Techniques of Materials Characterization
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Lecture - 31
Basic Components of SEM

Welcome everyone to this NPTEL online certification course on techniques of materials characterization. So, we are now in seventh week, module 7. We are still discussing scanning electron microscopy. And in the last week we started SEM discussing about SEM and first thing we discussed is like the differences and similarities between SEM and TEM. Basically, the component wise they are very similar both of them are electron microscopes.

But SEM has certain attributes which TEM does not have and vice versa of course. And why SEM is a more popular electron microscopy technique than transmission electron microscopy which is more like a specialized technique. So, we discussed all of this and then we were discussing about the signal generation from scanning electron microscope like most of the signals are generated through inelastic interaction between electron and materials.

So, various type of inelastic interaction, we discussed phonon scattering, plasmon scattering, single valence electron scattering, secondary effects, inertial valence electron excitation all of this. And then we discussed about two other special type of signals that is produced in electron scanning electron microscope, one is secondary electrons and one is backscattered electron. So, with all and then we discussed about those two signals as well backscattered electron yield.

What are the factors it depends on? And then secondary electrons, what are the factors that control secondary electron generation. And also, we discuss a little bit about the secondary effects in terms of characteristic X ray signal and then auger electron signal and all of this. So, now this new week on module seven we will be starting on a new subject altogether. And we will be talking about some basic components in SEM.

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And here we will be discussing mostly about the detectors in SEM and different types of detectors, SE detector, BSE detector, in-lens detector and another very important component in SEM which is typically found in SEM is a scan coils.

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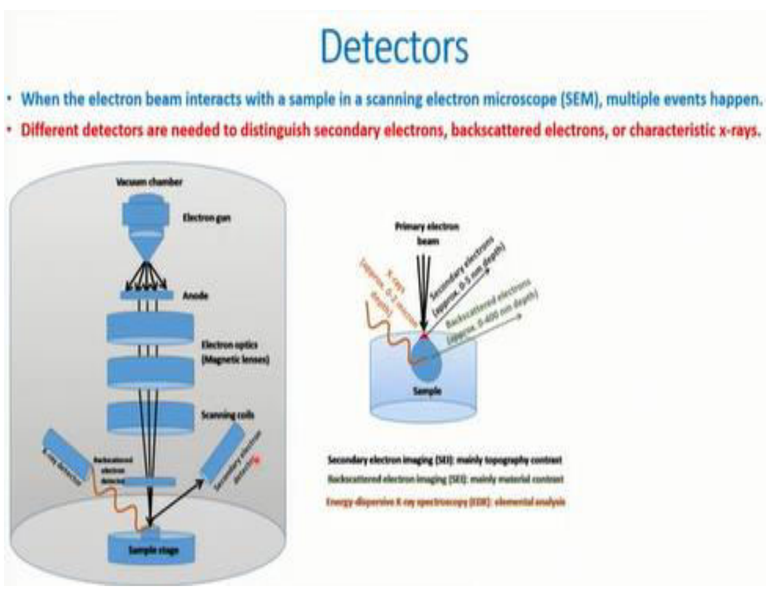

So, first thing is of course detectors. So, if you look at how the SEM basically looks like inside the cross section of an SEM. So, it has it escaped in the vacuum chamber this is a column so, you start with the electron gun and then it passes through the magnetic lenses and finally it hits the sample stage. So, this entire configuration is pretty similar to transmission electron microscope, exactly almost the same things are there.

In transmission electron microscope also, you find the electron gun and these are the same type of guns here. You have either thermionic gun or you have field emission gun and these electrons which are produced by the gun and the gun configuration also is exactly the same. The triode guns and in case of FEG it is having an extraction plate and so on producing a field emission effect. And then you have this anode plate which basically accelerates the electrons which gives energy to the electrons.

And the centre plate is also the configuration is also same. Only difference is that the SEM are typically operated at much lower accelerating voltages almost up to 30 keV whereas transmission electron microscopes are operated 100 to 300 keV. So, that is one difference but configuration wise there is no difference. And then it passes through magnetic lenses you have this condenser lenses first and then you have the objective lenses of course and you have the scanning coil.

So, scanning coils is as I was just mentioning that this is a typical component, this is a unique component in SEM which is not so much popular in TEM. Of course, there are STEM systems scanning transmission electron microscope where a similar scanning coil is used. And then you have the sample stage over which the specimen is kept and electron beam hits that. This entire configuration as I said is quite similar to transmission electron microscope.

And where it differs from transmission electron microscope is this various type of detectors. And this various type of detectors are responsible for capturing various type of signals which are generated in SEM. So, as we already understood that in SEM the three most common signals which are which are produced and which are detected is characteristic X ray and then secondary electrons and backscattered electrons.

So, secondary electrons is typically used for imaging purpose whereas X ray signals are typically used for chemical analysis of course with spatial resolution and so on. And backscattered electrons primarily used as imaging for imaging, but with suitable calibrations and all this can also be used for chemical analysis. We will discuss about all of this maybe in the next module.

So, because of this various type of signals that is used in SEM it gives so much diversity to scanning electron microscopes.

And large part of it is responsible for these detectors, different type of detectors which is available. So, if I compare this with transmission electron microscope basically in transmission electron microscope of course, it does not stop here. It goes in the other side because they are we use a electron transparent specimen and the typical detector that is used there is a screen, phosphor screen. And on that screen the electrons goes and hit and creates a fluorescence effect basically.

And this florescence effect ultimately is sensitive to the number of electrons which are reading and that generates the contrast and we are able to see these images. So, it is kind of direct image 'A' and also the detector is pretty simple there, it is just a fluorescence screen that is it. And then if we want to capture the image of course, we have camera either; we can good old days there were film cameras which were brought and this phosphor screen was captured.

The image was captured of the phosphor screen basically in a film camera. And these days of course, we have other type of image capturing devices we have this CCD or CMOS based devices and those devices also now is used. But basically, you have that same phosphor fluorescent screen and whatever the fluorescent screen whatever the lights are generated from there that is now transferred to the image capturing devices. This is very pretty simple in case of TEM.

On the other hand, in case of SEM, the detectors are pretty complex. Because in SEM, everything most of the thing is about detection of various signals. And that's where the entire the heart of the electron microscopes scanning electron microscope lies on the detectors. So, the detectors are very complex and very unique. And for each type of signal, usually there used to be one type of signal detector. Although there are exceptions, we will discuss about that also.

So, this is how basically the SEM works in terms of detectors. And this primarily most often, most of the electron microscopes these three types of detectors are used- electron backscattered electron detectors, secondary electron detectors and X ray detector. So, we will be discussing, most likely today we will discuss about the backscattered electron detectors and secondary electron detectors and the X ray signal detectors is a little special one which we will be discussed separately.

And these are the different type of signals that is produced with different type of depth and different type of interaction volume. Backscattered electrons of course, generated from a much larger depth and with a much larger sampling volume. Secondary electrons if we captured just SE 1 signal generated from a very small depth and mostly confined within regions very close to the primary beam where the primary beam hits.

And X ray signals are generated from even further depth and at a much larger sampling volume. So, this all things have a impact on the detection will come into that.

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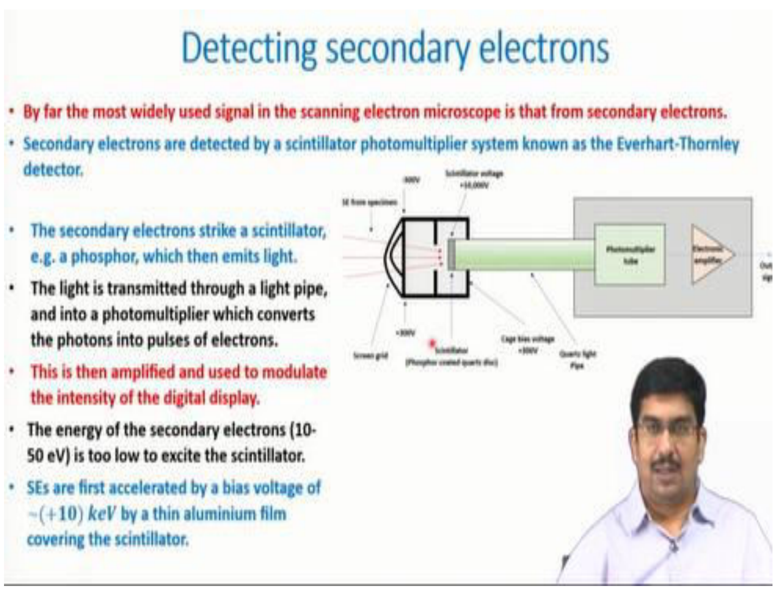

Now, let us first discuss about detecting the secondary electrons. And for secondary electrons the by far the most usually used signal in a scanning electron microscope is a secondary electron detector. So, if you also can understand that if there are no detectors at all then this electron microscope is not working. So, everything is happening here the sample is heated by the electrons signals are generated, SE electron generated, BSE is generated everything is generated.

But if there is no detector to detect any of the signals you will not be getting anything as an output. So, you will not be getting an image, you will not be getting any chemical analysis signal or anything. So, at least you must have some kind of a detector for it to run. And most often the only detector if you do not have any other kind of detectors, at least you will have a secondary electron detector that is for sure.

And there are certain systems where there is only one detector that is a secondary electron detector. For example, if you use the electron microscope for lithographic purpose in that you do not really need a Backscattered electron detector. Because the electron beam here is curving around a particular pattern. So, it just needs a beam, but at the same time you need to see the pattern inside. For that you need a detector and that is invariably the secondary electron detector.

So, secondary electron detector you can imagine that is basically by default. That is a default detector in SEM, of course it is the cheapest as well and the oldest as well. So, the first kind of first set of electron microscopes when they came if you remember in 30's and in 50's and so from Cambridge it came the first commercial SEM and all. And that those detectors were scanning electron detector, this secondary electron detectors.

And much of the development of scanning electron microscope is actually attributed to the development of detectors basically. Of course, there are developments in other components there are developments in terms of electron guns, there development in terms of lenses and so on. But those developments are mostly done for transmission electron microscope and then they were brought into the scanning electron microscope.

For scanning electron microscope particularly, the development occurs happen in terms of detectors. So, better and better detectors are always comes in the market and are always people are looking for detectors with better spatial resolution, better lower signal to noise ratio and so on. So, if we look at the secondary electron detectors this is a kind of scintillator photomultiplier systems. Now we will come what exactly is scintillator, what is photomultiplier and so on.

And it is named by the two people who invented or who designed this secondary electron detector Everhart and Thornley, it is named after them. So, what is scintillator photomultiplier detector? So, first thing is the secondary electrons basically hits a scintillator here. So, you have the secondary electrons which are generated somewhere within this from the specimen. If you go here secondary electrons are generated from this region from all over here.

And those secondary electrons are now coming towards the detector. And the first thing they will hit is this scintillator which is nothing but a phosphor screen. Now, if you remember our discussion when we were discussing about the fluorescence microscopy, I briefly discussed about fluorescence and phosphorescence. And the most important difference between fluorescence and phosphorescence is fluorescence is immediate phosphorescence is there the signal generation is delayed.

And usually, the signal which is generated in phosphorescence is having higher wavelength lower energy having higher low wavelength than the primary signal which is producing the secondary signals basically, like both of them are like so, you can imagine. So, in this case you have a phosphorescence and that phosphor material when the electrons goes and hit them, they generate a light.

Now, the; question comes one of my students once asked me this, this year itself that why we are using a phosphor screen here whereas in TEM we use a fluorescent screen? That answer is pretty simple, because in TEM, the image is a direct image. So, every part of the image is forming at the same time right there. So, the electron beam comes, hits the fluorescent screen, light is generated, you are seeing that image.

And now you are possibly bringing a camera to take that image and so on. But you want to see the entire image at one shot in one go. In scanning electron microscope however, the image is generated point by point pixel by pixel. So, what happens is this SE signal which is coming here is from one such pixel and then they are producing this phosphorescence they are producing this light signal so on. Now, this phosphorescence signal needs to be detected.

And that detection will take some time, because it has to been transferred. We will discuss about that it has to be transferred and finally that signal will be converted to current signal and it will go to the display or image capturing device will be modulated as per this signal. This has a time limit, a time gap. Every detector on every machine has a response time. So, this response time up to this response time, the signal should be produced from here.

So, here the signal production should continue over a such certain period of time. So, that this one is able to respond. It is up to the order or of the response time of this detector. If this is immediate signal then what will happen depending on your scan rate by the time this moves to the next one. So, it is from one pixel signal is there it generated immediately and light signal is generated converted to current and there will be a pixel modulated in the display.

That process is a lengthy it is a time consuming process. By the time that is getting over this electron beam has already moved to the second pixel and then a fresh set of SE signal will come and hit this fluorescent screen. Again, one more set of light signal will generated and that will be converted or that will be used to modulate the display or the image capturing device. So, there will be a mixing intermixing, depending on the response time there will be an inter mixing of the signal, chance of intermixing.

So, that signal will be very noisy. It depending on the response time and depending on the scan rate and so on, but it will be a noisy signal. So, that is why we do not prefer a fluorescence material to be used as a detector here, we prefer a phosphorescence material to be a signal or to be a detector material here. So, that is another difference between the direct imaging and transmission electron microscope versus the scanning imaging in case in the SEM, scanning electron microscope.

So, whatever it is, we have now a phosphorescence material which is here and that phosphorescence material basically electrons hit here that phosphorescence material and produces some kind of a light signal. Now that light signal is next it is transferred through a light pipe usually made out of quartz, pure quartz, it is glassy amorphous quartz, vitreous quartz state.

And usually, this light tube what it does is that it works in the just like an optical fibre, it works on the principle of total internal reflection.

So, that the signal strength remains constant, there is no loss and that signal is transferred to some other part which is now is the photomultiplier. Now photomultiplier what it does is that it takes the light photons and it converts the light photons into electrons. So, generates basically a current signal, it takes a light signal and generates a current signal there. So, I start with these SE electrons here and depending on their concentration.

I generate this phosphorescence material generates a certain signal, certain amount of light photons and those light photons are now generating an electron corresponding amount of electron in the photomultiplier tube here. After that, those electrons transferred to an amplified device. So, that amplifier will modify this current will increase this amount of current while I will come. Why is that? So, it will amplify that current and finally it will generate an output signal.

And that output signal will be used by the final display or image capturing device in that picture. Now, why this amplifier this entire process is needed? Why cannot we straight away take this secondary? This is another question asked to me by one student. Why cannot we directly take these SE electrons and then just use them as an output signal? Why do we need all of this in between? Why do we need a phosphorescence screen to generate light?

Then that light will generate another set of electron then I will be generating I will be amplifying that electron and so on and so forth. Why cannot we directly use the SE electrons and modulate the display? Problem is the SE electrons are very, very low energy. So, they will not be able to generate or they will not be able to modulate or they will not be able to be used to modulate the display. There was such a low energy and their numbers are also so low usually.

So, that is why this SE electrons this entire detector part is needed and that detector will then corresponding to SE electrons it will first generate the light signal and then that light signal will generate another set of SE so that signal will be really strong. The signal which is generated from this photomultiplier is much stronger than the signal that is directly generated by this SE. These are related of course, these two are pretty much related.

But this signal is much stronger than if we use only a secondary electronic signal that is the reason. Now point is since these SE electrons are so low on energy. So, they cannot be directly used definitely, but then energy is even not enough to excite this scintillator at times. They are so, low energy SE electrons and that is related to the Genesis the way they are produced, we have already discussed this.

So, they are of so low energy they will not be able to do anything with this detector, it scintillator here. Scintillator will not produce any light signal at all. For that what we need to do is to somehow accelerate them artificially. In order to do that what we do is that we use a bias voltage here on this screen, positive bias voltage of the order of 10 kilo electron volt. And that we do using a very thin aluminium film that basically covers the scintillator device.

So, this thin aluminium foil is given a very high positive voltage and that positive voltage basically attracts all the SE electrons here. Principally is it works pretty much the same way as this anode plate, the anode plate accelerates these electrons here. And this aluminium plate also works like an anode and it helps to increase the acceleration the energy of this SE electrons. So, that is when they hit the scintillator screen, they will be able to generate a light signal from here.

So, this is how the entire SE signal is produced, entire SE detector works and how it captures the entire secondary electrons signals.

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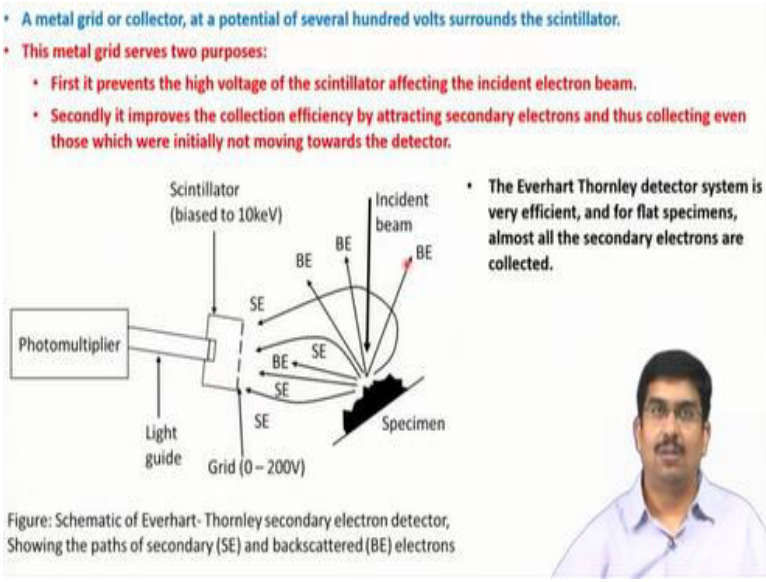

Now, there are a couple of other components in the SE detector. First of all, there is a metal grid something like this, a metal grid or metal cage is there which is called the collector, collector cage. So, this collector cage is kept at some hundreds of positive volts surrounding this scintillator. So, this is kept at slightly higher positive voltage around 200 to 300 KeV, 300 volts at this slightly higher positive bias is given to this scintillator cage or to this cage metal cage.

So, what does this metal cage do? First of all, it prevents the high voltage. So, this 10 kilo electron volt which is there in the scintillator screen that may affect the primary beam and that may attract even the primary beam as well. If you look at here, the secondary electron detector is closed it is kept a slight distance from the primary beam. But still, it can attract the primary beams here and it can deflect them in the process that is not one that is not what we want.

Then what we will be losing is that scan coil will not be able to make them move over this raster if this is affected by this secondary electron, the positive bias from the secondary electron. So, this metal cage basically ensures that the effect of this positive bias positive voltage does not extend all the way up to the primary electron beam that is the first purpose. And second purpose is that it improves collection efficiency of the secondary electron detector.

And it attracts by attracting the secondary electrons which are not directly in the line of sight for this detector. So, if you look at here this is the specimen primary beam is sitting here and SE electrons are produced in all possible trajectory. Why and how we will discuss this when in the possibly in the next module when we discuss about the contrast generation in SE mode and BSE mode and so on.

There we will discuss this but just at this moment just remember that SE signals are generated with all kinds of trajectories. So, out of that the SE signals which are directly in the line of sight for this detected they will be anyway going there. Now the SE electrons which are moving somewhere else, so, those SE electrons will also be attracted because of this slightly positive bias in the metal cage or metal collector.

So, in the process, the collection efficiency or the solid angle of collection for this detector will increase. So, these are the two purposes that this metal grid serves. And by and large this Everhart Thornley detector system this is very efficient because of this all of this attachment, metal cage and because of this positive bias and so on. It is very, very efficient and very rapid as well. So, these signal that this detection, their response time by the detector is very high.

That is why this detector can be used as a very high scan rate. So, even if the beam is moving very fast in the raster over the raster still that this detector the response time of the detector is such that it will be still able to modulate the output signal will be able to modulate the display or image capturing device point by pixel by pixel exactly in the same way this beam is rastering electron beam is rastering over the specimen.

There will not be any problem because the detector which is in between has a very fast response time and that is why the secondary ET detector is almost by default present in any SEM. And for flat sample completely flat sample they almost able to detect all the secondary electrons from this ET detectors.

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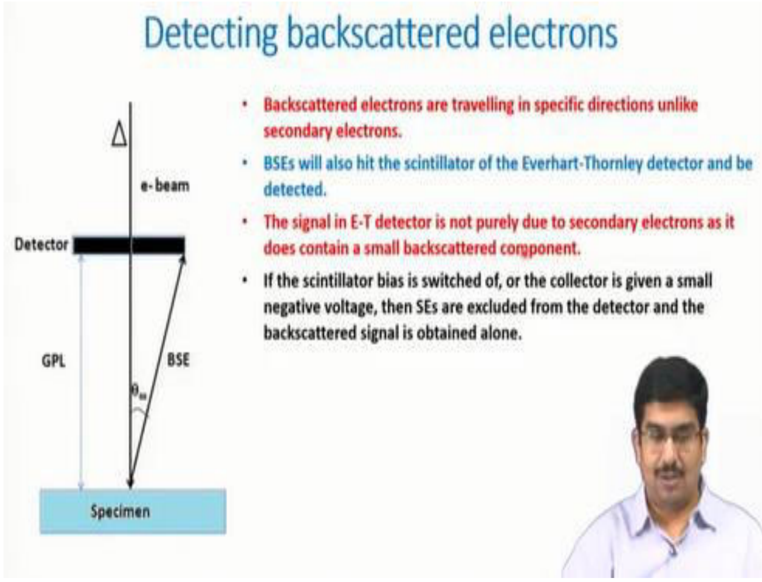

Now, from SE signal we are going to discuss about the backscattered electron, detecting the backscattered electrons. Now backscattered electrons are a special one we already discussed; they are the elastically scattered electrons. So, number one electrically scattered electrons because of that, they have much higher energy than any other electron signal, be the auger electrons, be the secondary electrons whatever it is.

Because of this elastic scattering and if you remember we have discussed we have drawn this energy versus number diagram. So, backscattered electrons have much higher energy than the secondary electron that is the first thing. Second thing is backscattered electron that yield is very much sensitive to the direction. Because backscattering is a special event out of all different type of elastic scattering.

Back scattering we are calling those electrons as backscattered where the scattering angle is close to 180 degree. That means if the primary beam is falling like this, the backscattered electrons will be generated in and around this primary electron beam within a certain angle. Right Because that the complete 180 degree will be just retracing the same path as the primary electron. So, close to a 180 degree means the backscattered electrons will be generated with a very small angle with this primary electron beam.

That is the main difference between secondary electrons and backscattered electrons in terms of detector at least in their detection. And that affects the kind of detector where the detector will be placed and so on and so for. Everything changes just because of these two properties of backscattered electron. One they are much stronger than secondary electron detectors secondary electrons and second thing they are generation is also very much sensitive to directions.

Now, as it is shown here, the backscattered electrons are also detected by this ET detector. Because certain backscattered electrons are also generated by, I mean the yield is highest if you remember we told that backscattered electrons are generated also generated from other places. So, not only they are confined within very close to the primary electron beam like secondary electron SE 1 signal, backscattered electrons can also be generated from some other place.

So, what will happen is some of the backscattered electrons will generate from the specimen in such a way that they can be attracted towards the ET detector. So, that means the ET detector will also capture some amount of backscattered electron. Now, remember one thing for the scintillator for the detector there is no difference between SE electron and backscattered electron it is an electron, it is a negatively charged particle. The only difference is their energy level.

So, that ET detector, the scintillator screen the response will be exactly the same whether it is a backscattered electron or whether it is a secondary electron they like the light signal will be generated. Of course, the intensity of the light signal everything will change definitely. But the point is that ET detector will also be effective in collecting the backscattered electron. And this is how in good old days the backscattered electrons was usually captured by the same ET detector.

So, that means the ET detector, the signal that is generated from ET detector is usually not only from secondary electrons. So, it is not a pure SE signal, it is a mixed SE some part very little, little our backscattered electrons will always be mixed with the SE signal in an ET detector. And what how we can ensure that we are completely capturing the backscattered electrons? We cannot ensure that we can completely capture the SE signals, no not possible.

Some BSE will always be mixed with it, but we can try to stop SE signal and can capture complete backscattered signal that is possible. How this is done is Basically, the scintillator bias is switched off. First of all, scintillator biases switch off means this 10 keV this bias is switched off. If you switch it off remember the purpose of this bias is to accelerate secondary electrons which are of very low energy. So, that they can go and hit the scintillator and produce the light signal.

Otherwise, they cannot produce. So, if we switch it off, SE signals which not be able to produce any light signal, but BSE backscattered electrons since they are of much higher energy than secondary electron, they do not need this acceleration and still they can be able to produce the phosphorescence signal. That is one way we can get signals out of the backscattered electron or this detector can be operated in backscattered electron mode.

For backscattered electron detection that is one. Second thing what we can do is that same thing just because of this energy difference we can produce a slightly negative voltage in the metal cage. This collector if it is kept at a slightly higher negative voltage, it will repeal all the secondary electrons from here. And it will only allow the backscattered electrons which are of higher energy. So, those backscattered electrons will only be able to hit the phosphor screen not the secondary electrons.

So, these are the two ways we can operate the ET detector only in the backscattered mode. But we cannot ensure that secondary signals are backscattered signal we cannot stop. There is no way we can stop the backscattered signal to enter and to reach to the phosphor screen. That means we cannot ensure a pure SE signal here, but we can ensure that it is a pure or almost pure backscattered signal that is possible in case of SE this ET detector.

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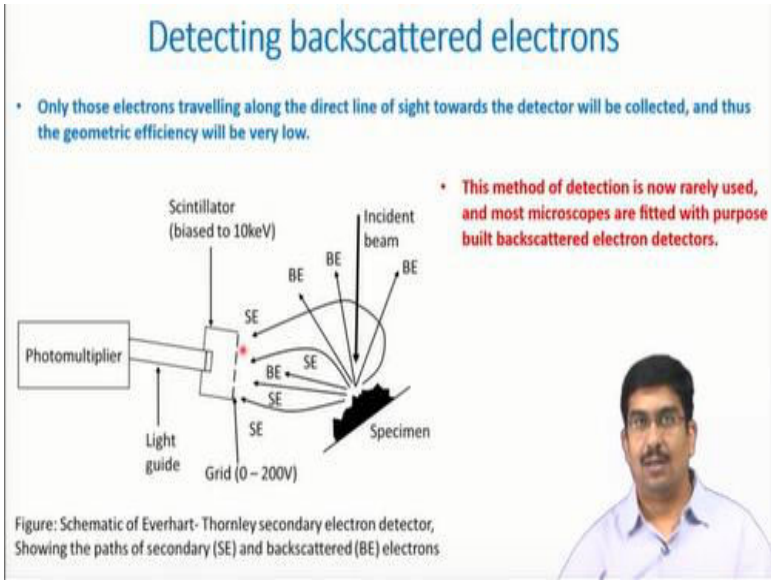

Now again problem of the ET detector, what is the problem of using it for backscattered signal. As I said the backscattered signal, another property of the backscattered signal is that their direction. So, the signal generation of the signal or the strength of this backscattered signal is highest in and around this primary electron beam whereas this ET detector is kept at an angle with the primary beam.

And that is in order to increase the collection efficiency of SE signal or in order to generate maximum contrast we will discuss about that. There is a advantage of keeping this SE detector at an angle with the specimen like this. Then the contrast generation is maximum, the way the contrast is generated due to the SE signal is sensitive to this tilting this angle. So, SE detectors are purposefully kept at an angle to the specimen.

So, that this contrast generation is maximum in that configuration. But what happens is that as a result of this tilt or as a result of this angle between the specimen and the ET detector, the collection efficiency of this ET detector is very poor for backscattered electron because most of the backscattered electrons are generated in and around the primary electron. So, in this signal, so, ET detectors sees very little of the backscattered electrons.

Only those electrons which are in the line of sight of this backscattered of this ET detector, those backscattered electrons will be collected here. So, the collection efficiency will be very very low.

And that is why present-day ET detectors are very rarely used for capturing backscattered electrons. There are purpose made custom built backscattered electron detectors which are used mostly for most of the microscopes almost all the high-resolution microscope that is used present day.

A scanning electron microscope that contains custom build backscattered electron detectors, only very old microscopes or some microscopes just now I give an example like microscopes used for electronic lithography and so on where we do not need to see them with any the specimens other than anything like a secondary electron mode or anything. There the ET detector can be used for capturing a backscattered electron or generating a backscattering electronic image or so.

Other than those purpose if it is a high-resolution SEM modern normal SEM where we used to see a lot of different types of specimens. Generally, we tend to have a completely separate custom-made backscattered electron detector. We do not rely on ET detectors at all. With this we will stop here and we will continue our discussion on detectors in the next class. Thank you.