Advanced Material Characterization by Atom Probe Tomography and ElectronMicroscopy

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Week-11

Lecture-35

So welcome to this class. Now, as in the last class, we just introduced the extraction of electrons from a metal surface, usually tungsten or lanthanum hexaboride. Tungsten is used for thermionic sources and also for the FEG, which is a field emission source. So, as in the last class, we talked about the field emission sources. So here, the advantage of a field emission source is its very high brightness, which is around 10 raised to the power 13. It needs a couple of anodes to extract the electrons from the surface, and also the energy spread is less than 0.5 electron volt.

This is very low compared to the 1 to 2 electron volts for thermionic sources. This will have a direct consequence on the resolution of the electron microscope. Remember, we have talked about the variation of lambda in optical microscopes with light. So here, that lambda is directly related to your energy spread. Correct. So here, it is less than 0.5 electron volt. Okay, so now

What we do is first, we have now generated the electrons and accelerated them. Correct? Now, these electrons actually have to be accelerated much faster with a velocity across the column. Correct? For doing that, we use a certain number of lenses, which are called electromagnetic lenses.

Okay? So, these electromagnetic lenses are very important for acceleration and also for deflection. Okay, so the deflection of electrons is very important when these electrons travel across the column. So, these electromagnetic lenses in electron microscopes can be used to focus the electrons into a small probe, as small as 1 nanometer.

to produce an electron image of the specimen. So, these focused electrons are used to image the specimen. So, this electromagnetic lens consists of coils. So, this is called a cross-section of a lens. Okay? So, usually the lens is a cylinder which has a small hole at the center.

Okay, and if you cross-section it, then you will see this cross-section as it is. And this coil consists of a large number of wire turns. And this particular wire is made of copper. And it is wound on a soft iron core, which is also called a pole piece. Okay, and there is a very small gap.

So, this is called a gap, a very small gap across which you can generate the field. These are the field lines while passing the current through the copper coil. So, this field is generated by the principle of electromagnetic induction. Correct? So, the force can be given by this particular equation.

E is the charge. B is the magnetic field strength, and V is the velocity. Correct? So, if you zoom out this particular region, you have a magnetic field direction. These are magnetic field directions which are neither horizontal nor vertical.

Due to this, it has certain resultant components: the vertical component is called B-axial, and the radial component is called B-radial, depending upon the electron travel trajectory or the electron movement direction. Either B-axial will come into play or B-radial will come into play; in certain regions, both come into play, applying a force on that particular electron depending upon its direction. So, this particular force is called the Lorentz force, and this Lorentz force is created by

The experience of the electron by the electric and magnetic field, and due to this Lorentz force, there will be a deflection, which is the physical basis of any electron lens. Okay, and this deflection process while the electron travels across the column, then usually these are used to focus the electron beam, okay? And these magnetic lenses are preferred because they create low aberrations. Now, to understand it better, when you do not apply any electric field, usually the F is a vector normal to velocity and the magnetic field, which are inclined to one another at an angle phi, given by this particular equation.

So, to understand in a simple system, the direction of force acting on a moving electron in a magnetic field. So, consider that the electron is moving in a magnetic field B. This is your electron. It moves in a magnetic field B in this particular direction. And the force on the electron can be given by E cross B cross V, E into B cross V. And this force is

As per the rule, this force is applied in a direction perpendicular to both the direction of motion and the magnetic field B. Okay? So, the force direction is perpendicular to the motion, the velocity direction, and also the magnetic field. So, as the electron enters the lens, it experiences a magnetic field B. If we consider the electron is lying at this position and it experiences a magnetic field B, which can be resolved into two components: B axial and B radial. Now, you can see that the electron direction is downward.

And your B axial component is parallel to this direction. It means that it is at an angle of 180 degrees. So your sign, if you take B cross B cross V, the force will be 0 in the axial direction. But the B radial direction is perpendicular to the motion of this particular electron. So you will have a force which is

exerted by or created by the B radial direction. And due to that force, the electron will deflect in this particular direction; the electron will try to deflect. Okay, so initially, the electron is unaffected by the B axial because it is parallel to the direction of travel, but it experiences a B radial. Okay, of magnitude B radial EV because it is 90 degrees, sin 90, okay? From small, so it generates a small radial component B radial, which exerts a force, and this force causes the electron to travel in a helical manner.

The electron will travel in a helical manner along the lens. As soon as it spirals, it has a component of velocity which is V circumference. which we also call V radial. So you can see that the velocity direction is perpendicular, lateral, like along the field, but as this force is applied, the electron actually moves in a helical pattern and it has a velocity component which is in the mode of V circumference, and due to this V circumference, the V axial component will also get activated, and it will have another force.

which is related to B axial EV circumference in the radial direction. So this is how you can see that as the electron moves, your force direction also changes along with the movement of that particular electron. And what will happen is this helical path gets tighter and tighter and you will get a very sharp spot of the electron beam. So this is how the electron beam is focused by using these electromagnetic lenses. So the parallel beam of electrons which are entering the lenses converge to a singular point.

It is similar to the lens which uses light to focus to a certain point. Correct? So in magnetic lenses These extends over a short distance along the axis. So in thin lens we can apply for the it is similar to the thin lenses.

So your magnetic field should have a optimum value of strength and that size and shape. So that it will apply the magnetic field homogeneously across the across the circumference of the column. And this can be tuned by the current which is passing through the coils or the copper wires. So the magnetic field strength and the focal length can be varied by controlling the current which is passed through these copper coils.

So this is how we achieve the focused electron beam in any microscope. Okay, so this is different from a light microscope where the light is spread. Okay, and this magnetic field is also used to deflect the entire beam of electrons. So you can use these coils, or there are different coils. It is not only about the function related to the focusing of the point.

Usually, these electromagnetic coils can also be used to deflect the beam. Okay, and also it can be used for scanning. Scanning the beam, especially in the SEM. Now here, this is one cross section. It is a very nice image where you can see that this is your magnetic lens.

This is your soft iron pole piece. These are the coils. You can see that the electron travels along this green axis and accelerates along the column. And it is nothing but you are using your light and there is a lens. There is a glass lens, and that particular part is focused.

Okay, now, if you assume this in an optical system, you can actually visualize it properly by placing these electromagnetic coils in the place of a lens. It exactly resembles a lens here. What is the function? And this is how you can actually visualize in an optical system where, if you use this electromagnetic lens, you are actually doing the same thing as light focusing, and you are focusing the electron beam by using the electromagnetic lenses.

This is just to visualize. Now, this is the typical electromagnetic lens. Okay, you can see that there are two points here. These are water-cooled because, as current passes through the copper coil, it generates a large amount of heat, and that heat has to be extracted. So, these are always water-cooled, chilled water-cooled, and you can see these are the knobs.

Where you can see that these relate to the passing of the current across these copper coils. Correct? So, a real lens is cylindrical in shape. It conceals the copper wire coils inside this. So, the copper windings will be like this.

Across the thickness. Okay? And the two conical pole pieces beside the lens sits inside the central hole. So, you will have a pole piece here. So, these are called pole piece and the three pin electrical connections provide current to the coil to magnetize the pole pieces and the cooling water is circulated in and out of the two holes

which I have shown here the two holes of the top plate of the lens to dissipate the resistive heat generated in the coils and this heat dissipation is very important because depending upon the heat dissipation rate it actually controls the it also affects the current in the copper coils and hence the magnetic field which is induced in the column okay. So here I am showing you just a difference between the thermo ionic emission source and the field emission sources. So, you can see that it is just a revision that in thermionic sources you have a heated filament which is a cathode,

there is a walnut cap, anode, there is a resistance heating and the tungsten and laxation large energy spread in thermionic sources. But in Schottky emission thermal effects where you use the tungsten tip typically of radius of 15 nanometers, these are coated with zirconium oxide, there is an anode. And you induce a very high electric field which cause emit of the energy electrons. Now, Fermi energy. So, tungsten has a lower Fermi energy and cathode is operated at 1800 Kelvin.

So, here also, you are increasing the temperature, but you are using the electric field. Not the bias voltage, so that you are generating—you can actually extract the electrons—and brightness is three orders of magnitude. Energy spread is around 0.6 to 0.8 electron volts. Nowadays, the new advanced systems have cold FEGs, so these are thermal FEGs where the temperature has to go up to 1800 Kelvin. Here also, you are using the tungsten tip.

Okay? And you can see that it is on the same basic principle: you need to generate a high electric field.

But here, you do not have to put the cathode at a high temperature. It can be done at room temperature. So your brightness is three orders of magnitude higher, and also the energy spread is much lower, which is 0.3 electron volts. Okay? So this is just a comparison of the type of source.

Cathode material and all the parameters are very important to select for a particular type of imaging in an electron microscope. So this is your comparison with the tungsten source, thermionic, LaB6 thermionic, thermal FEG, and the cold FEG source. The important takeaway here is the work function. And also the operating temperature here—you can see that at a very low temperature, at room temperature, you can get very high brightness. And one more important term is the coherence.

I will describe this coherence now. So, you can see that the coherence of the beam is very important. It is the lowest in thermionic sources and the highest at high temperatures. This is very important for high-resolution imaging using the cold field emission gun. So now, coming to coherence.

Why is coherence important? So, the coherence of the electron beam is very important when you want resolution. So, what is coherence here? Coherence of an electron source reflects the phase difference in the emitted beam, and thus it determines the degree of interference that can occur between the direct and diffracted waves.

So, it means that two waves are coherent when they have a constant relative phase or when they have a zero or constant phase difference and the same frequency. Based on coherence, there are two important types of coherence to understand, which are called spatial coherence and temporal coherence. Spatial coherence is related to position. Temporal coherence is time, related to your time. Okay?

Spatial coherence—what is spatial coherence? It is nothing but all the electrons. If you have a tungsten needle, all the electrons should come from the same direction. So, if an electron comes in this direction from this region, and if another electron comes in this direction, they induce a spread or a blurred image. So, electrons coming from here and here will induce a blurred image.

So, how does it happen? It happens when the electrons originate from different places on the tungsten tip. So, by the time these tungsten tips are used, this is actually destructive, correct? So, this gets blunted. So, if your tungsten source is blunted here, and electrons are accelerated from here and here, they will not form a perfect image.

They will form a blurred image. This means that all the electrons should come from the same position. So, the origin of electrons on the source—different locations of the source, different directions. So, it creates an image at different position of the image plane. So, your image plane will not change, but it creates an image at different locations.

This will create a DC, which is the effective source size, which depends upon the alpha angle at the source, which is given by lambda by 2 alpha. Similarly, the temporal coherence. What is temporal coherence here? All beams... should have the same speed from the source.

For example, if your source From the source, if you have one electron beam which is accelerated with 300 kV, one electron beam which is accelerated at 302 kV, what will happen is the image is formed at here, but for this 302 electron kV, the image form will be at a different plane. So, you will get the blurred spots as a blurred image. They will not be focused at a same place.

They will be at a different planes. So all the electrons should come out of same energy. So if it is a 300 kV, if it is a 302 kV, this particular electron will have a low speed. This particular electron will have a high speed. And you know that with this relation, it will have a direct consequence on the image formation at different planes.

So this we call as a temporal coherence. So here the speed of electrons from the source. So it is not from the position. From the same position if the speed of electrons is different then it will have this temporal coherence. And different energies at different focal points at different planes and create image at different planes which is given by so usually it is by lambda C VH divided by delta I where V is the electron velocity. So, these are the two types of coherence which are very important to choose which type of source you are using in an electron microscope. Just for repeat spatial coherence it is related to the position, temporal coherence it is related to the time or the speed with the same energy. This is called temporal coherence. Now, in the ideal electron microscopes.

You will in the ideal you will have a point like monochromatic source. So there will be a no chromatic operation. So the energy spread delta is almost equal to zero. So your electron does not have any energy spread and the source is fully coherent. These are the ideal electron microscopes which is not possible.

So in real EMs, electron microscopes, depending upon the source used—thermionic sources or field emission sources—you will have an electron source that has a finite size. There is an energy variation, which is delta E, and it is not zero. There is a certain energy spread. And the source is partially spatially coherent and temporally coherent. They have both spatial coherence and temporal coherence issues with these real EMs when using thermionic sources.

By using field emission sources, you will have very high spatial coherence, which is related to your position due to the very small source size. So, you will have a tip size that is around almost 10 nanometers. So, it is a very sharp tip. It is a very small tip, and your energy variation is minimized at 0.3 electron volts. Okay, so based on this, what we can see—if you observe any FEG source, as I told you—these are the

warm and cold. Cold at room temperature, the electric field induces the electron tunneling process. Warm, the temperature has to reach 1800 Kelvin, and these are thermally activated effects. So, here this is a typical probe size, okay? As I told you, depending upon the coherence—spatial coherence—the actual beam diameter results from the diameter of the original beam leaving the electron gun, which is dg.

And due to several factors related to the electromagnetic lenses and other aberrations, you will have an effect of spherical aberration which is related to ds. There is diffraction at the aperture which is related to dd. And this depends on the current I, convergence angle alpha, brightness B, spherical aberration coefficient CS, and the wavelength l. So, your total d, the total beam diameter, is given by the square root of ds squared, dg squared, and dd squared. Okay.

So, this is your final beam diameter. Okay, so with this, I will end this class now. So, we have described the importance of different types of sources which are used to extract the electrons for imaging purposes. We also went through the coherency and its effect on probe size. And in the next class, we will talk about how the electron and the matter interact and what type of signals

we get in the transmission electron microscope and how these signals are used for specific characterization purposes. Thank you.