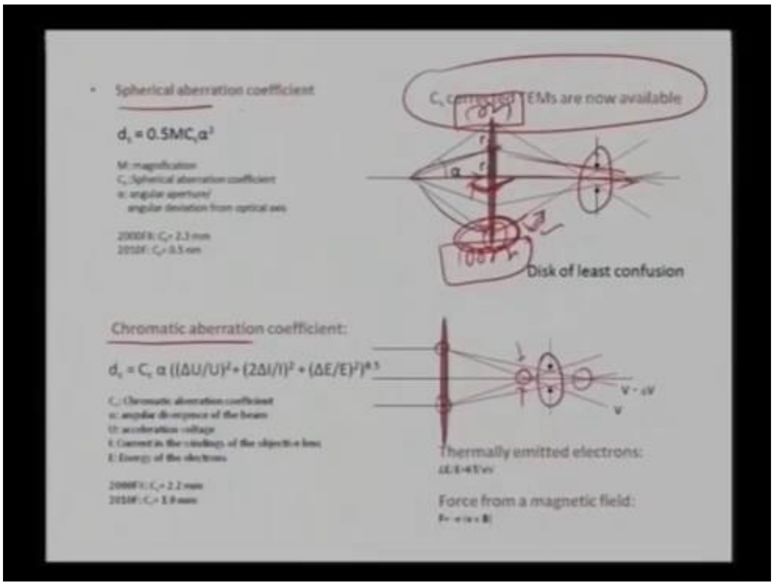

Similarly, we have spherical aberration that is giving rise to the region of minimum confusion and that thing comes from this particular thing what we discussed earlier. Then we can also have chromatic aberration and that chroma means colour. So, we have wavelengths of different wavelengths, so even when the two wavelengths they are starting from the same point. The wavelengths which are much more smaller tend to focus much earlier because they have very high energy, whereas for the longer wavelengths they tend to focus somewhere else. So, again we some regime of minimum confusion, so we can get that chromatic aberration also can be very much prominent in terms of deteriorating the image. So, in spherical aberration we have again the wave fronts are not matching properly and the chromatic aberration over wavelengths are not matching properly.

That is the reason they create differences where they focus on and again we have some lenses which are available, which have been corrected for the spherical aberration because now, we can create certain electromagnetic lenses, which can tend to form fields, which are much more regular or much more uniform either at the centre or at the same time at corners because once have particular electromagnetic lenses they are located around this side.

So, once the electron is passing through it will absorb much more stronger field once, it is near the particular electromagnetic field. Whereas, once it is very near to the centre of the core it will experience a little lesser field. So, that is the reason it will tend to go much more forward in terms of focusing. So, these will get bent to a little lesser degree as compared to the electrons at the periphery. So, the bending will be much more higher near the particular electromagnetic lenses, where it is much more tubular at the central part of the particular lenses.

So, that starts giving rise to the spherical aberration and the chromatic aberration it arises because of the interaction of the electron with the material itself. Some of them get elastically in elastically scattered, elastically absorbed and they start losing the energy which can be order of 15 to 25 EV that starts giving rise to the chromatic aberration.

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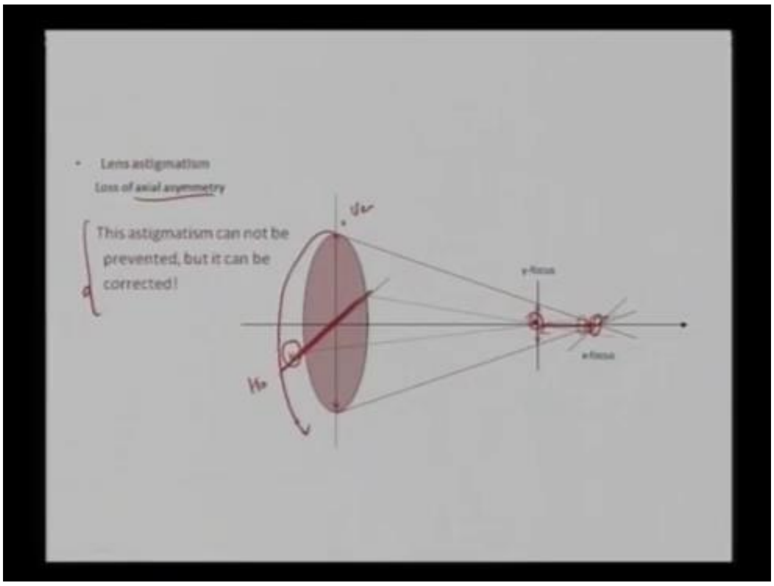

And further, and again it is around due to the non-uniformity of the magnetic electromagnetic lenses, my axial symmetry is lost. So, what is happening is my x and y which is my x direction, which is the vertical direction and my horizontal direction is the y. So, my horizontal direction and my vertical direction they do not tend to focus at the same point. So, I am seeing here my horizontal portion it is getting focused at some particular point, whereas my vertical direction is getting focused at some other point. So, again I get certain area which is the least confusion, but again I am getting a dispersion of the image along this particular point. That is arising because of the non-uniformity of the lens in itself, so that part also I can really observe out here and again the astigmatism cannot be prevented, but it can only be corrected.

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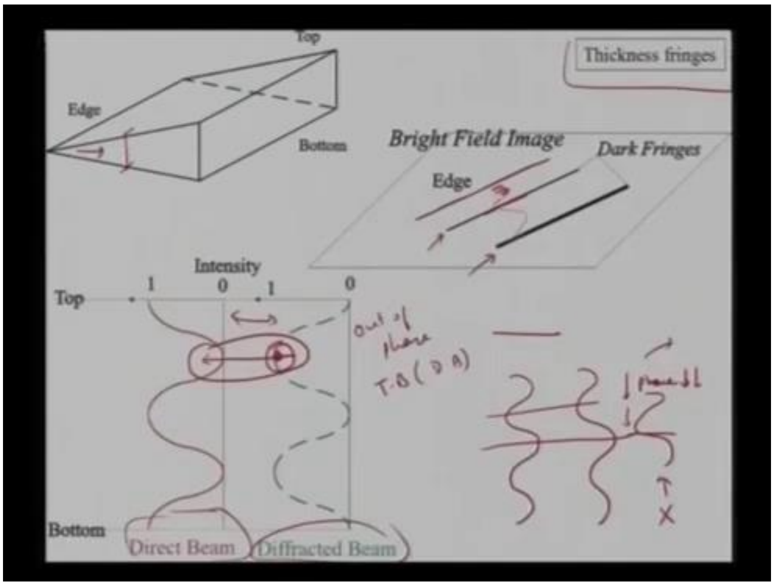

And later on, I can also get something called the thickness fringes and we learnt earlier that. Once, we have very thin specimen, most of the electrons are getting transmitted, but once we have thicker portions, my electron beam will start getting absorbed by that particular material and it will start rendering a much more darker image. So, I am getting much more brighter portions which are much thinner regions.

Whereas, I am getting very nice information or very huge information from the points where I have I am getting, my thick regions are giving me much more absorption of the electrons. And I am getting a very dark image, but there is something called thickness fringes. That thing can arise because initially I have a direct beam and I have some diffracted beam. So, what is happening is at certain points because of the thickness I can start getting a feature that my diffracted beam is exactly opposite in phase, as compared to the direct beam.

So, emergence of my direct beam and the diffracted beam because of the thickness my diffracted beam has gone out of phase, as compared to the transmitted beam or the direct beam. So, my diffracted beam it has gone completely reverse in terms of phase with respect to the direct beam. So, what I get finally, is 0 intensities at this point total cancellation at certain thickness level because initially I had a direct beam. So what I get my direct beam was in phase with it, so I get some reinforcement as soon as the thickness starts changing the phase starts changing.

So, once the phase is changing what is happening is at the edge I had very bright intensity? As soon as, I start getting into the material I start getting some point where, I am getting cancellation of my, cancellation of the direct beam with the diffracted beam. There I start getting some dark fringes, so I had certain overall I had a bright field image, but because of the change in the thickness part, I start getting a phase difference.

And from the phase difference, I start getting something which is completely deleting my incident beam or the direct beam and I start getting some dark fringes. It is happening here is my direct beam is getting completely annihilated by the diffracted beam. And then again I start getting something much more in phase once, it is cleared this particular portion it will be completely like this, completely opposite.

So, I will get complete annihilation where I am getting no intensity and soon I will getting some shift in the diffracted beam. So, again I start getting some more brighter region and again it starts reducing in the intensity and again I come back to the dark fringe. Then again my intensity starts increasing and then again I dropped down and I get again dark fringes. So, that is what, that is how the dark thickness fringes come using this particular electron, the interaction of the direct beam with the diffracted beam. So, in this particular case when I have thickness fringes contributes, what is happening is I have two beam situation.

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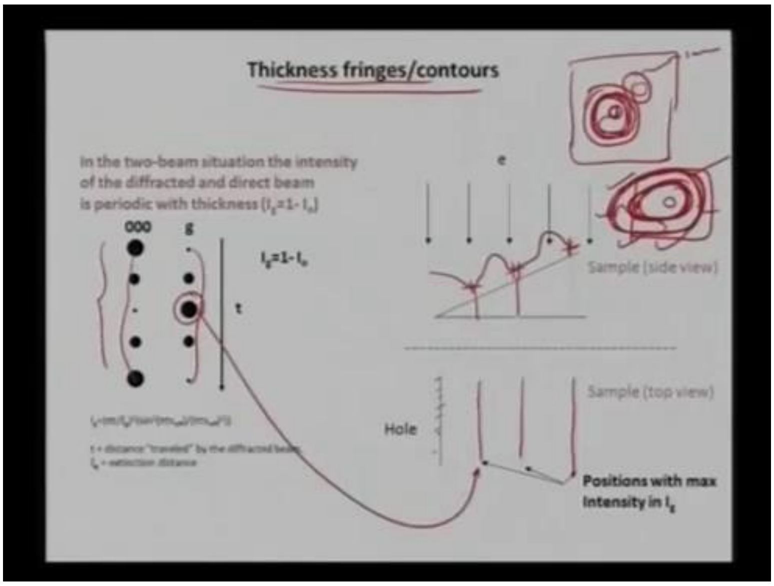

I have a diffracted beam and a direct beam and they tend to go periodic because the phase difference is arising with respect to the thickness. So, depending on how much what is the overall thickness of the particular crystal, I tend to get the overall interference of those two beams and I get something which is much more periodic in nature. So, I can see that the intensities they keep gradually from high to low to again back to high or from low to high to back to low.

So, that is what is happening in case I had a hole out here, so then because of thickness I start getting certain fringes. So, my intensity was, my intensity has gone has dropped down to this particular level to 0. Then again it starts increasing then again it drops down, so again it starts increasing and again it drops down. Once, my phase is exactly negated by that, so if I see it from the top what I see is my hole was here, so I start getting some dark fringes.

So, ideally once I make my TEM sample, I have generally we make the sample by creating a hole in the centre. So, what we can see is wherever we have hole and we have thick enough of a sample to cause this particular interference between the direct beam and the diffracted beam, what we can see is certain dark fringes. So, what is happening is all this fringes correspond to the same thickness, so all these fringes are nothing but similar thickness.

So, initially I had a hole which was much more brighter then I had the intensity going down to 0. So, I get a dark particular, dark circle around it and that signifies that I have a particular material which is a similar thickness, then again around this particular regime I see the intensity. So, if I had particular feature like this and one more like this out here, this region is where we have a constant thickness or nearby similar thickness around this particular regime, which has become totally dark.

Then what is happening is the region nearby, it I am getting increase in intensity and again the intensity decreases and again I have a region which is a has a similar thickness. So, those similar thickness regimes are given by certain fringes and that thing result the thickness fringes or the contours. So, these contours are called thickness contours and that we can visualise from the intensities, so we can see the intensities out here. So, with the maximum intensity I am getting a particular dark point, so in terms of that so that is giving me thickness fringes.

So, advantage of this one is so basically, this one tells me what are the regions? where I can say that the thickness of the sample is same in all those locations. And again what is happening is again I am seeing some difference in intensities out here, so again this region will again have the similar intensity, similar thickness. So, this particular regime and they have a similar thickness and this particular contour has a similar thickness. The contours which is inside and the contours which is outside they will have a different thickness. So, the single contour it means they will have a same thickness.

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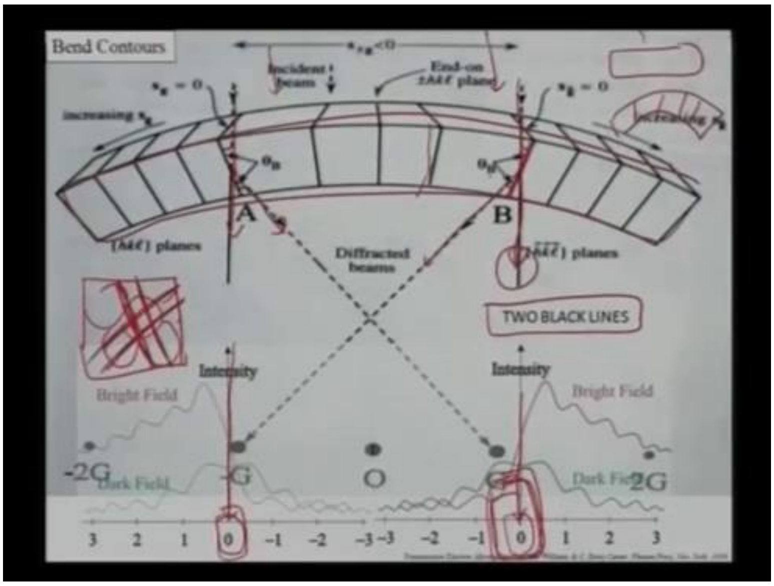

One more thing which can arise in this particular case is something called a bend contour. And the bend contours can arise from a very soft sample, during sample preparation if you can induce enough stresses into the material. Then what happens is some of the planes can really bend, while we are preparing the sample. So, that sample preparations can also induce some sort of defect which is called a bend contour.

So, what is happening here is we take a particular crystal which was supposed to be straighter. This particular orientation or this particular set of planes was supposed to be straight horizontal, but what is happening here is because of the sample preparation we are inducing some stress into the material. Through which there is bending of this particular planes and once the particular planes are bent, then once the transmitted beam strikes the samples. Some planes they oriented perfectly because even less than 1 degree can yield a diffraction of that particular plane.

So, once we add planes which are oriented parallel and they can get tilted by a degree or so and that will lead to the satisfaction that can even satisfy the Bragg's law. At certain point it may start satisfying the Bragg's law and so that beam which is supposed to pass through will get not diffracted. So, what I will get is the beam which are supposed to get diffracted, the beam which are supposed to pass through is now getting diffracted. So, this point I get a very low intensity, so I get a 0 intensity beam here.

As, well some other location which was bend in the negative direction of there also the beam instead of passing through it is now diffracted, so here I will get one more diffracted beam. So, what is happening here is I am devoid of any intensity out here as well as I am devoid of any intensity here. So, I get something called two black lines. And appearance of those two black lines in the bright field image is the reasoning that we get, we are getting a bending in the sample and that result in the bend contour.

So, this is a particular feature which says that the sample was not prepared properly. So, in a particular bright field imaging, what we start getting is a two pair of dark lines. And the pair of dark lines can arise anywhere in the bright field and doing nothing but spoiling our observation and that is the example, of the bend contour. That clearly, tells us that our sample preparation was not good.

And that is the reason it also spoils the overall imaging in the bright field because now, the place which are supposed to pass through the light ray become obstacles and they are tending to diffract the light. And the transparent beam which are supposed to be pass through is not getting diffracted. So, the overall region which is very, very bright that is now devoid of a particular beam the transmitted beam. So, that particular portion appears dark so the overall intensity of the beam has gone down and that results me in a dark spot or the dark line. The continuous flow of that particular thing gives me a dark line and that that is nothing but a bend contour.

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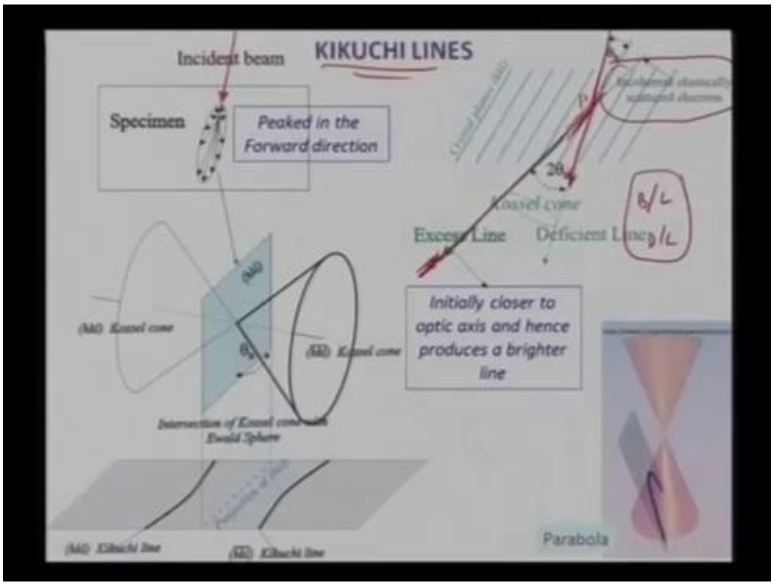

Secondly, we can also get something called Kikuchi lines, it might happen that the transparent beam gets somehow in elastically scattered. So, I can get some incoherent elastically scattered electrons to those are not in basically, phase with the transmitted beam and they can now get diffracted by the certain plane. So, I had some elastically scattered electrons and now those are getting diffracted by certain planes. So, I had some energy of the beam, which has lost some energy by scattering and now that particular beam is getting diffracted.

So, diffraction of that we can clearly see that beam which was supposed to pass through is now getting diffracted. So, I will get a set of two lines which is the axis line, the line which has got diffracted and the line which is supposed to get transmitted, but did not. So, I get now pair of bright line which is axis line and one line which is devoid, so I get one dark line. So, what essentially I am getting, I am getting essentially a pair of bright line and a dark line, so that is what is called as a Kikuchi line

That we have a transmitted electron beam, which in elastically scattered somehow and then instead of passing it through the material it gets diffracted. And one gets the diffracted beam becomes axis line and the beams which are supposed to get transmitted, which did not pass through result a dark line. So, overall I get a pair of dark line and bright line in the Kikuchi lines.

So, I get a particular Kikuchi line which is an excess or energy higher energy, which is much more brighter and a deficient line which is darker line, but the one thing which we can really see here, is that they are highly dependent on the orientation of the this particular crystal planes.

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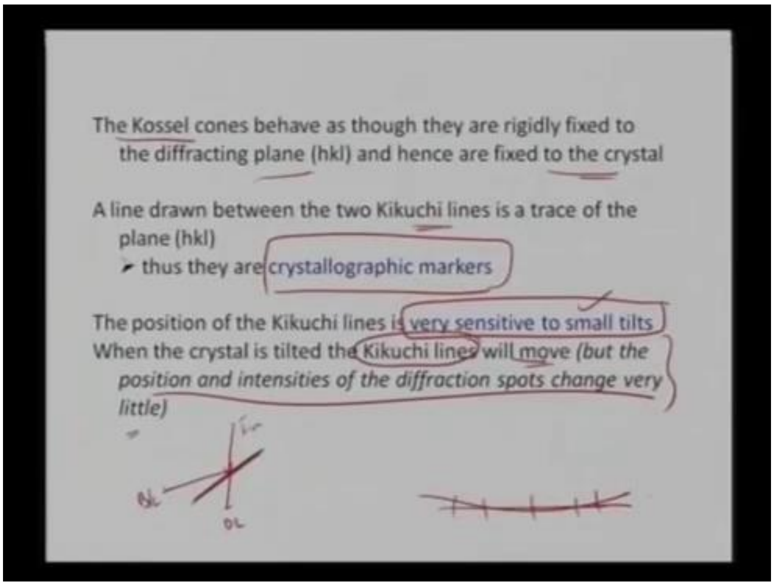

They are also called crystallographic markers because once we are getting a diffraction pattern they form rail rods not with here and there little bit of change in the orientation of the crystal, still we will get diffraction spot in the same location, but that is not true with the Kikuchi lines. In Kikuchi lines, we can exactly orient them in a particular manner so that they can get diffracted from all the particular symmetry.

So, they can maintain a symmetry of the crystal, if they are getting diffracted from 1 1 1 we can exactly trace where the 1 1 1 plane is going through, what kind of orientation the kind of symmetry which the 1 1 1 has the 3 fold we can clearly see in the Kikuchi lines as well. So, the Kossel cones they behave has though they are rigidly fixed to the diffracting plane and they are fixed to the crystal and but Kikuchi lines once we tilt the particular material, they will also tend to move out.

So, the position and the intensity of the diffraction spot they change very little in the diffraction pattern, but Kikuchi lines they move along with the tilting of the particular crystal. So, they are very sensitive to the even to the very small tilts and that is the reason they are called crystallographic markers. In this Kikuchi lines how we are forming it, forming it is we are allowing that in this case elastically scattered beam it gets diffracted.

So, we get a bright line and in this case we get a dark line where we were supposed to get transmitted and they are dependent on the orientation of the planes only. So, the lines which are appearing now here are highly dependent on the orientation of particular planes. That is the reason they are called crystallographic markers and they are very sensitive to even small tilts.

Whereas my diffraction spots the resulting from the interaction of my sphere with the rail rods not any with the points, but with the rail rods which are resulting from the atoms at the in the reciprocal lattice. So, still when I tilt my particular sphere or my crystal little bit my diffraction spot will appear at the same location. So, they will get unaffected, but my Kikuchi lines they are so dependent on the crystal orientation that they will change their position with the small tilt in the in the crystal again.

So, this is the way with the Kikuchi lines in this particular thing we can really see that how Kikuchi lines are important in terms of tracing a particular plane, how they are following. And we can also maintain the symmetry of a particular crystal as well. So, in this lecture we learnt about the bright field image and the dark field image. Once, we have a particular back focal plane, if we allow only the transmitted beam to pass through we get something called a bright field image.

And that is very essential in terms of the overall characterising how the distribution of phases, what is the overall grain size and all such things, but once we allow only the diffracted beam to pass through. We can highlight, we can produce a very high contrast image and we can also see a particular feature, which is dislocation or a grain boundary or even some stacking faults or some other things some precipitates or any preferably oriented grains as well.

And we can get much more detailed information from that particular dark field image because my field is totally dark, so I see much more clearly how my feature is behaving. So, that part we can see from the dark field image and then again we learnt about how the thickness fringes are arising and what kind of aberrations are there. So, we learnt about how what kind of different aberrations are inherent in a TEM such as spherical aberration, chromatic aberration or astigmatism and how they result. And again, we learnt about the thickness fringes or the bend contours or even the Kikuchi lines. So, that is all I have for the today’s lecture.

Thank you.