Techniques of Materials Characterization

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Lecture – 14
Electron-Material Interaction

Welcome everyone to this NPTEL online certification course on techniques of materials characterization. We are in the third week and we were discussing about general concepts of electron microscopy. So, we have discussed so far about the history of electron microscopy and then the relationship between acceleration voltage and electron wavelength and so on and then how the electrons are generated from an electron gun.

And then in the last class we discussed about the electromagnetic lenses, scanning coils and so on and how those all those components of electron microscopy are used in order to reduce the aberration of electron microscope. So, now today we will be discussing about the electron-material interaction. And let me tell you the electron-material interaction is possibly the most important part of this entire subject of electron microscopy.

Because this is the heart of the electron microscopy, electron-material interaction. And we will be discussing here some of the general concepts which are mostly applicable to transmission electron microscopes and we will just do a few discussion about other kinds of interactions which are important mostly for scanning electron microscope. But, we will discuss about those interactions which belongs to scanning electron microscopy during our discussion about scanning electron microscopes.

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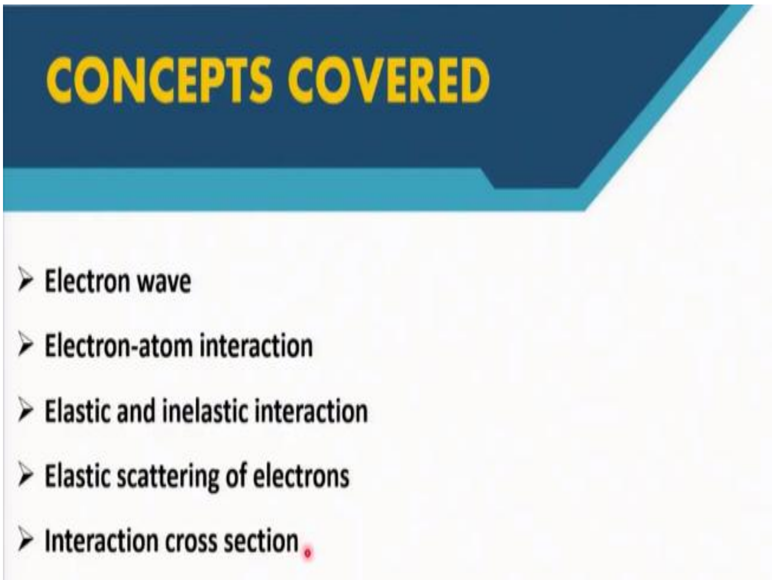

So, the concepts we will be covering today is like electron wave first thing and then electron-atom interaction, about elastic and inelastic scan interaction, these are the two different types of interactions possible. Then elastic scattering of electrons and interaction cross section. This is what the concepts we will be trying to cover today.

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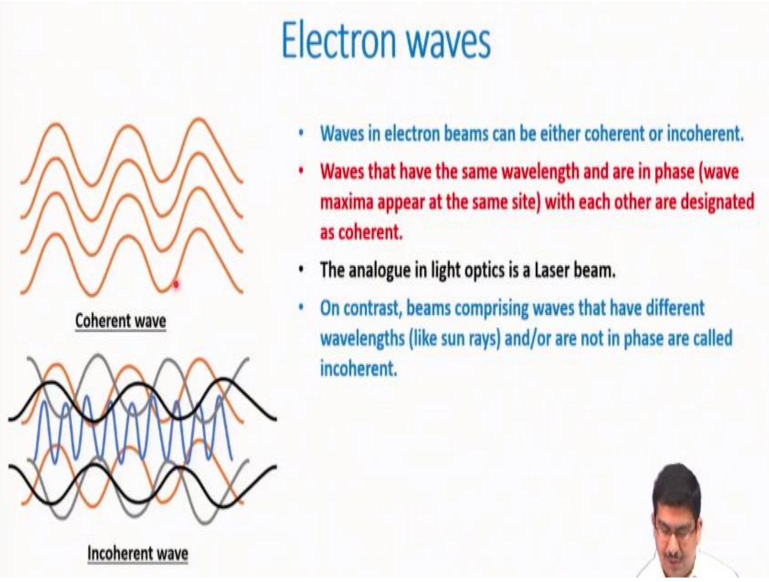

So, first thing is of course the electron waves. As I said these are like very basic concepts which can be applied to any kind of waves and electrons have a dual nature and they can be considered as particle sometime, they can be considered as waves sometime. Right now, we will be mostly considering them as waves and we will be seeing that what different kinds of electron beams can be.

So, let us consider all the electron waves in one electron beam, they can be either coherent or incoherent. So, what is basically means by these two terms coherent and incoherent. So, in case of a coherent wave the waves are all in phase that is what is very important. So, they are mostly all in having the same wavelength. Electrons with the same wavelength and same phase that are called coherent beams.

And most of the times they will have the same their amplitude also maybe sometimes the same. So, this kind of electron waves when an electron beam contains this kind of electron waves which are all in phase having the same wavelength all are in phase wave maxima appear in the same side, they are called the coherent electron beam. The analog to this in a light optics is basically a laser beam.

Then we have also called something called incoherent wave. So, incoherent wave the all the waves, all the electrons which are present within the beam they are either have different wavelengths and or are different phase altogether and these are called the incoherent waves, mostly like sunrays or white light for example or already we know that when we have thermionic guns mostly we produce these kind of waves, incoherent waves. Compared to that, when we have a FEG electron source, we have mostly coherent waves.

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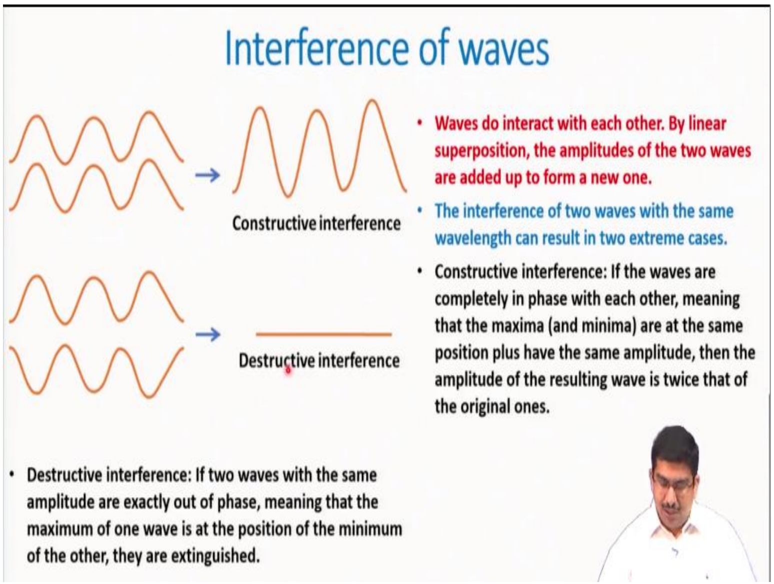

Of course, another thing to consider is the interference of this waves. So, there are two types of interference possible. So, waves when they interact with each other, there is a linear superposition of the amplitudes of two waves and that will give us a completely new wavelength of waves altogether. So, the interference of two waves there can be completely two extreme cases.

One is the constructive interference and in constructive interference what happens is that you will start with the coherent waves the two waves which has exactly the same phase which are in phase to each other. That means that their minima and maxima will appear at the same position and most often they also have the same amplitude. Then the resultant wave will have an amplitude which is twice than that of the original two waves.

So, just linearly you can add their amplitudes. They are completely in phase. Of course, a completely reverse situation is the destructive interference when the two waves are maybe of the same amplitude and they are exactly out of phase. So, that means the maxima of one is corresponding to the minima of the other and what will happen is that the resultant wave will not have any amplitude.

So, it will be completely zero, this is called destructive interference. So, most often anything in between these two extreme situations depending on the phase relationship between two waves, there can be either constructive interference at places or there can be destructive interference at places. These are the two extreme cases which are possible.

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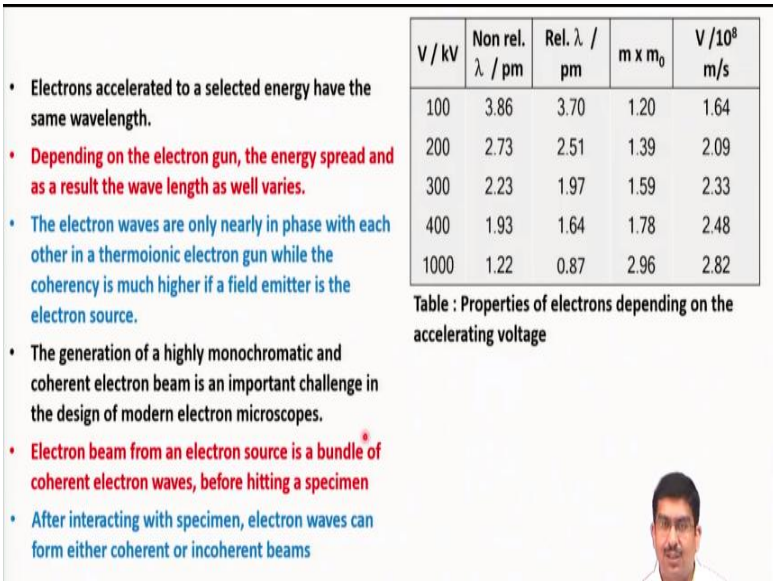

So, as I already said the electrons these are accelerated to some selected energy, they have the same wavelength and this is the table; again we have discussed about this table. Depending on the acceleration voltage, the electrons will have different type of wavelengths possible depending on the relativistic correction if you do or if you do not do relativistic correction.

We also discuss the importance of relativistic correction when we are working something like 200 to 300 kV which is typically used for transmission electron microscope. The reflective relativistic correction becomes really important and that is why when we work with a field emission gun, we are basically generating mostly a coherent electron beam. With a thermionic emission we generally do not get that kind of a coherent beam.

But if we consider that for all practical purposes, we are working with a FEG source, then the electron source will produce a bundle of coherent electron beam which will be hitting the specimen ultimately, we can imagine that. And after interacting the specimen, now this is what we are going to discuss today. So, until up to now we were discussing about mostly the electrons which are or how to produce the electron beam or how to work with the electron beam.

And now today we will be discussing that what will happen after the beam hits the specimen and interacts the specimen. It will either produce a coherent or incoherent electron beam depending on the kind of interaction it will have with the atoms in the beam itself.

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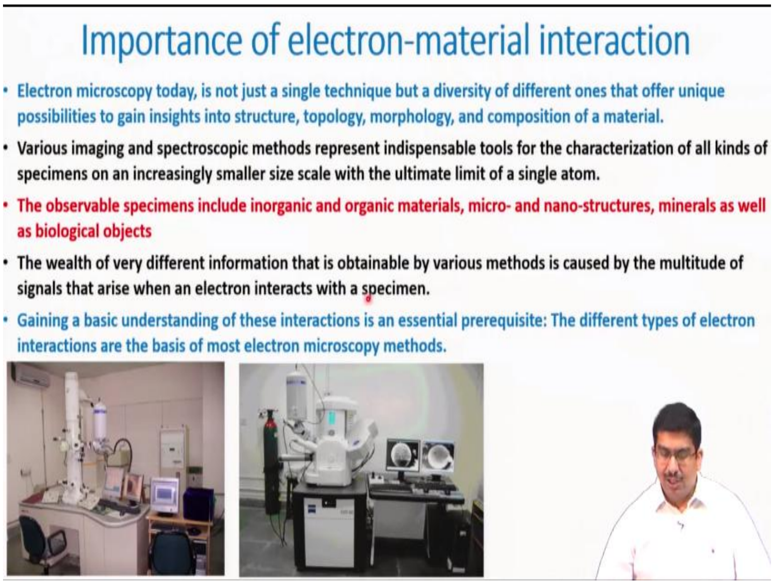

So, now as I said this electron material interaction is basically the heart of the electron microscope and that is because that interaction produces many different types of signals.

It is not only one type of signal that is produced by this unlike any other microscope for example if you simply think about optical microscope, there is only one type of signal. The light goes and then light passes through the specimen and finally you capture the light and see the contrast formation.

In this case, it is not one single detection or one single detection signal that is generated from this electron-material interaction, various different types of interactions happens and various different types of signals will be produced. And those signals will carry various type of information about the material. For example, you can get information about the crystal structure of the material.

You can get information about the morphology of the material surface morphology, you can get internal structure of the material and even you can get the composition of the materials, elemental composition of the material, you can obtain this. That means the electron microscope can be used both for imaging as well as the spectroscopy. So, this is the uniqueness of an electron microscopy.

This is one single characterization technique and within that you have all different types; you have the chemical composition analysis possibility, you can get the crystal structure, you can simply use it for imaging. For example, I often tell this to my students to tell them to show them how diverse an electron microscopy can be. So, this is basically a scanning electron microscope.

I asked them to identify how many different attachments it had. So, this part is only used; this column if you see this is the only part used for imaging that is it. And then if you notice there are various other attachments to this. So, this one is one, this one is another one, this one is one. So, this is one electron microscope which is kept in our Central Research Facility at IIT Kharagpur and this itself has at least three different types of attachments.

And out of this, this is called WDS, wavelength dispersive spectroscopy, this is called energy dispersive spectroscopy. Both of these are working as a spectroscopy technique and they give you the electronic or atom elemental composition of this material and this another detector here another special detector which is called EBSD electron backscatter diffraction and this gives you information about the crystallography of this material, orientation crystallography and so on.

So, these various detectors are usually attached and they capture different types of signals and give different types of information about the material. Same thing for transmission electron microscope, this central column is the only one usually used for the imaging purpose and then you have this other kind of detectors. This is for elemental composition.

You can add another few other type of detectors here on the bottom called electron energy loss spectroscope and so on. So both of these are capable of doing imaging as well as crystallographic information plus elemental composition. All of these are possible in one single equipment that is why these electron microscopes are so useful for any kind of materials you can think of.

So, you can have inorganic or organic materials, micro nano structures, minerals, biological objects, you name it. So, in any institute or any university if you go and if you see an electron microscope and if you look at the list of users, you will find departments like people from biology departments, life science departments, people from materials department, people from chemical departments.

All of them are using this one single equipment because it can cater for all of them. It has so many diverse types of applications and all of these is because of this electron-material interaction, various signals that is generated from this electron microscope that is why it is such a unique method.

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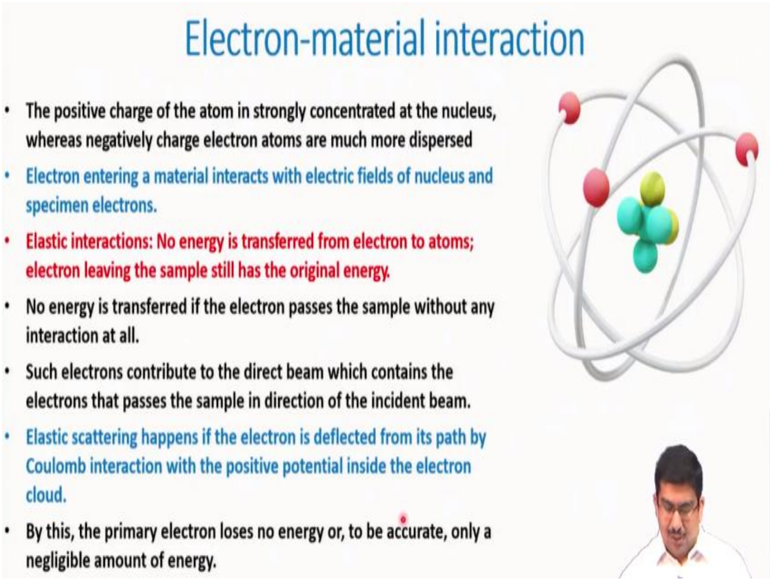

As I said, first thing we have to understand is electron-material interaction of course, and for that we can start again from the very basic of electronic structure, what is the structure of the atoms in a material. So, of course it has a central nucleus where all the mass is there and the protons are there, it is positively charged, plus we have electrons which are circling around this nucleus we can imagine and then forming the electron cloud.

Now, the incoming electron that is also carrying certain amount of negative charge. So, that electron will encounter two entities within the atom. First it will encounter these electrons which are negatively charged and they will repel those incoming electrons because both of them are negatively charged and then of course those electrons will get attracted by this central nucleus as well because of the positive charge.

So, this kind of interaction, so this two will form the basis of all kinds of interactions. So, first kind of interaction that we can think of is called elastic interaction. And in elastic interaction, no energy will be transferred from the incoming electron to the atoms. So, the incoming electrons whatever energy they carry, whatever energy they are entering the specimen, the same energy they will be leaving the specimen.

If that is happening then we can call or we can say that these incoming electrons are undergoing an elastic interaction. Of course, we have to understand this that no energy is transferred if the electron is passing through the material without any interaction, without even not getting interacted or not seeing either the nucleus or the electron clouds at all. Then also there is no change in energy, right.

But that kind of electron will just form what we call us direct beam. So, just like light here also it will be direct beam where it will contain all the electrons which does not undergo any kind of interaction. So, it will not go on elastic interaction or what we will study in a minute is inelastic interaction, neither of the interactions and just passing through the materials without having any kind of change either in the energy or in the direction nothing so that forms that direct beam.

So, elastic interaction or scattering, mostly elastic interaction occurs by some process called scattering, we will come to know. So, this scattering or elastic interaction happens and this will happen by a slight deviation of the electron. So, their energy is not changing, the waves their energy, the amplitude is not changing, but what is changing is the direction or phase of those waves basically by this elastic interaction process.

So if you think about in terms of a wave, so in the wave the amplitude is not changing because of elastic interaction, but their phase is changing. Wavelength remains the same, but the direction is changing, phase is changing in this case.

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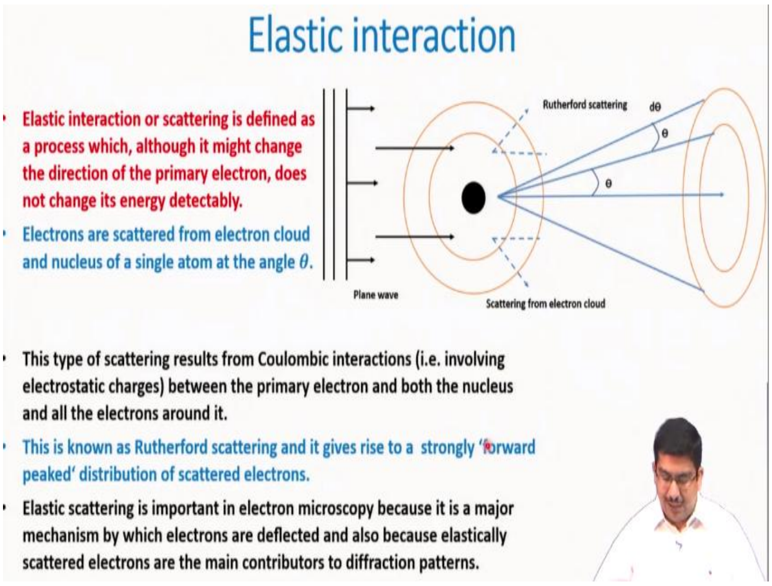

So, this is how the elastic interaction happens. So elastic interaction, again the scattering; elastic interaction or scattering is defined as a process which where the direction of the primary electron change, but without any change in the energy of the incoming electrons. It is just a direction which is changing.

So, if we imagine that there is a plane wave of electrons entering in the specimen and after when it leaves, then those electrons will be deviated from its direct path by certain angle, scattering angle which we generally call set scattering angle theta. And this type of elastic interaction mostly happens by Columbic interaction, Columbic interaction between the electrostatic charges, we will see that what exactly is happening there.

But in this case electrostatic means between two fixed static charges. We can imagine that these charges can be either the primary electron and the electrons which are present within the atom the negatively charged electrons in the atoms or between the incoming electron primary electrons and the positively charged nucleus, either of these two will cause a scattering of this Columbic interaction and this is also called a Rutherford scattering.

And it gives rise to a very strong forward path direction of the scattered electron. And elastic interaction is mostly important because it is a major because of this elastic interaction as we will learn in the possibly the next few weeks in the coming weeks, that elastic interaction basically forms the signal for transmission electron microscopy. Image formation in transmission electron microscope, contrast formation in transmission electron microscope is mostly occurring by elastic interaction.

Also elastic interaction is very important for diffraction related experiments. So, when we are we capture something called diffraction patterns, then we have to use elastic interaction. The electrons which undergo elastic interaction they can only produce or they can only be used for diffraction experiments, we will discuss about that in a little later.

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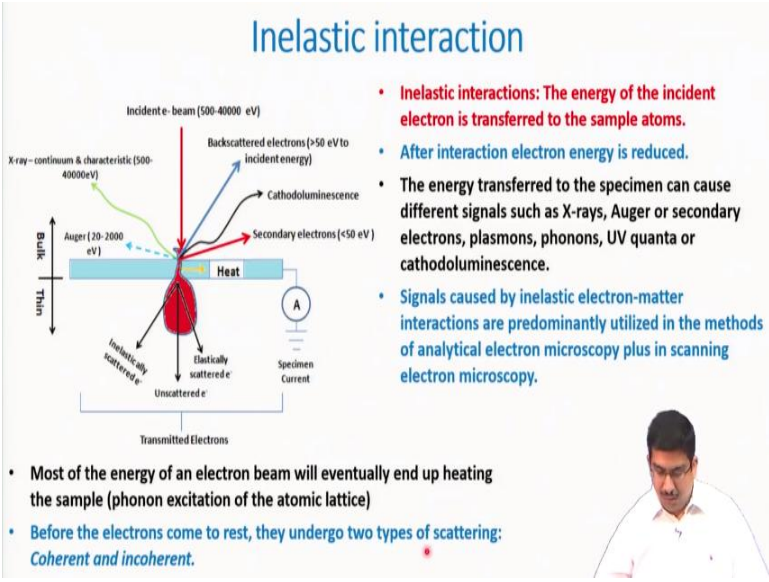

So, obviously there is another type of interaction possible which is called inelastic interaction. So, inelastic interaction here the energy of the incident electron is transferred to some part of the energy is transferred to the specimen atoms. And that means after the interaction the energy of this electrons will be reduced and that will cause some kind of a secondary signal generation from the material, most often.

And those most often what happens is that most of this energy of the incoming electron goes into heat as a heat or phonon generation. So, material gets heated up because of this incoming electron, some energy loss and inelastic interaction from the incoming electron. Other than that there will be some secondary signal generation as well, for example there is something called X-ray generation.

And there can be two X rays, we will discuss; continuous X-ray and characteristic X-ray, both are possible. Then there will be some kind of electron generation called Auger electrons or secondary electrons, plasmons, phonons, already I said heat is generated, some UV quanta or even cathodoluminescence. Visible range light also can be produced and this kind of inelastic electron-matter interaction, different signals which are produced these are mostly used as a spectroscopic method.

For analytical purpose these electrons are used or these signals are used and also in scanning electron microscopy, these various signals are mostly utilized, particularly the secondary electron signal is utilized for imaging purpose in secondary scanning electron microscope. So, this is what inelastic interaction. Again, we will be discussing about inelastic interaction in more details when we discuss in scanning electron microscopes.

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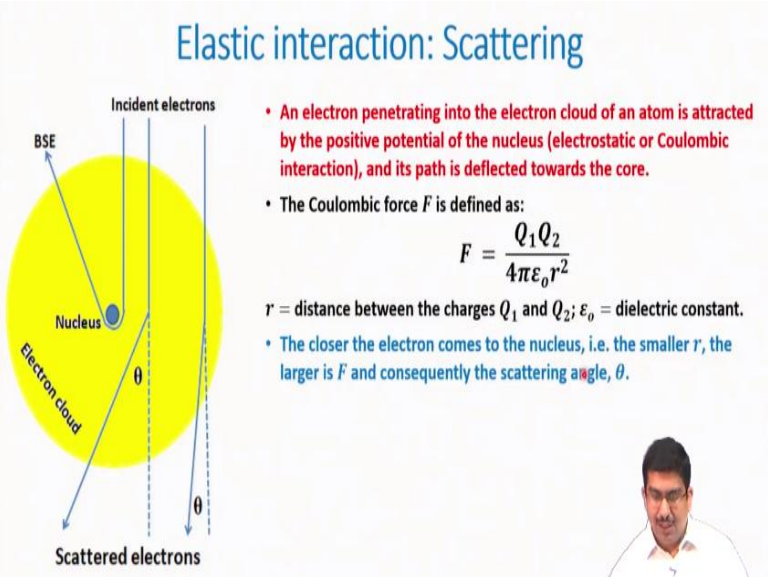

Fine. So, let us now discuss the elastic interaction part or scattering part. So, as I said when the incoming electron that passes through the atom. We can imagine that this is what the atom the how it looks like, very simplistic output and all the charge is there in the nucleus and we have the electron clouds somewhere over here. So, as this electron is penetrating into the electron cloud or the nucleus by both of them, they can be deflected by certain amount because of the Coulombic interaction.

That columbic force $F = Q_1Q_2 /(4\pi\varepsilon r^2)$; r of course is the distance between these two charges Q_1 and Q_2. We can imagine that either Q_1 or Q_2 is basically the charge of this electron cloud or this nucleus, the other one is the charge of the incoming electrons, epsilon 0 is basically the dielectric constant between these two charges. So, the first thing we can realize here that if r is lesser, smaller, then this force will be much higher.

And force much higher means of course the scattering angle will also be larger. So, this is coming out of this Rutherford scattering experiment. If this force the Coulombic force is higher the scattering angle will also be consequently higher and higher. That means, these two will if we consider only for example the nucleus then any electron which is coming very close to the nucleus actually will be scattered by a much larger will experience much higher force and it will be deflected by a larger amount.

Compared to that if any electron which is coming closer to or farther off from the nucleus and only experiencing the electrons which are of course the charge is much less that also is a possibility, but then they will have a very small amount of scattering. So, that is the first understanding we can have about the electron elastic scattering by the atoms to an incoming electron.

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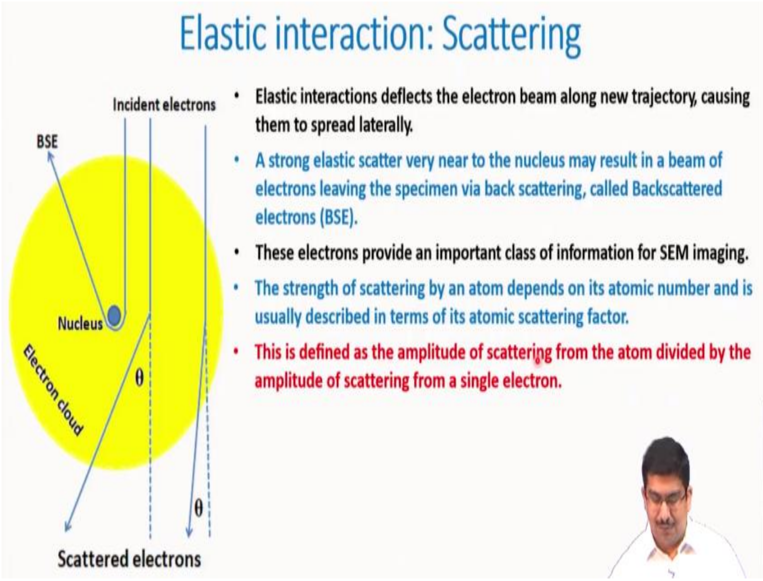

So, then after scattering what will happen if you can imagine that a direct beam is passing through here and the scattering is happening and that too the amount of scattering, the scattering angle is varying depending on the electrons exactly what is causing the scattering, how far it is from the nucleus or how close it is the electron cloud depending on that the scattering angle will change.

So, this elastic interaction will basically so once we are working with a coherent beam which is falling over here and after the elastic interaction happens after this scattering phenomena happens, the beam will be spread lateral. So, that can be still a coherent or incoherent depending on the phase. So, of course the most severe or most strongest scattering will have again because of this Coulombic force will be very high because r will be very less if the electrons are very close to the nucleus.

And in those cases, in extreme cases sometimes the incoming electrons the scattering angle will be close to 180^{o}. That means the electrons will be following a trajectory which will be nearly parallel to the incident electrons, the path of the incident electrons. So scattering angle will be so high if the electrons are hitting or coming very close to this positively charged nucleus, those are special electrons and called Backscattered electrons.

And those backscattered electrons are very essential for image formation in case of SEM, and we will discuss about that later. The next thing of course you can understand that this scattering phenomena will depend on the atomic number because the atomic number will be dictating the charge here, these two quantities. So, atomic number will dictate that how much or how heavy the nucleus will be or how much charge will be there in the nucleus and the electron cloud.

So, atomic number will also dictate the scattering phenomena and usually the larger the atomic number, the higher the atomic number, the more will be the Coulombic and the more will be the scattering angle as well. So, this is given by another factor called atomic scattering factor and atomic scattering factor we will be discussing in more details when we discuss about X-ray diffraction, there the atomic scattering factor will make more sense.

And for now, we can just think of that the atomic scattering factor is given as the amplitude of scattering from a single atom divided by the amplitude of scattering from a single electron, so that is what is called the atomic scattering factor. So, how much scattering is happening from individual atom with respect to the electrons which are present in those atoms.

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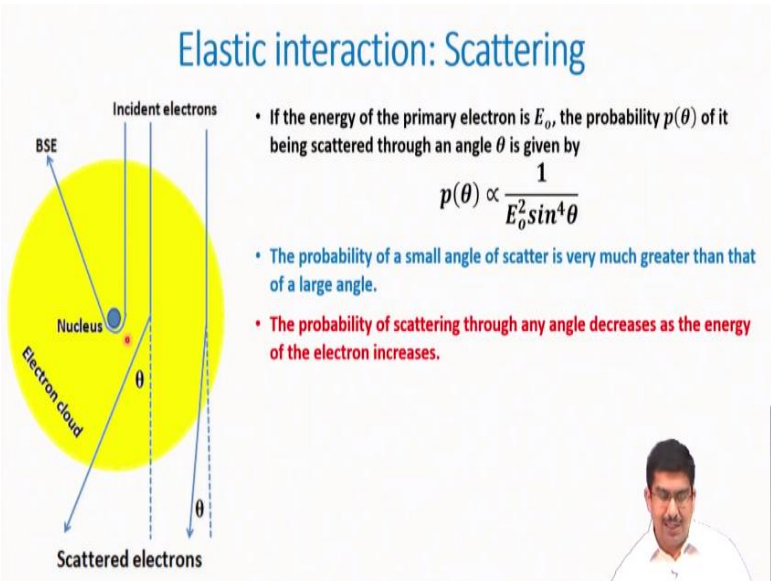

Anyway, so this elastic scattering we can also think of it from some probabilistic approach and we can see the effect of various other factors in this elastic scattering or elastic interaction. So, the probability of having an elastic scattering by an angle ϴ this is related to this p(ϴ), this is the probability of having of the primary electron getting scattered by certain angle ϴ this is given by or this depends on, this is proportional to this $E^2_0 \sin^4 (\theta)$.

So, this E_0 is of course the energy of the primary electron or the acceleration voltage or energy of the primary electron. So, two things become very clear here. Number one the probability depends on the acceleration voltage or the energy of the electron. If there is a very high energy, if the electron contains a very high energy, then the probability for their scattering is also quite less through any angle, any kind of angle.

If you just imagine any angle whether backscattered, whether small angle, whether a large angle scattering; the possibility for everything decreases if the electron energy is very high. You can imagine this to be something of this sort you are throwing a ball with a very high velocity and then you have a net and then there is every possibility that the high velocity ball will just go through the net without being affected anywhere.

So, you have the net and it will just torn that net apart and then it will leave so that much of that you can imagine for this high energy electrons. Thus, they will be just going through without even interacting anything, they will be having so high velocity they will not interact with either the new electron cloud or this nucleus here. And another thing you can notice here that the possibility for small angle scattering will be, so the angle theta is small p theta is very high.

That means possibility of small angle scattering is much greater than that of a larger angle and that is very much so because the nucleus is containing only a very small area of the entire atom. The rest of the portions is just electron cloud and electron cloud will have a smaller value for Q_1, the charges less, so the smaller angle scattering will be much probable than this large angle scattering which is entirely due to this positively charged nucleus here.

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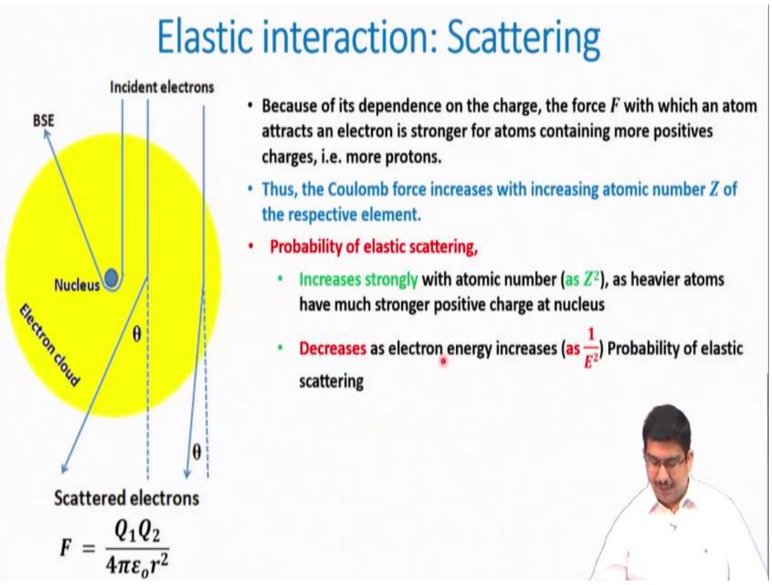

So, again as what we were saying that dependence on the charge following this equation, the force increases with more protons with the atomic number. So, if you have higher atomic number, force also is increasing. So finally, the probability of elastic scattering, this increases with atomic number basically Z^2 as heavier atom have much more stronger positive charges nucleus.

So, then they can increase the possibility of high angle scattering and even backscattering and this elastic interaction, elastic scattering again decreases with electron energy. As the electron energy increases the probability of elastic scattering also decreases.

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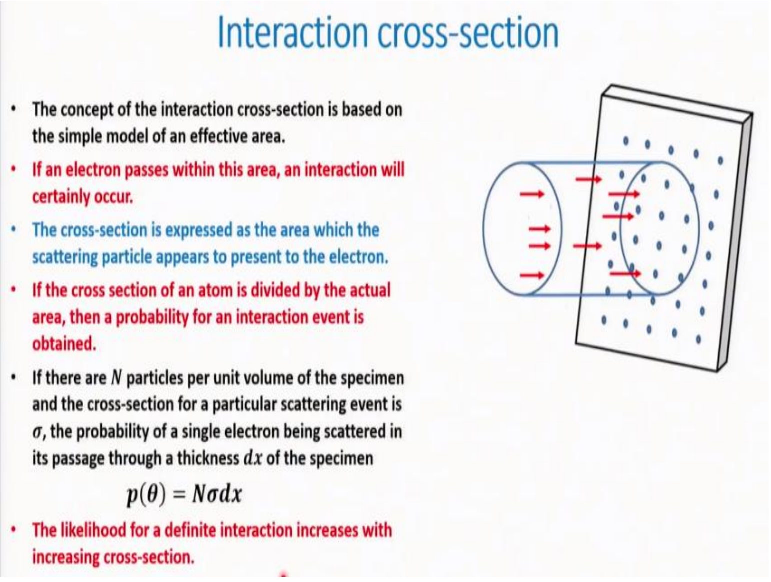

Now, the final thing we can discuss about this is the probability of electron scattering. Now, this probability of electron scattering is explained by this one, this schematic. You have this electron beam here where all these electrons are there and then you have this material here which is having these atoms. So, now we have to define that when the electrons pass through this specimen, then what is the probability of this electrons to encounter these atoms?

If you imagine that these are the atoms which are arranged in a regular pattern within the material, this is a crystalline material all the atoms are arranged in a regular manner, then what is the probability for these electrons to encounter this regular pattern atoms here. So, when electrons are going through, they can either experience these atoms not at all that also we discussed.

That they will contribute only the direct beam without any change in their path, any change in their energy, neither elastic interaction or inelastic interaction, they can just simply go through this specimen without any interaction. So, that is one possibility. Then it may also happen that if the electrons can interact only with one atom at a time that we call it single scattering.

So this material is so thin that in their pathway electrons are just encountering only one atom at a time, so that is single scattering. The thickness is more, the electrons can undergo a couple of such interactions several times what we call plural scattering or the material is so thick that electrons are undergoing many, many such interactions, both elastic and inelastic, we are not differentiating between them, both elastic and inelastic many times that is called multiple scattering.

Many times, my students ask me that what is the number, plural scattering, multiple scattering; there is no such defined number. How many scatterings is called plural? How many is multiple? There a vague definition of course is there in terms of some equation probabilistic, we will come to that in a little while. So, this probability of an electron scattering we can define it by two terms here.

So, probability of a scattering event is defined in terms of something called interaction cross-section. This is an area, an area over through which if electron passes through it will have an interaction for sure, 100% probability for the electron to have an interaction. So, such area can be defined and that is called interaction cross-section. Another approach is to define an average distance that an electron travels between two such interaction events and that is called mean free path of the electrons.

So, these are the two ways that a probability of an electron scattering elastic or inelastic scattering can be defined and these are the two things which defines basically the entire electron scattering process, electron material interaction process, the probability part. So, this we will be discussing in the next class both the interaction cross-section and the mean free path plus another topic we will be discussing there called interaction cross-section. So, with this we are closing today's class. Thank you and goodbye.