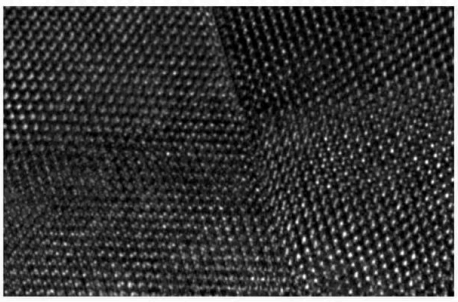
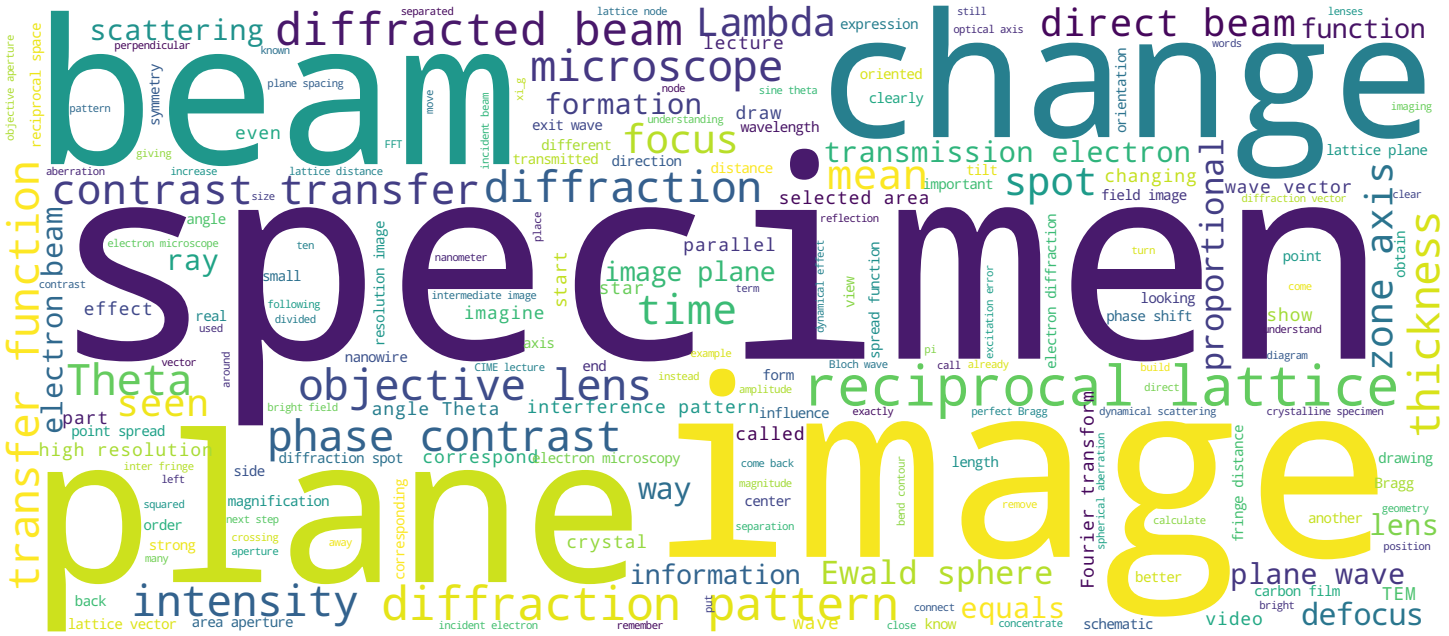


Phase contrast: HRTEM

Transmission Electron Microscopy

Prof. C. Hébert & Dr. D. Alexander



Search MOOC

Video

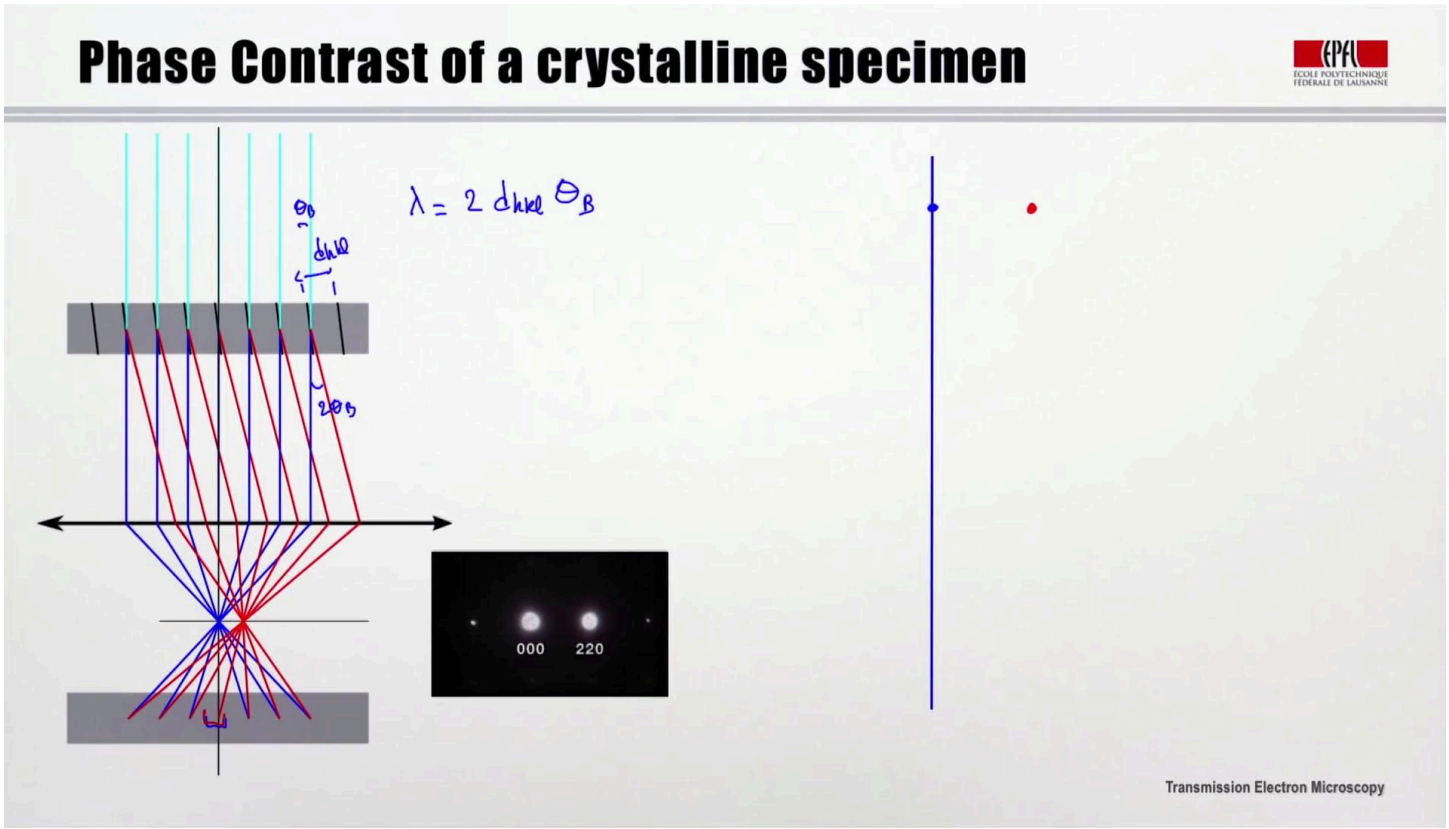
EPFL

Welcome to CIME's lecture on Transmission Electron Microscopy for material science. In this video, we will connect what we have seen before on phased contrast transfer function, as well as, on diffraction to get an intuitive understanding of the formation of a high-resolution image.

Notes

Summary

0m 04s

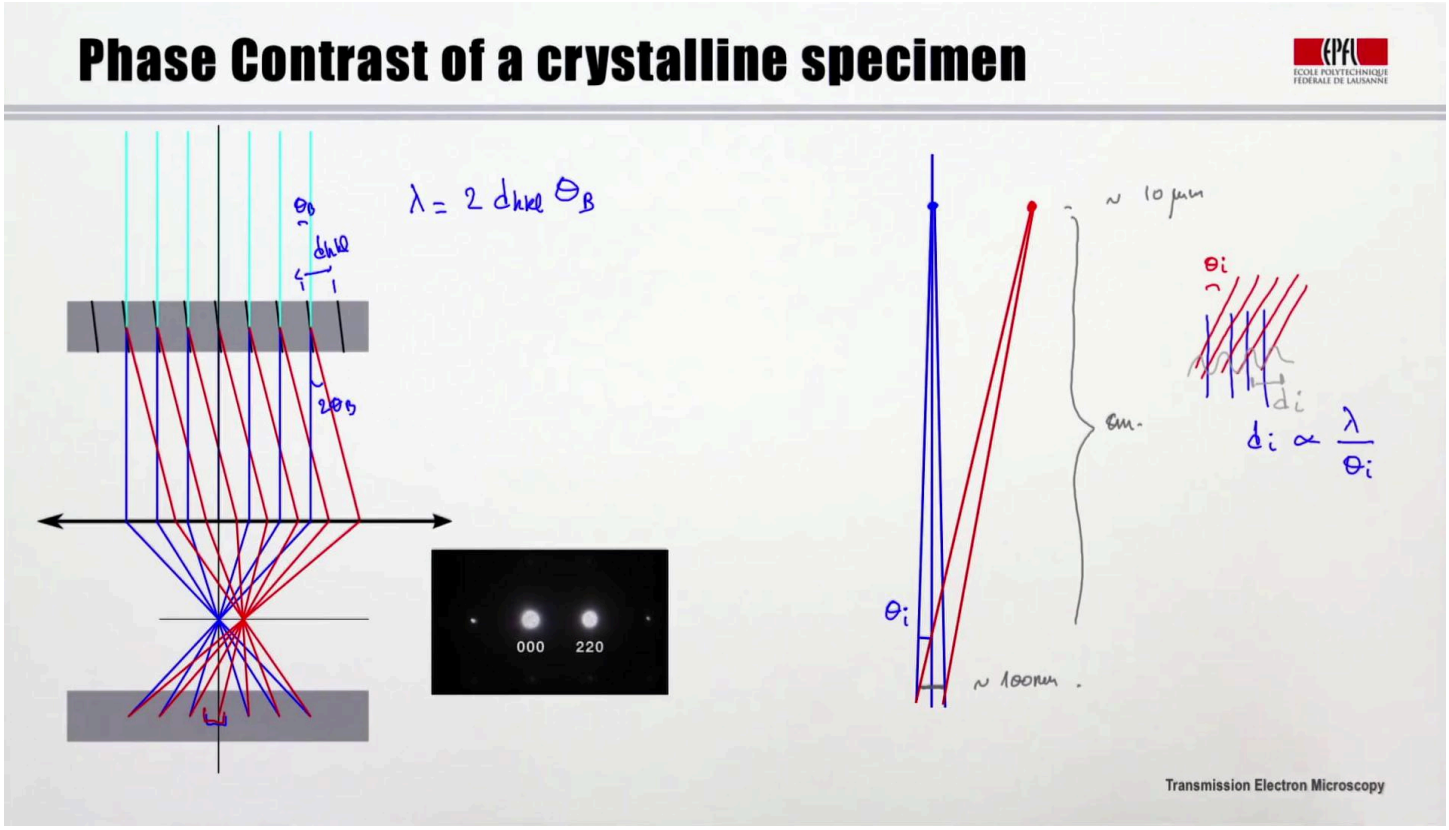


So, let us come back to a crystalline specimen that we have here, but oriented in a tubing case, or in Bragg condition. In this case, we have the lattice planes which have a distance dhkl which are at an angle Theta B with the incident beam. With this, we have two beams; the direct beam and the diffracted beam which comes out as an angle, two times Theta B. I remind you of the Bragg law that gives us the relationship between Theta B and dhkl. Lambda is equal two times dhkl normally sine Theta B, Theta is small, so we can keep Theta B. Now remember diffraction is a coherent phenomenon. So what we have is this direct beam and this diffracted beam, and both will be combined together to form the image in the image plane. If instead of looking at the large field of view on the specimen, we concentrate on a very small field of view. So we want to go at high magnification. How can we draw the schematics in this case? We still have the optical axis. We have the formation of the direct and diffracted beam, direct beam and diffracted beam. Typically, they will be separated by some tens of micrometers. Now, if we want to look at atomic resolution, the field of view that we will look at that part of the specimen, will be in the order of magnitudes of some ten to maybe 100 nanometer.

Notes

Summary

0m 25s

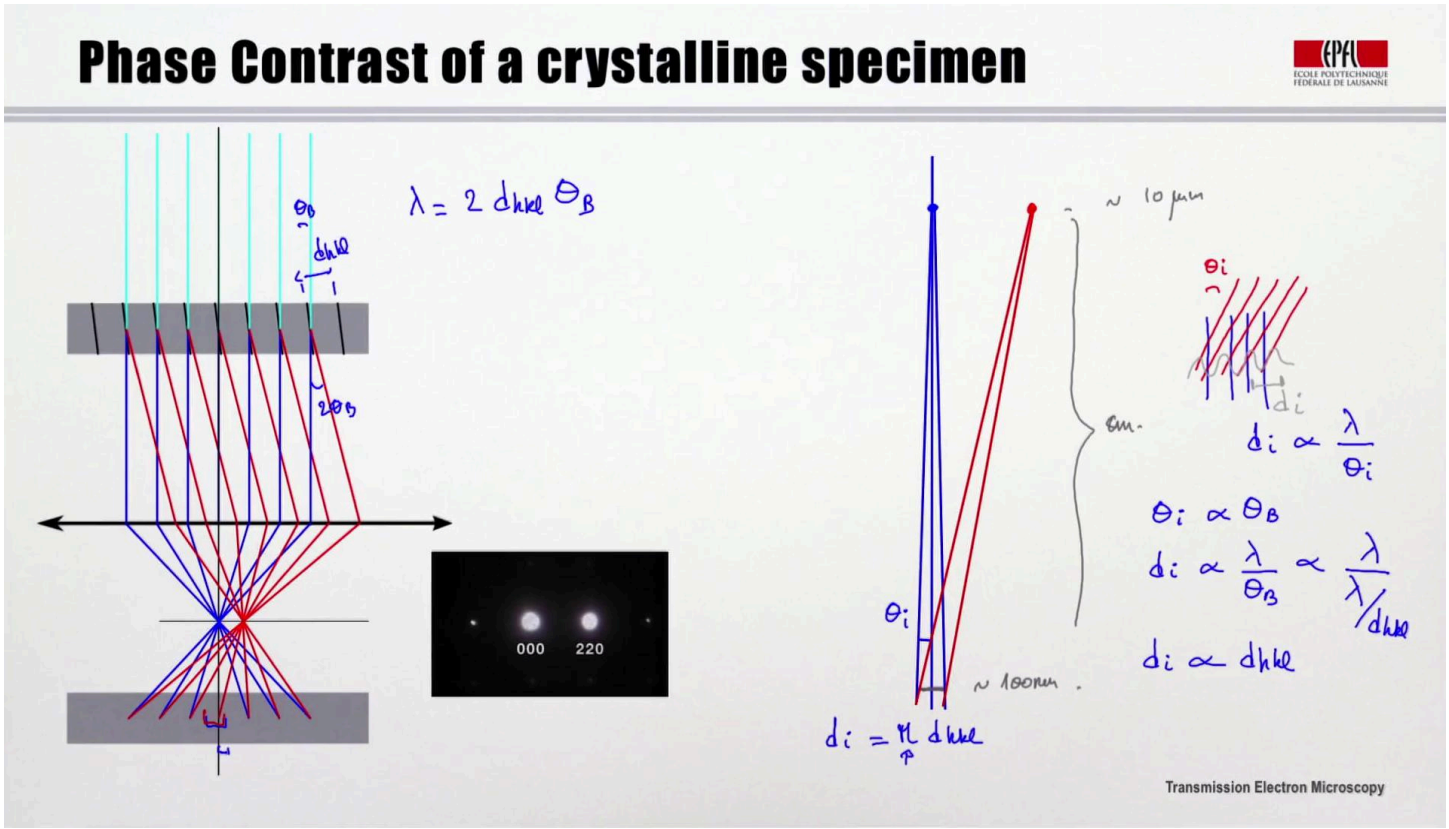


This means that I will look at a small parts there which is say 100 nanometer, while we have their separation of ten micrometers. At the same time, the separation between the diffraction plane and the image plane in the microscope is in the order of magnitude of centimeters. It's not even at scale, but its better than the drawing on the left. So, now, if I try to draw the rays originating from those direct and diffracted beam, I see that I have two electron beams that come together on the image plane, and each one is very close to a plane wave. Which means that they will have two plane waves which have between them an angle Theta y, I call it Theta y because its in the image plane. But if I have two plane waves which have a phase relationship, and this is the case of those two waves because diffraction is a coherence phenomenon that comes together with an angle Theta y between them, then I will see the formation of an interference pattern between those two waves. The distance between two fringes which I will call dy depends on the wavelength of the wave, and on the angle feet away. The relationship tells me that dy is proportional to Lambda, the wavelength divided by Theta y.

Notes

Summary

2m 44s

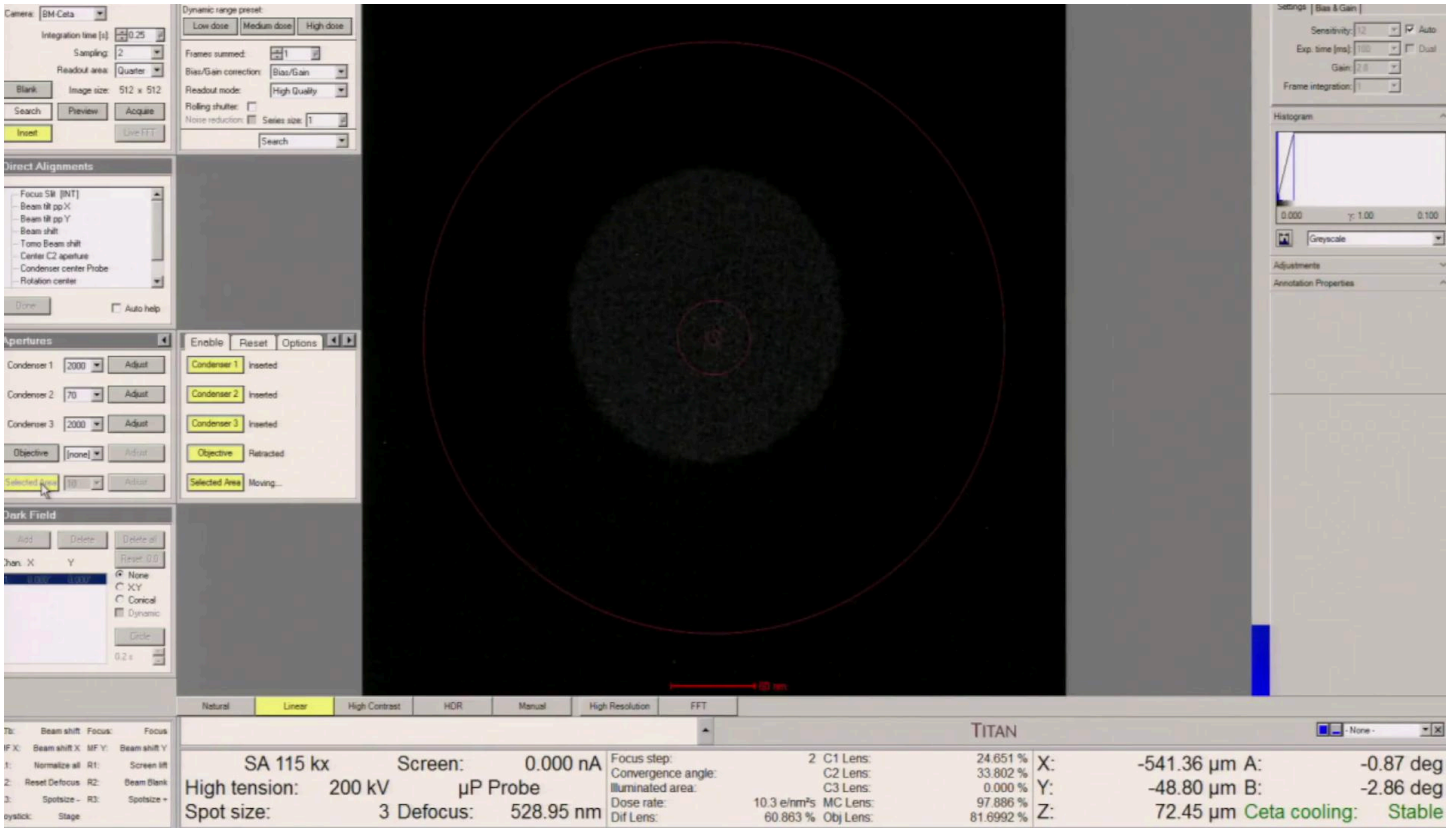


Theta y is clearly proportional to the distance that we have between those spots which is proportional to Theta B. So Theta y is proportional to Theta B. Now, if we connect those two equations with Bragg's law that will tell us that dy is proportional to Lambda over Theta B, which is in turn proportional Theta B being proportional to Lambda over dhkl. So, is proportional to Lambda over Lambda over dhkl. So dy is proportional to the dhkl, which means that the inter-fringe distance of this interference pattern that we expect in the image plane is directly proportional to the distance between the lattice planes. Actually, it's even better. It's not just proportional to it, it is actually multiplied by the magnification applied by the objective lens when you consider the formation of the image from the sample to the first intermediate image plane. So, if I look at this inter-fringe distance in the first intermediate image dy will be equal to m times dhkl with m being the magnification of the objective lens. This will be the subject of one of the exercise that we have this week. Now, I will take you back to the transmission electron microscope.

Notes

Summary

4m 55s

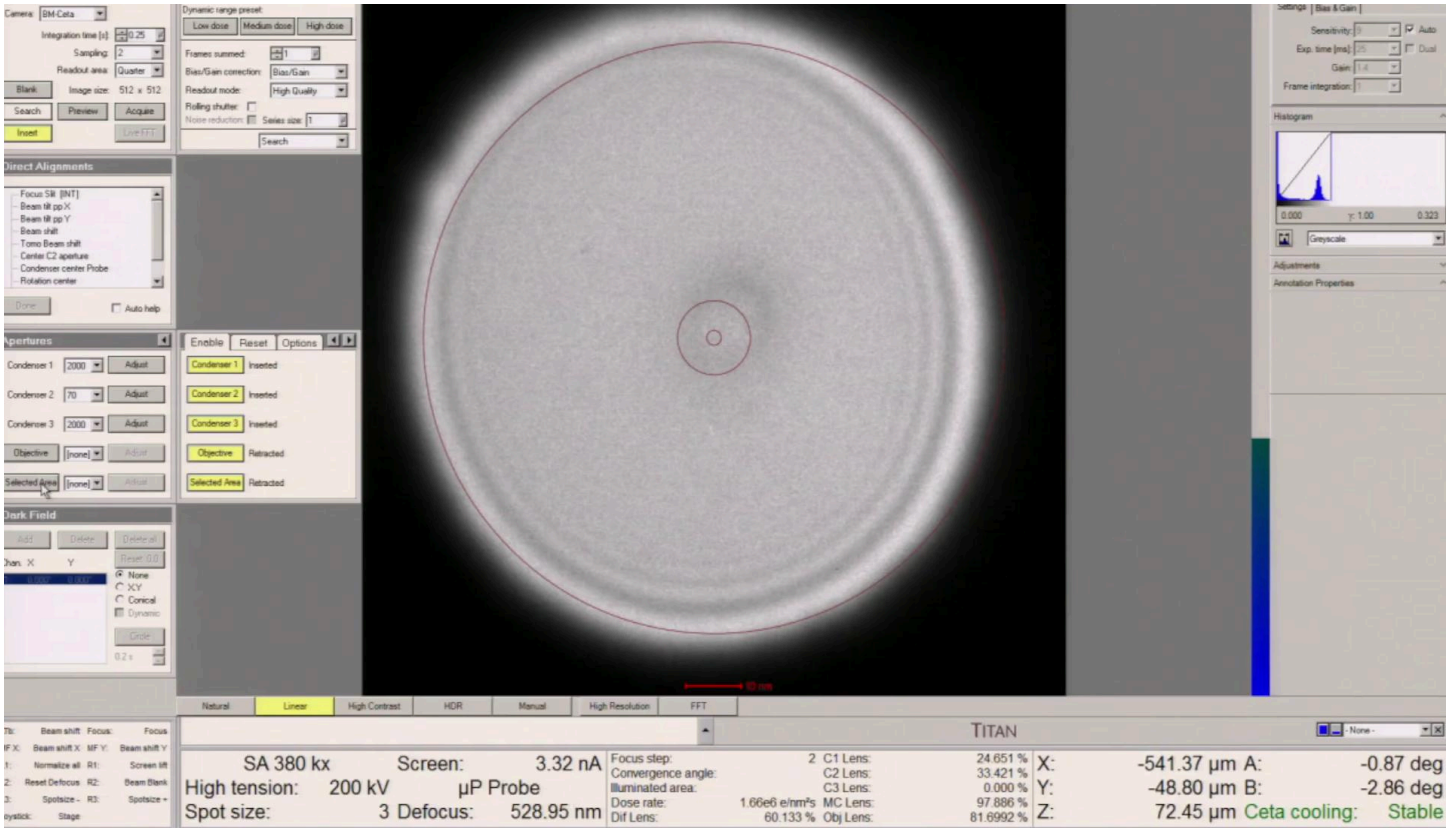


The specimen that I have chosen is a silicon specimen oriented in the OO1 direction, and I will check the orientation with a diffraction pattern. I'm not too far away from these OO1 orientation. To convince you I will tilt the specimen closer to zone axis. Here we are. In the next step, I will tilt the specimen back to an orientation where have only a systematic role, and in that case, I will try to choose a three-beam gaze with only the central beam and two spots on the role that does strongly excited. Here I have a three-beam gaze with the 220 and b2b20 spot excited.

Notes

Summary

6m 47s

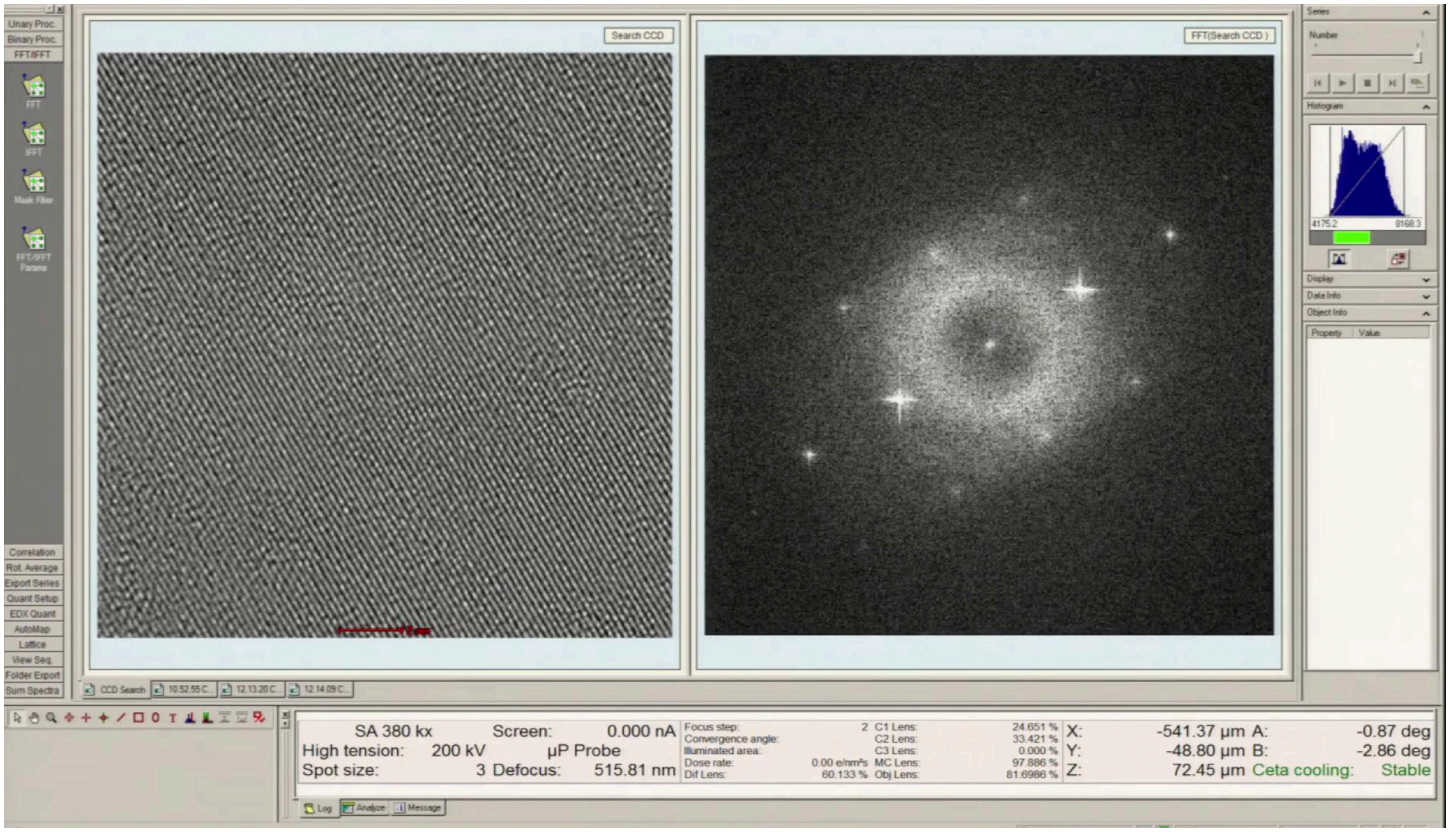


I switch back to image, I remove the selected area aperture and now I will increase the magnification. So, you see it on the bottom of the screen moving to a 380,000 times magnification. Here we are.

Notes

Summary

8m 05s



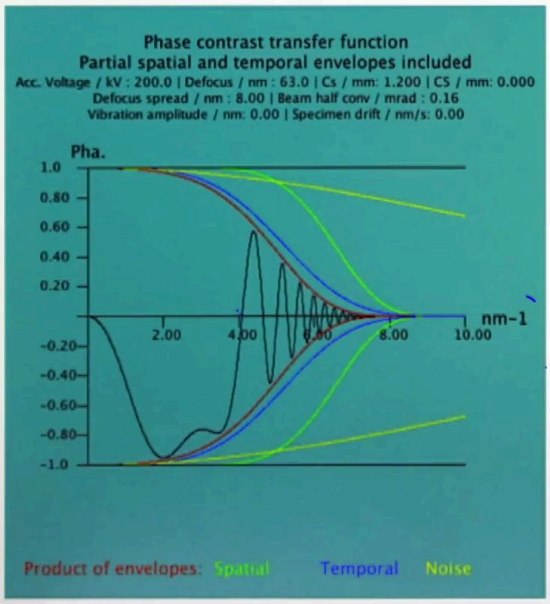
In order to see what's going on, I have to switch to a better camera and now you see the image on the left and the FFT of the image on the right. The specimen is covered with some amorphous material. Therefore, we see the black rings due to the phase contrast transfer function, superimposed with the two spots due to the fourier transform of the periodic fringes. In the following, I will now change the focus. While I'm changing the focus, you can observe on the image that the fringe distance does not change but the contrast of the fringes is changing a lot. Sometimes they are well visible, sometimes they are buried in the noise. Here I reached a focus where the contrast is weak. I start changing the focus again. At this focus, the fringe contrast is very good.

Notes

Summary

8m 26s

Phase Contrast of a crystalline specimen



Transmission Electron Microscopy

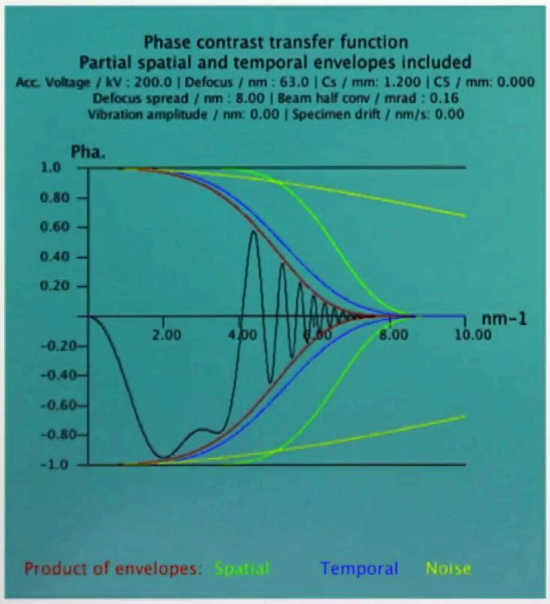
Coming back to the phase contrast transfer function that we had seen before, you remember that this function describes the ability of the microscope, so of the optical system to transfer information as a function of the spatial frequencies. When we have a large bands like this, the information is well transmitted and when the phase contrast transfer function cuts zero of the axis then we have a dark ring in the FFT of the image of an amorphous specimen. This corresponds to a place of where the information is not well transmitted or not transmitted at all. Connecting this was the video that we have seen before. You can imagine that if you have a specimen with an inter fringe distance which is exactly falling onto one of those zero then you will not have a good transfer of information.

Notes

Summary

9m 42s

Phase Contrast of a crystalline specimen



Transmission Electron Microscopy

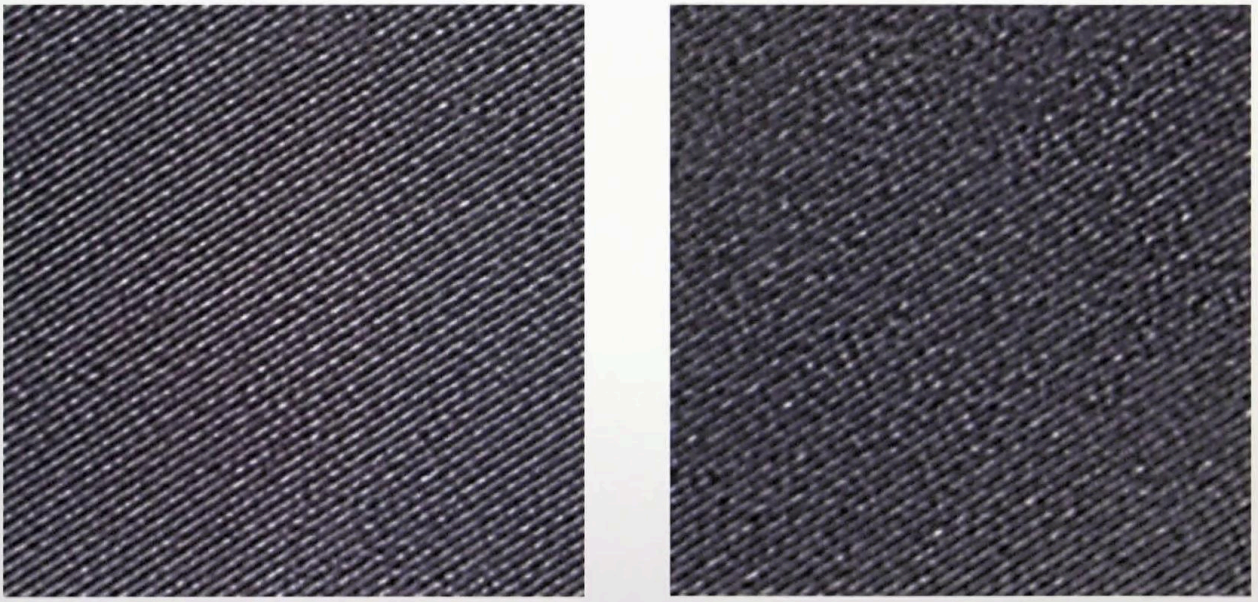
These are two images. Those two one which have been acquired on the same specimen as I used to show you the microscope but with different defocus. Changing the defocus will change the phase contrast transfer function and move the zero crossing. On the left image, the contrast is much better than on the right image and this is because on this right image, you have a zero crossing of the phase contrast transfer function coming exactly at the frequency where I have the inter-lattice distance for this specimen.

Notes

Summary

10m 54s

Phase Contrast of a crystalline specimen

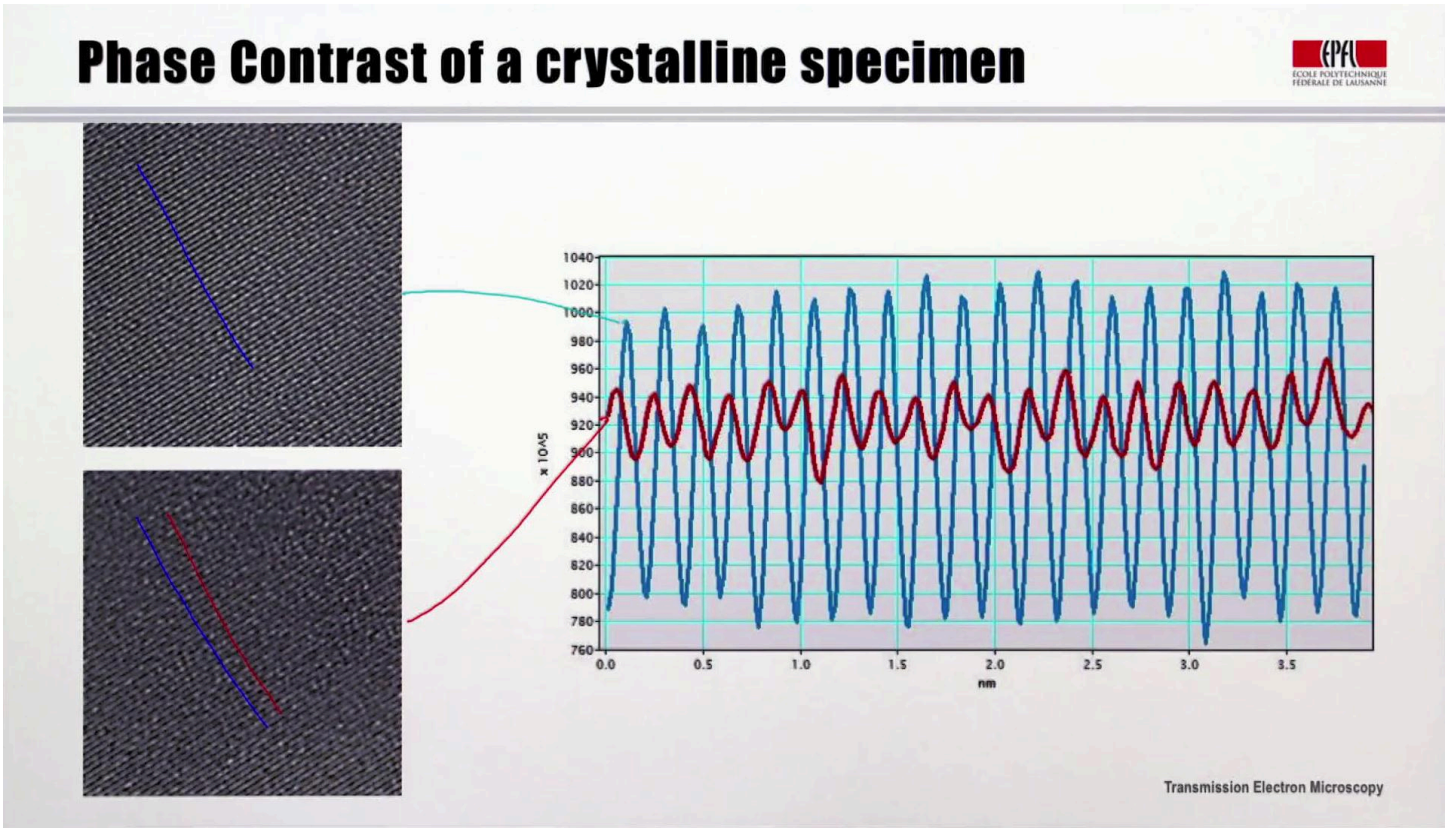


If I enlarge the images you can see much better that the contrast across those lines is better than the contrast across those lines.

Notes

Summary

11m 43s

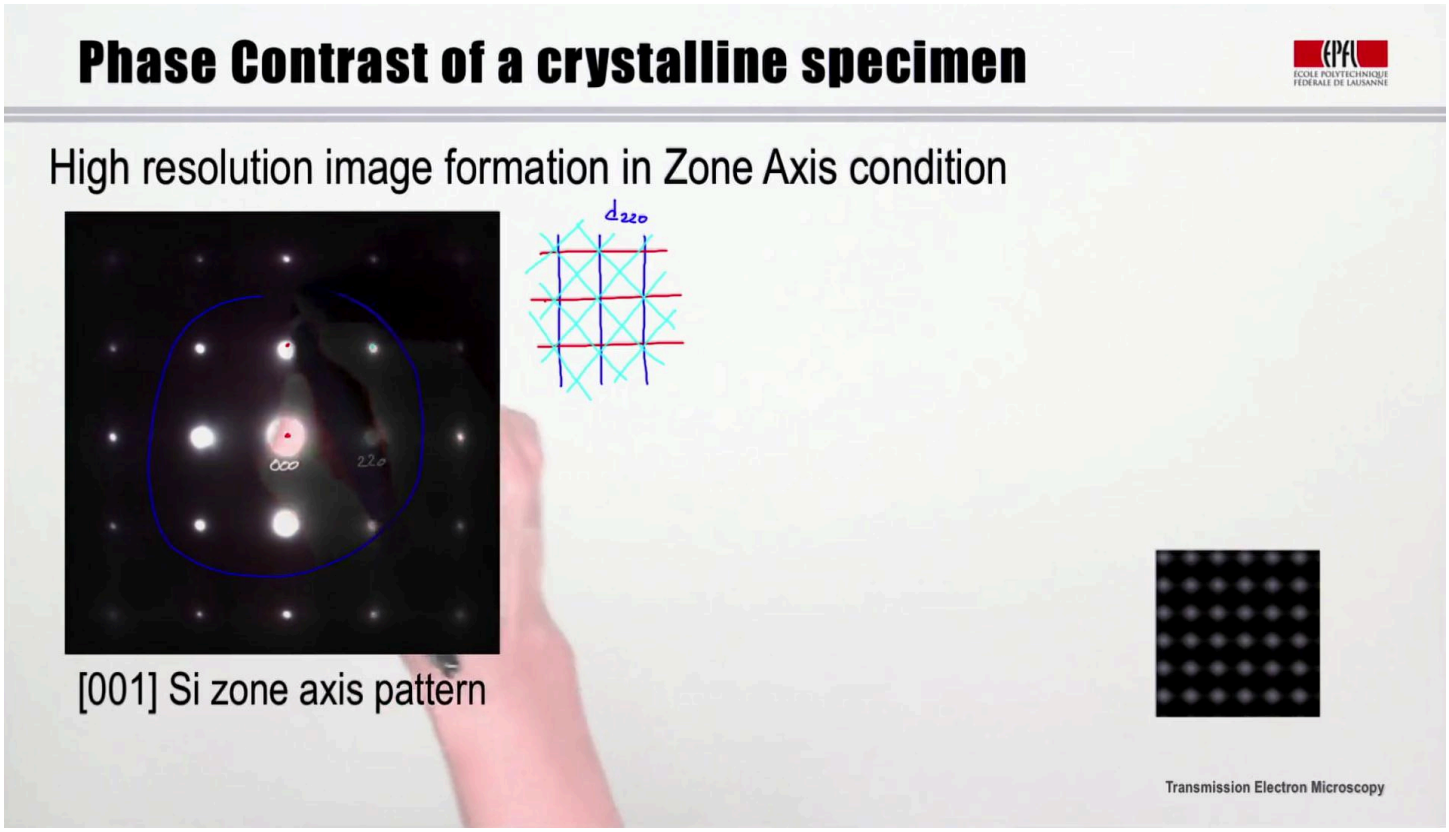


A way to get a quantitative information on contrast is to build a line trace. So, those two traces corresponds to integration of the intensity perpendicular to the lattice planes. The blue one, this one corresponds to the top image where I have the good contrast and the bottom image is corresponding to the red line trace where I have a much lower contrast. With this, we see the connection of the phase contrast transfer function was the transfer of information about lattice distances.

Notes

Summary

12m 00s



The next step is to see the influence of a crystalline specimen when it is oriented in zone axis. So, let's imagine that we have a silicon specimen oriented in the 001 zone axis. The diffraction pattern of such a specimen is shown here and in this case, you have many more beams than just the two beams that we had in the two beam condition. Which means that we will not only have the interference of those two beams but also the interference of those beams, those beams et cetera. If we concentrate on those two beams, we have the same 000 beam as before as well as the 220 beam. They will produce interference fringes which will be at a distance corresponding to this d220, but we also have other spots, and those spots will produce interference fringes at the corresponding distances. If we add all the interferences of all those spots, we will obtain a pattern with the same symmetry as the one of the crystal viewed in the corresponding orientation. Because we need to build the interference pattern between those beams, we have to use a large objective aperture when acquiring a high-resolution image.

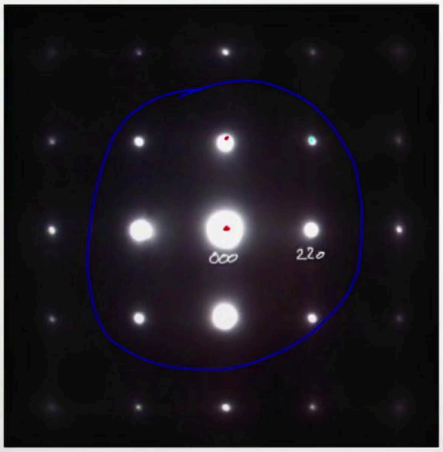
Notes

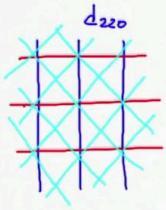
Summary

12m 49s

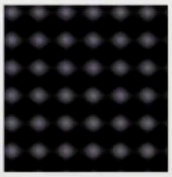
Phase Contrast of a crystalline specimen

High resolution image formation in Zone Axis condition





[001] Si zone axis pattern



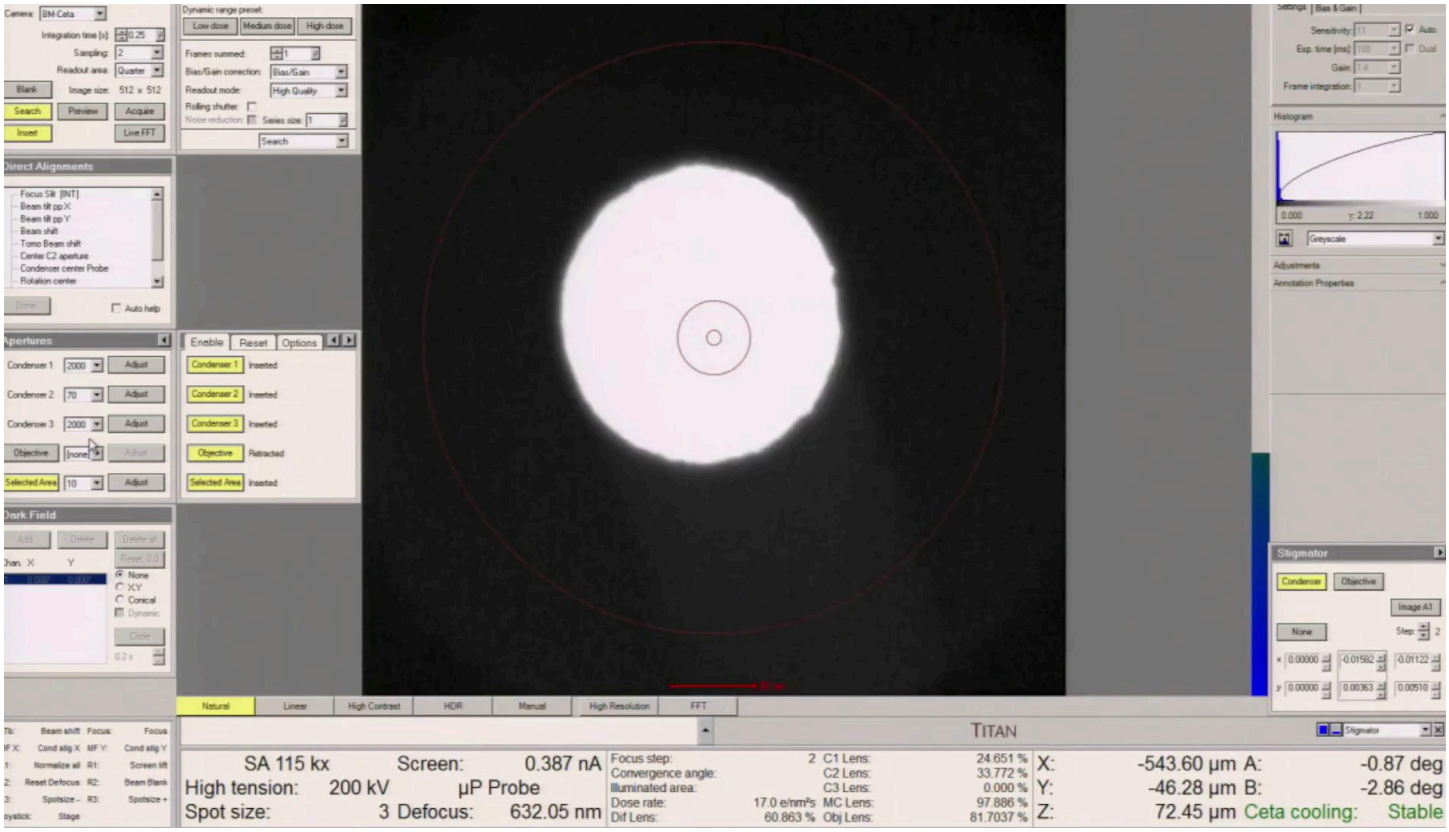
Transmission Electron Microscopy

Now again, we might hope that the image that we will see will resemble this one with very well separated spots where it would be tempting to say that we will see atoms but actually depending on the defocus that we will apply to the objective lens, we will have a change in the phase shift applied to the different diffracted beam and this in turn will completely change the interference pattern that we see. Let's look at this at the TEM.

Notes

Summary

14m 43s

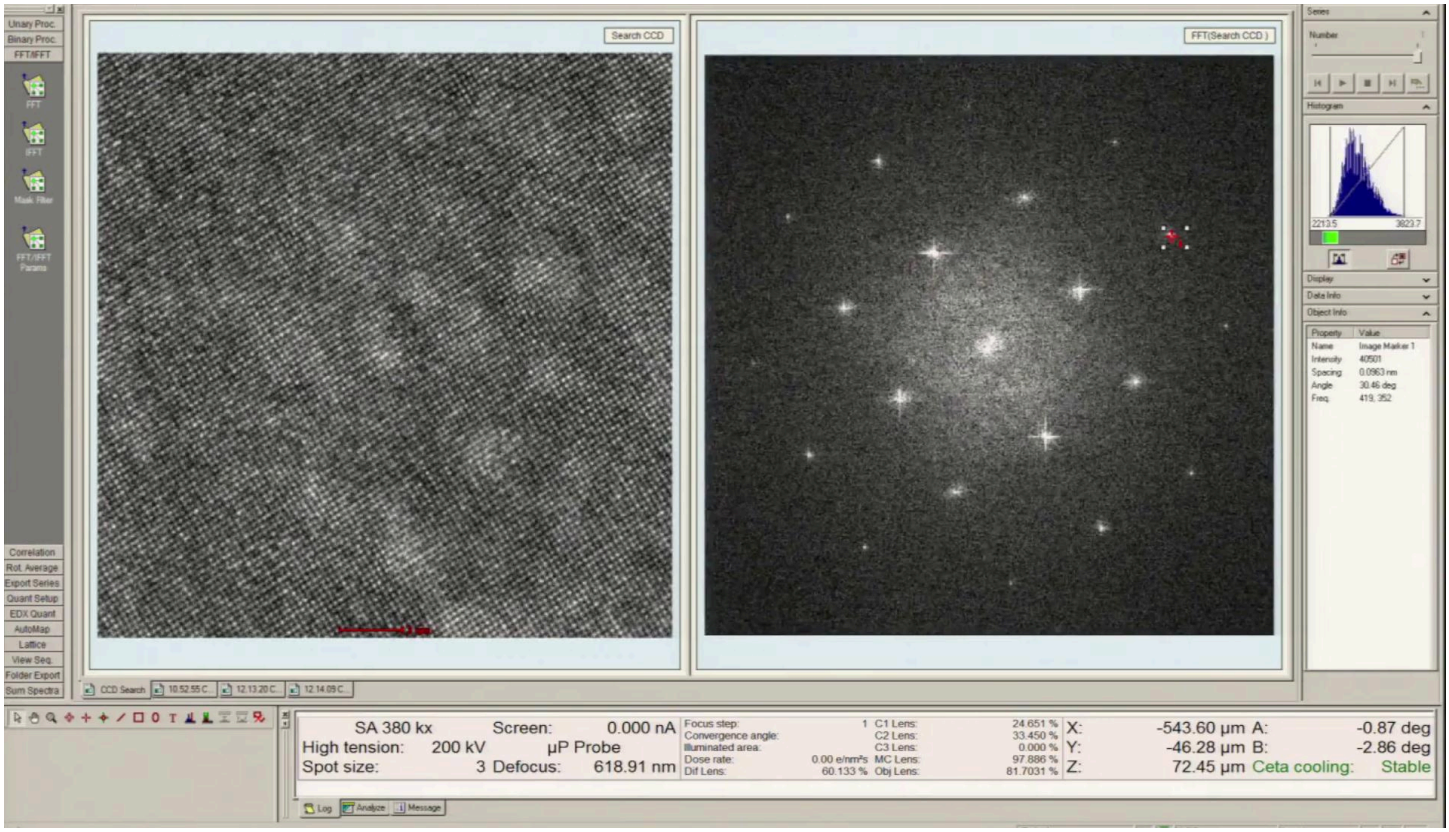


So, I'm taking the same specimen as before. I will check the diffraction pattern, inserting the selected area aperture moving to diffraction, and I see that I am already well oriented in 001 orientation. Moving back to image, I now remove my selected area aperture.

Notes

Summary

15m 21s

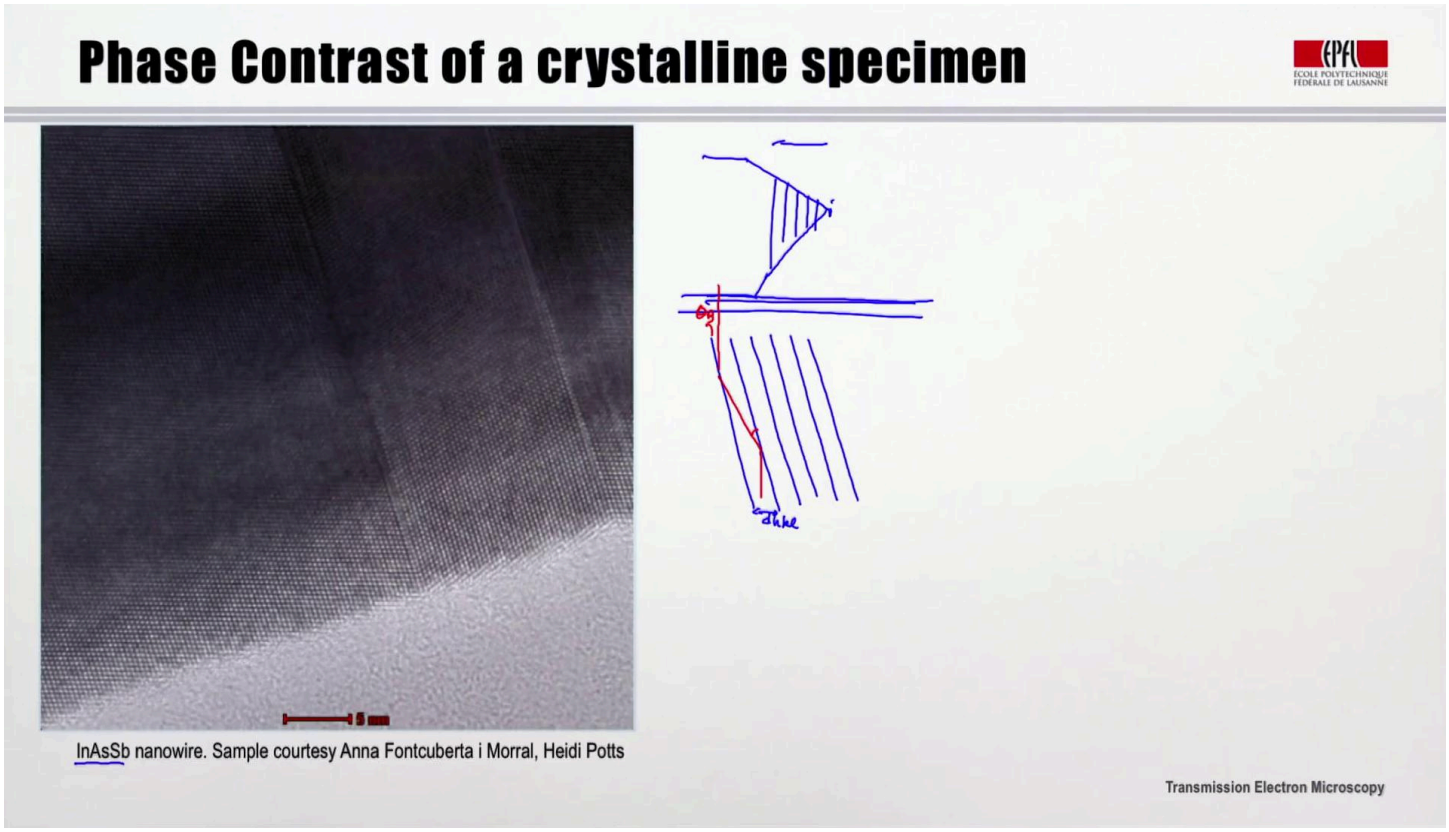


And increasing again the magnification up to 380,000 times moving to the other recording device. So the CCD camera and now I see my high resolution image in zone axis and its Fourier transform which shows the same symmetry as I had in the diffraction pattern.

Notes

Summary

15m 55s

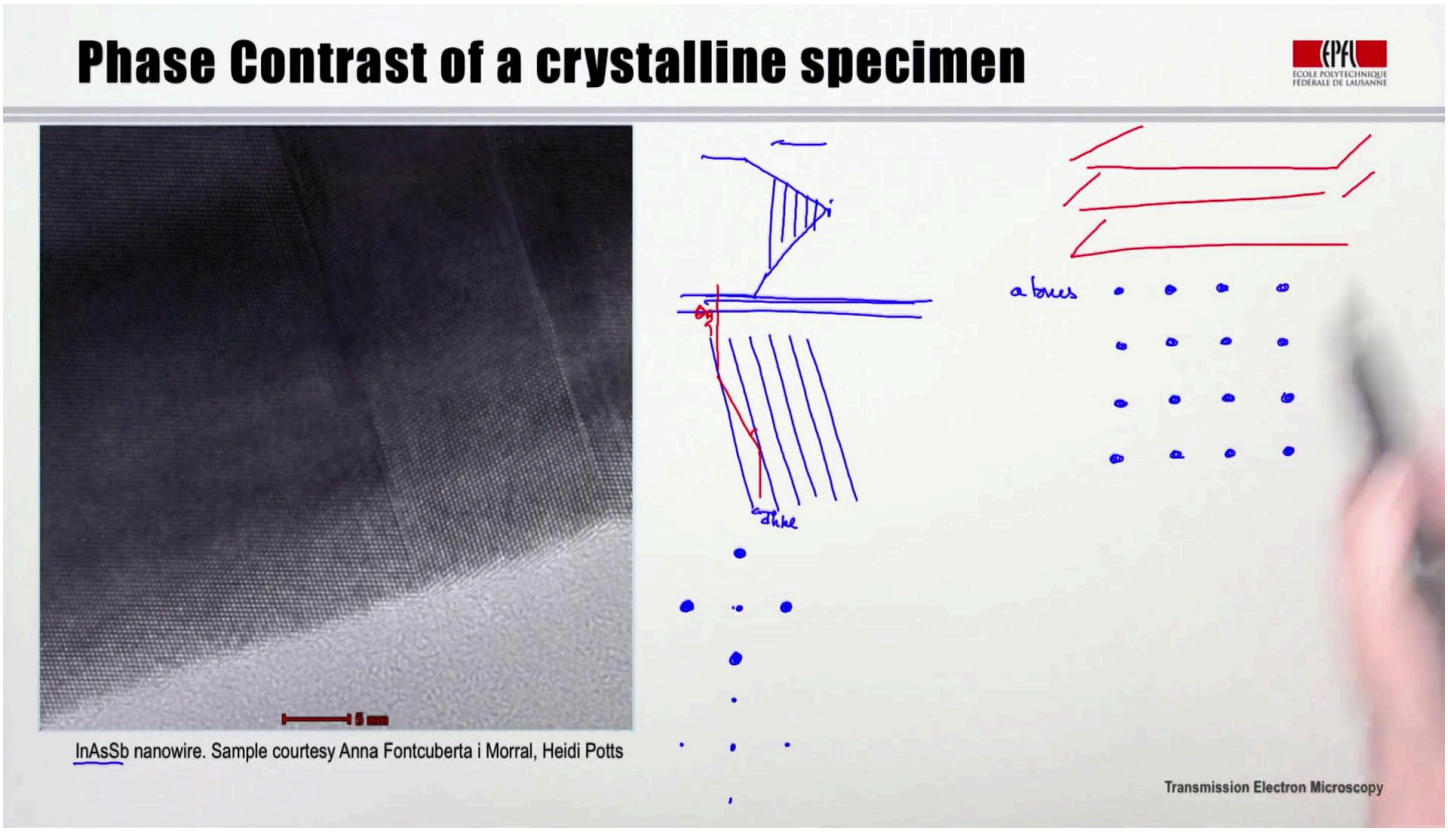


It's time now to come back to the first video that we had in this phase contrast lessons. If you remember well, I showed you the image of this nanowire which is laying on a carbon film. As a remainder the geometry of the specimen is the following: We have this nanowire with hexagonal shape lying on the carbon film, which means that from the side of the specimen towards the center we have a change in thickness. If I change the defocus of the objective lens, I see strong changes in the contrast that I have in this nanowire. But also even in this static image you see that as a function of thickness, the contrast is changing a lot. We will have two way of explaining this. One is to look into the reciprocal space and the other way is to look into the direct space. Let's start with the reciprocal space explanation. If we imagine that we have a thick specimen with the lattice planes drawn here and separated by d, h, k, a, we have the incoming beam that will be diffracted if we are at the right angle theta B. But then this beam can be rediffracted by the next plane or by the next next plane, and this is what we called dynamical effects. You have seen this with Duncan.

Notes

Summary

16m 31s

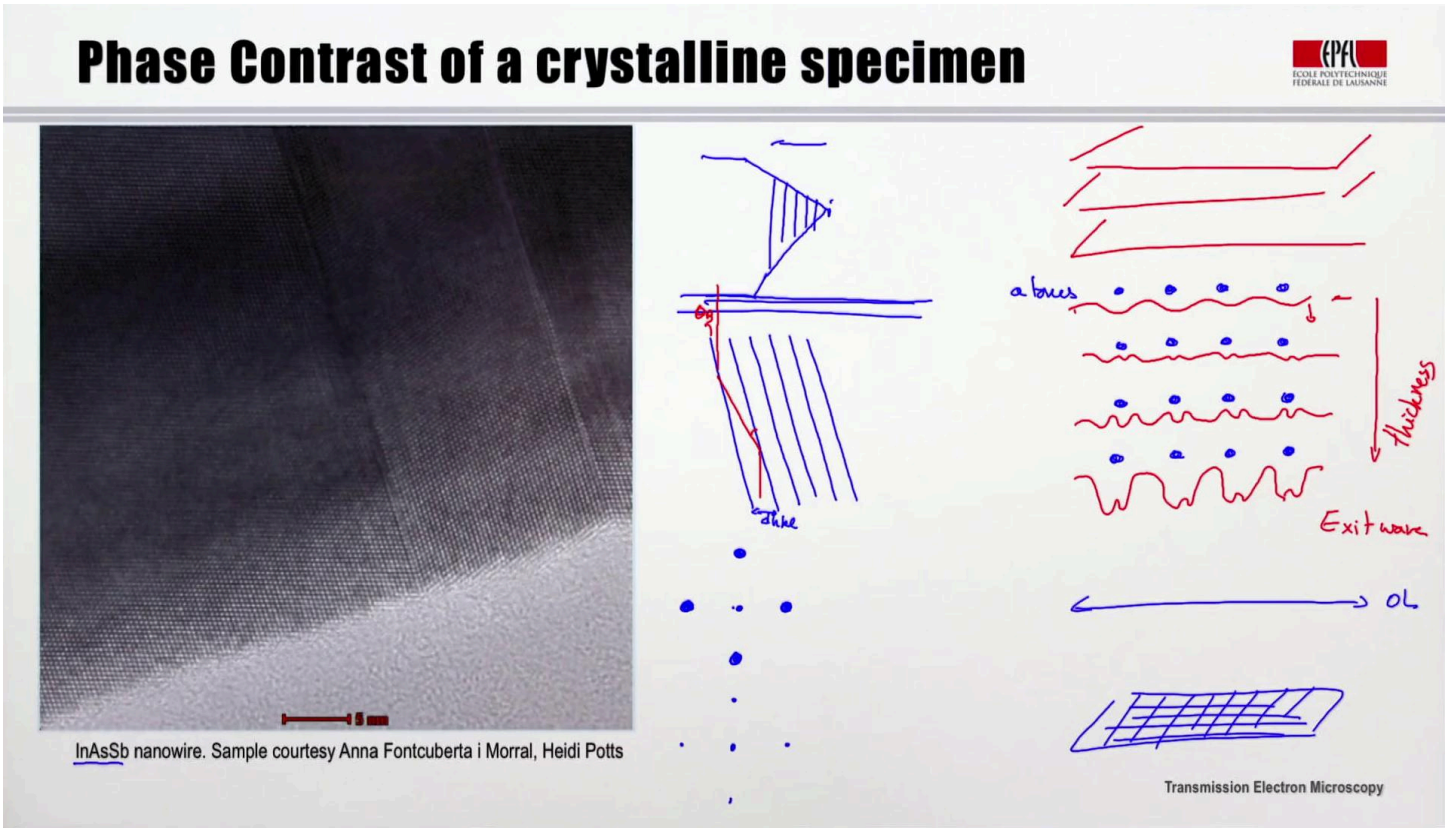


One of the outcome of those dynamical effects is that it will change the intensity that you have in the diffracted spots as a function of the thickness of the specimen. So you can imagine your diffraction pattern, and as you change the thickness of the specimen maybe some diffraction spot will gain more intensity and then at the thinner region they will lose intensity again and your diffraction pattern will look like this and so on. This in turn will have a direct effect on the interference pattern that you see here. If you take into account the propagation of the beam in the complete specimen, but for this you need to know the thickness, then you are able to calculate the exact intensity of the beam and applying the phase shift due to the objective lens, you will be able to calculate how the image looks like as a function of thickness. A second way of thinking of this problem is to imagine that we have the atoms in the specimen and that they are well arranged. This means that we now look at them in the real space, that we think of this periodic arrangement of atoms. Though what we have is a plane wave which arrives on all specimen.

Notes

Summary

18m 36s

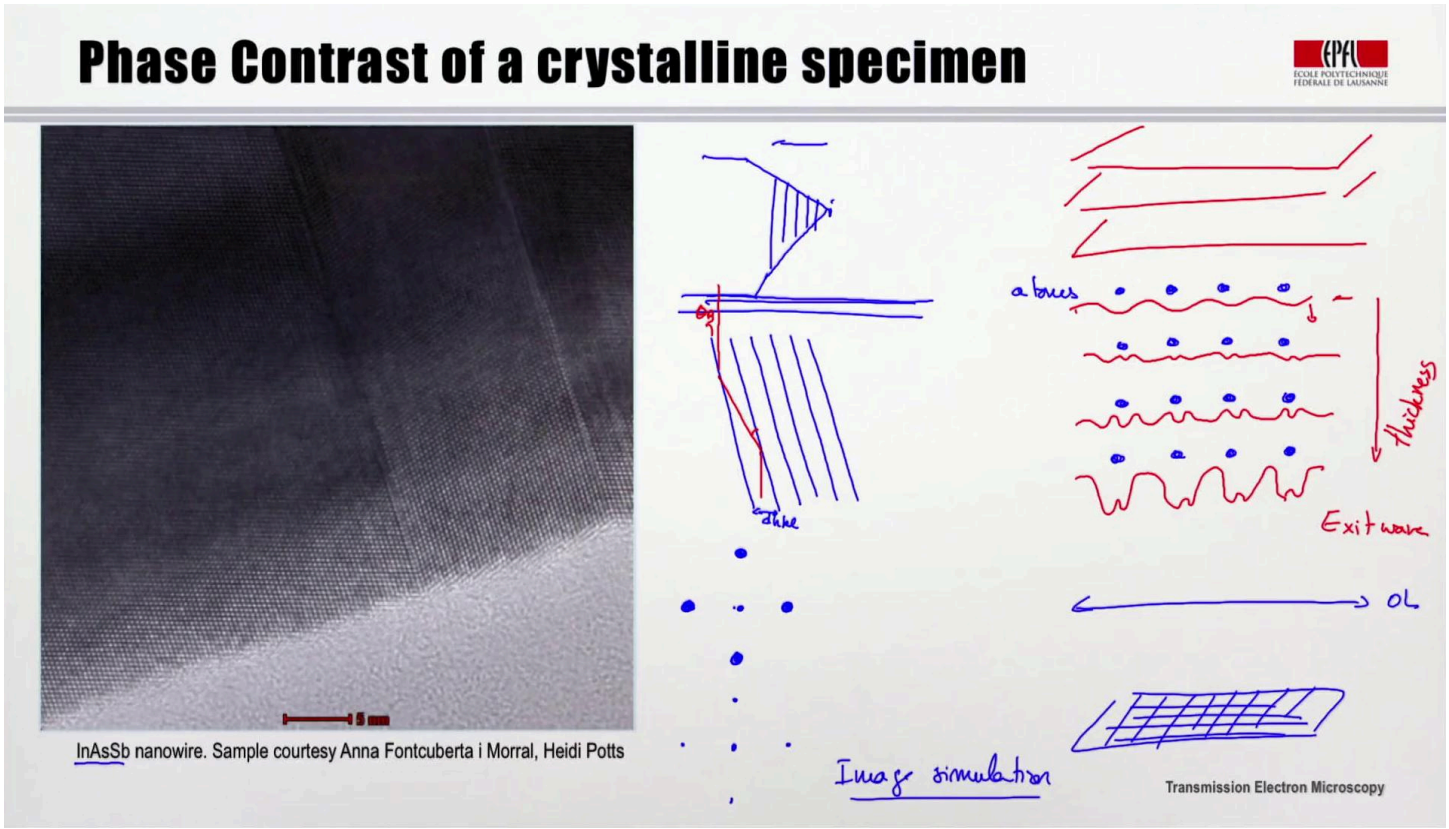


As soon as the plane wave will start to interact with the specimen, we will have phase-shift and they will be periodical because of the periodicity of the specimen. So let's try to draw this. But then this deformed wave will come and see the next atomic layer and this will be again change and maybe in a different way, and so on. Then the next layer, and then the next layer again maybe looks like this. This is just a schematic. It is clear that as the thickness of the specimen changes, this wave front will be changed and changed continuously. At the end when I reach the end of the specimen, I have my so-called exit wave. And this exit wave that will be taken by the objective lens and then convoluted by the point spread function. At the end I will finally have this convolution product between the exit wave and the point spread function, and this is what I will detect on my detector. Again, in both approach the important thing is that it is evidenced that the thickness of the specimen will have a very strong influence on the image that I will record. Basically that means that I have two options if I wanted to do high-resolution images.

Notes

Summary

20m 33s

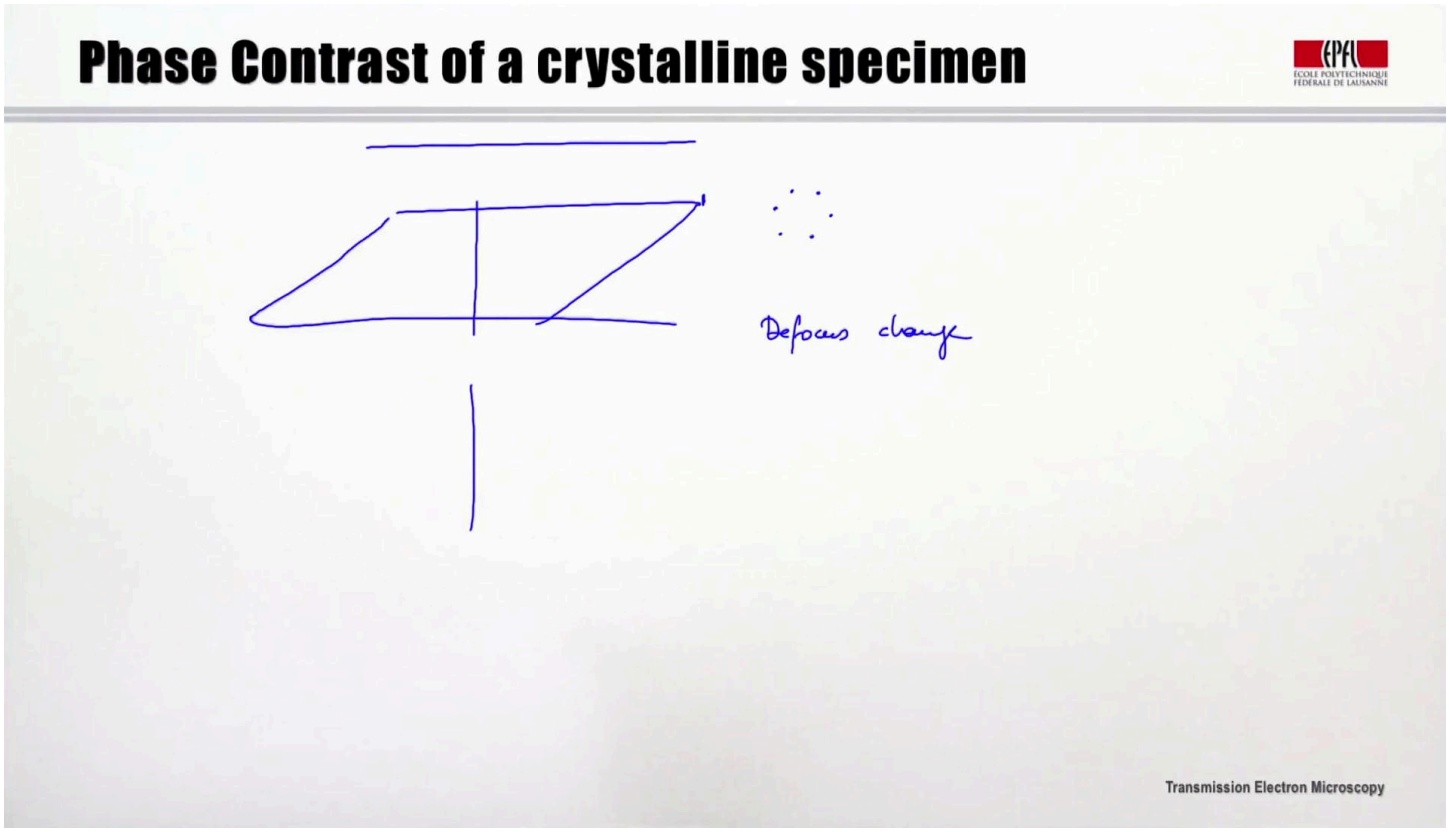


The first one is to use extremely thin specimen so that I can avoid this multiple scattering or the second option is that I will def forms an image simulation to be able to compare my simulated image with the experimental one. Image simulation can be for example done with the gems software that you have seen to plot the phase contrast transfer function.

Notes

Summary

22m 39s



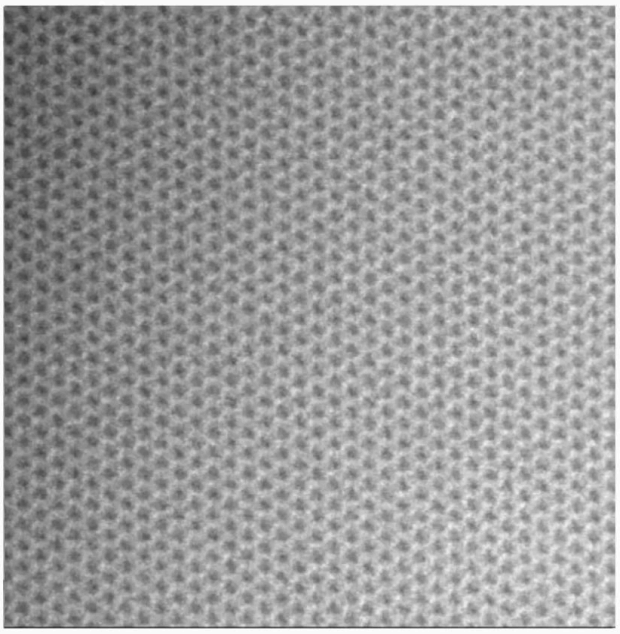
But even if I have a very thin crystalline specimen, the effect of the aberrations of the microscope is very strong on the image. So in the next slide I will show you the image of an extremely thin graphene layer. So it's a mono layer of carbon atoms organized in a hexagonal pattern. When it's illuminated by the plane wave of the microscope, imaged with a CS corrected machine and only changing the defocus of the objective lens. So let's look at this specimen.

Notes

Summary

23m 13s

Phase Contrast of a crystalline specimen



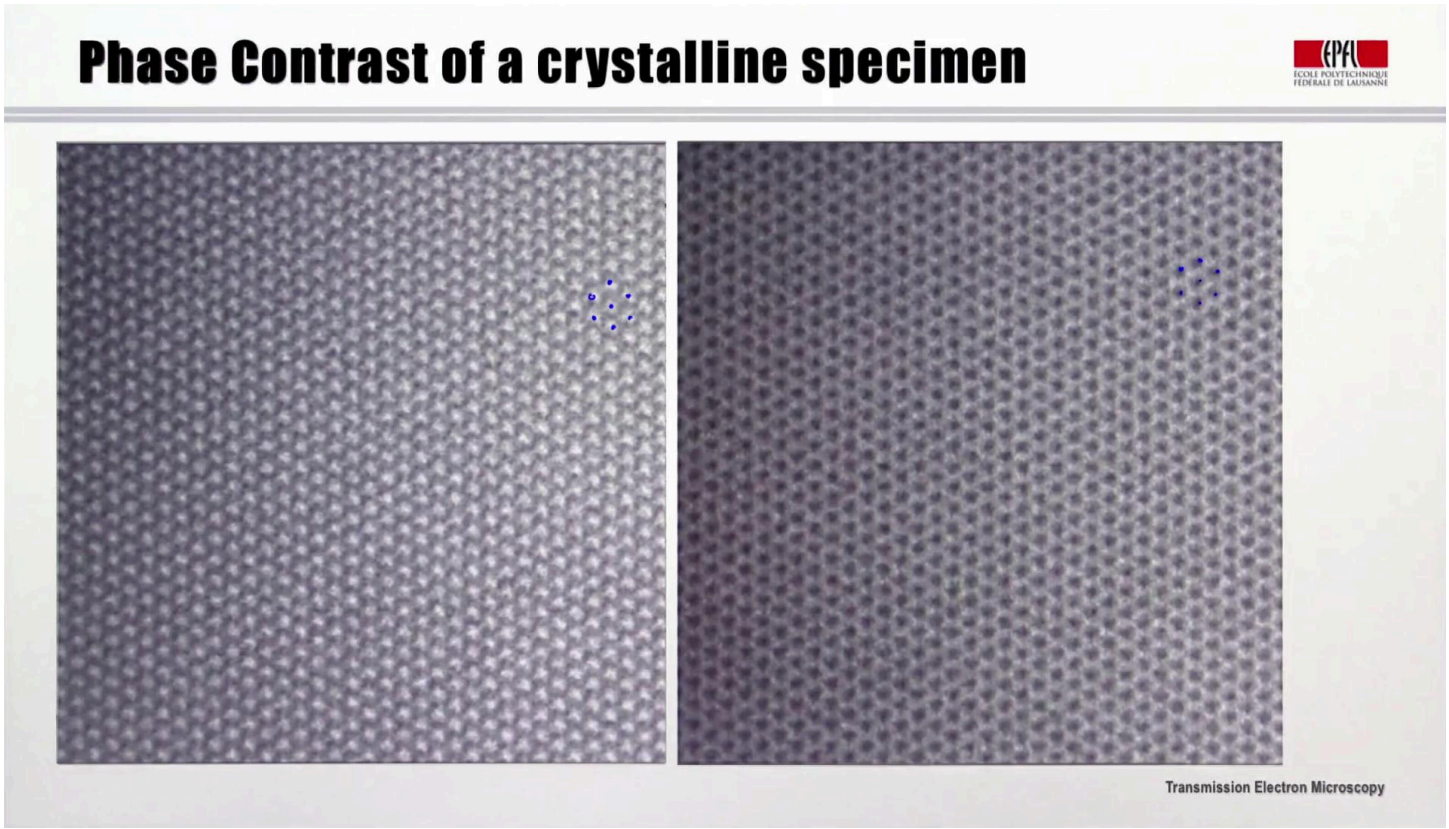
Transmission Electron Microscopy

Here we have our specimen and you clearly see the hexagonal pattern with the symmetry of this graphene layer. Now if I start to change the defocus you see how the contrast is changing, passing through a minimum contrast and moving from white atoms to black atoms. Since I have a CS corrected machine, the no contrast corresponds to the perfect in-focus of the objective lens where the phase contrast is 0.

Notes

Summary

24m 04s



You have here a nice comparison of the two images acquired under the different condition where you clearly see this contrast reversal between there, the white dots and on the other sides the black dots.

Notes

Summary

24m 56s

Conclusion

Okay. With this you have got an understanding of the influence of the microscope and the influence of the crystal on the formation of a high resolution transmission electron microscopy image. The take-home message is really that what you see in that case is an interference pattern at not the projection of atoms scene from a special viewing angle.

Notes

Summary

25m 17s