Fundamentals of optical and scanning electron microscopy
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Module – 03
Unit-6 Instrumental details and image formation
Lecture – 17
Image formation and interpretation

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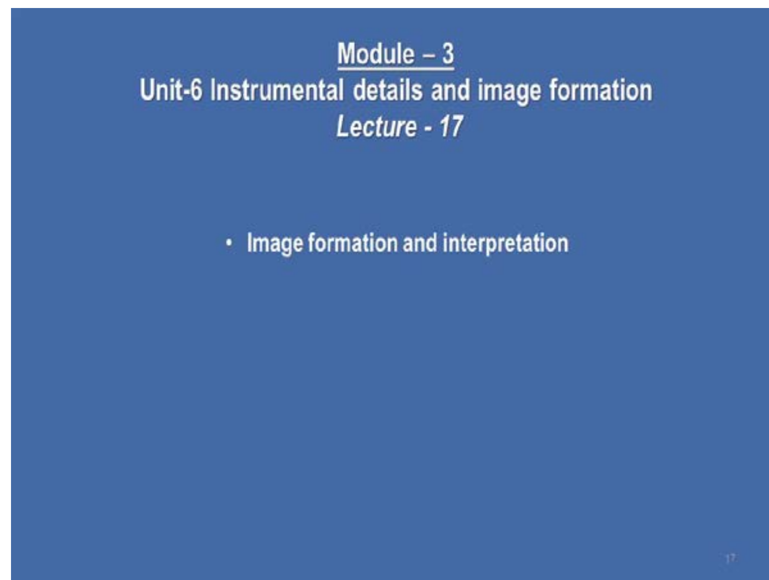

Hello everyone. Welcome to this Material Characterization Course. In the last class we have just looked at some of the instrumentation details of the Scanning Electron Microscopy, and we also looked at the details of the detector parts and its capabilities and how one can execute this imaging experiment in the laboratory conditions and so on.

Before that if you recall, we were also discussing the interaction volume that is, electron beams specimen interaction volume. Then we looked at the various aspects where the interaction volume is significantly influenced by the atomic number of the elements, and also the acceleration voltage under which the SEM is operated. So, in today's class, we would like to discuss little bit about the Image Formation and it is Interpretation. You see, the image formation and SEM is very different from what we normally go through in optical or light optical microscope or a transmission electron microscope.

So, in that respect it is better to get into the details of how the images formed and then how do we interpret these images, and what kind of contrast mechanisms operate. All this details one should have some basic idea. Unlike the other microscopic techniques, in scanning electron microscope you have, not the signals coming out of the specimen because of the electron beam interaction, such as secondary electrons and back scattered electrons and these signals are collected by the detectors.

So, lot of geometrical parameters involved for example, as these witnessed in the laboratory demonstration your specimen is just kept below the pole piece and then your detectors are kept at different angles, especially the second electron detectors are kept at particular angle. So, the amount of signals a detector can collect it depends upon the angle at which the detectors are kept as well as the specimen surface are kept with respect to the beam direction. Also so many other parameters also involved about the characterizing the electron beam and so on.

So, it is not that straight forward to understand the kind of contrast one can get from these any specimen through scanning electron microscopy. It is very interesting to look at the details, and how we are able to obtain the information about this surface of the specimen.

So, in this class we will now review the instrumentation details once again.

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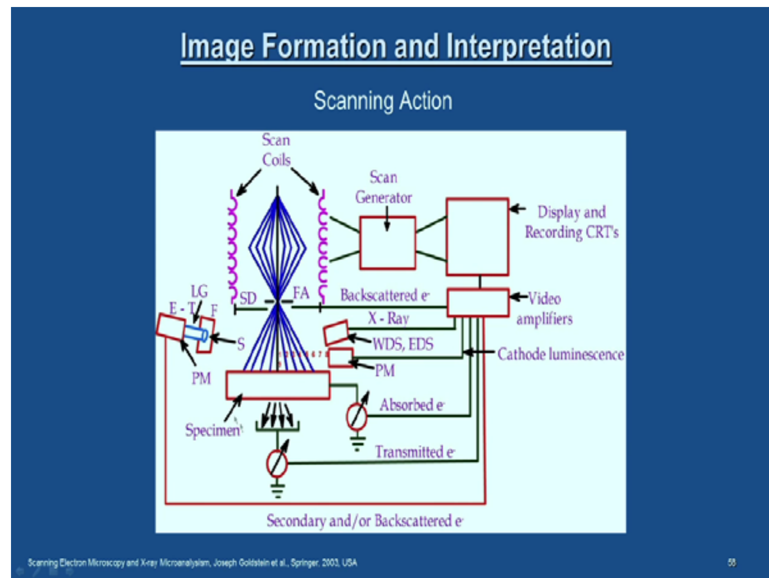

You look at this schematic and most of the parts we have already discussed, but today we will just see the functions of each of this instrumentation parts and it is action during the SEM operation. With respect to the scanning action we will discuss the response of the each parts of this equipment. So, what you now look at here is, the scan coils and then you have this is in an electron beam which is falling on the sample.

Then you have this detector, it is E-T detectors we will see what is that, and then you have this faraday cage, and then you have the scintillator, then you have photomultiplier, and you have the a scan generator here and of course, you have the display and recording CRT's, you have a set of detectors, x-ray; characteristic x-ray detectors, and you have set of spectrometers, wavelength dispersive spectrometer, and energy dispersive spectrometer, you have photomultiplier, you have other electronic device which are connected to this instrumentation details. So what we are now interested is, what exactly this coil do as the scanning action.

As we have discussed earlier, you see that the, upper portion of the coil does the job of reflecting the beam, half the move away from the optical axis and in other set of coils again bring it back to these optic axis, in a such a way that a rectangular raster scan is established on this sample.

Of course, we know that this is a limited by the final aperture, here and then it is being made to fall on the sample in this fashion. So, what we have to understand here is when we say that electron beam is falling on a specimen and it gives out some signal, we always talk with respect to a particular point. That means, the signal which is coming from the specimen surface either it could be a characteristic x-ray or a secondary electron or a back scattered electron. And we can just interpret from these signals about the specimen surface at that particular point. But then we are interested in the complete surface area of the specimen, so that means this beam has to scan from the one point to the other point. So, it is like the beam scanning point by point in the on the specimen surface, and then that is what the scanning action is all about.

So, you see that, the each line shown in the schematic is scanning the specimen at particular point here, 1 to 10 actually this numbers are displaced here. Actually it is to be written here, to in accordance with this lines so that it scans, it displays the scanning action of these electron beam from the left to right in one direction. So, similarly you have the scanning action is possible in y axis or y direction. And then you get the information, I mean you collect the signals and then you interpret the images and so on. So now, with that background we will get into the first line scans.

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The schematic shows, you have the beam location of the specimen and this is on the CRT. So, what you have to understand here from this schematic is, whatever is the beam does on the specimen surface that it is scanning action. This action is synchronized with the CRT screen; one is to one. For example, we are talking about a line scan though the line scan starts from this one end and it scans point by point, actually this signal is having some duel time on each point and then it proceeds like this scanning action. And also you have the signal in y axis as well which sometimes we can use it for the characterizing the characteristic x rays and other signals and so on.

So, what we can have the summary of the remarks for the lines scan can be a beam scan along a locus of a points in the specimen and the beam on the CRT is scanned in a similar locus along the horizontal x axis. So, this is the x line of action which we are talked about. A signal measured from one of the detectors is used to adjust the vertical position. See you can use this back scattered electron or a characteristic x-ray which you can adjust the vertical position, and this kind of signal is very useful for the quantitative measurements the trace corresponding to the locus of the points should be recorded along with traces corresponding to the signal zero and maximum values.

So that is how the lines scanners a performed, especially this particular line scan operation is useful if you are interested in a local composition in the some of the fracture surface or some of the interface or some multi component alloys or segregation and so on. We will see whether we can take up some specific examples in due course.

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What we are interested in is not just a line scan but we are interested in a area of the imaging, so the schematic illustrates the principle of area scans. You have this a beam locations on the specimen and the area is scanned on the specimen and this is a linear dimension L on the specimen which is in synchronization with the area displayed in the CRT which can be understood by this, each area is scanned and then it is also simultaneously showed on the CRT screen. The principle of image display by area scanning is shown here basically. A correspondence is established between a set of locations on the specimen and a set on the CRT. As we all recollect the magnification in SEM is, L's the length of the linear dimension L CRT divide by L specimen. This is the linear dimension where, the magnification is realized.

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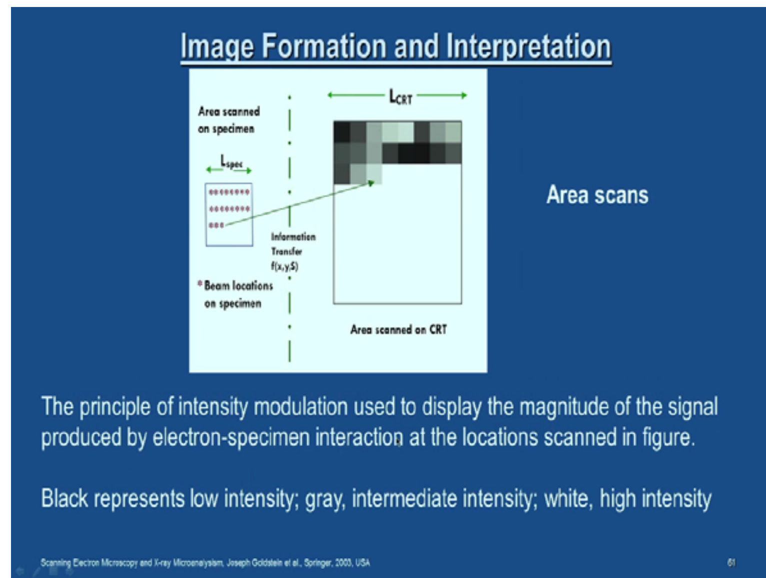

Now, what we actually do here is, you can see that the specimen area where you have the beam locations what actually you see it on the CRT is the intensity modulation. The principle of intensity modulation use to display the magnitude of the signal produced by the electron specimen interaction at the location is scanned in the figure. Most of the time when the SEM is operated and if you in order to adjust the bright signal from the specimen this operation is performed called Intensity Modulation. You see that, you optimize the electron or a signal collection from the each detectors and then proceed with the a scanning action. Where, you have the black square represents a low intensity, gray is intermediate intensity, and white is a high intensity signal. That is how the intensity modulation is adjusted.

You see, another important point to remember in SEM is, in SEM the image is generated or I would say the image generation operation consists of the signal mapping, rather I would say that whatever we obtain in SEM is not a true image something like what you get in light optical or transmission electron microscope. Where, you have the light ray path corresponding to the specimen points connecting to the image points, one is to one ray path connection is correspondence is there, and such a where you put a film or a recording medium to record the image in those devices is not possible in this SEM. In a way it is a signal collection and it is mapped. Fortunately it gives very very interesting

and useful information in team in terms of topological details of this specimen. Here, the signal is converted into a digital domain, or you can see that the digital mapping or a signal mapping we can understand it like that as compared to light optical and transmission electron microscope.

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In SEM you should have to understand another important parameter where the magnification is talked about, numerical value of magnification in this instrumentation as we have just seen before it is L CRT by L specimen. Because the maximum CRT scans length is fixed to the full dimension L of the tube. For example, 10 centimeter and an increase in magnification is obtained by reducing the length one of the scan on the specimen.

Since the CRT screen length or dimension is fixed, the any adjustment you do in terms of increasing or reducing the specimen area will reflect on the magnification of the image. So, the table summarizes the kind of image magnification one can obtain, and the corresponding area which is scanned on the specimen. For example, 10x is equal to 100 mm square; 100x 1 mm square, 1000x 0.01 mm square and so on, assumes that magnification is relative to the CRT screen that measures 10 centimeter by 10 centimeter.

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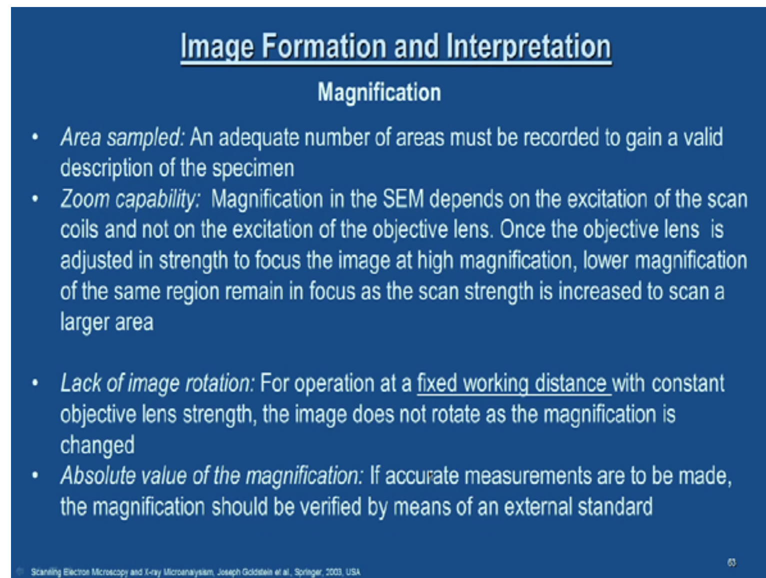

And we have to be very careful about this high magnification images because, the area sample has to be kept in mind, an adequate number of areas must be recorded to gain a valid description of the specimen. So then only you can say that, you have image the specimen with the reasonable representation of the bulk information. If you collect only very high magnification images in 1 or 2 locations, it may not represent with the bulk information of the specimen. So, we have to make sure that the number of area which we examine on the specimen is adequate enough to represent the bulk nature of the specimen.

The second thing is zoom capability. The magnification in the SEM depends on the excitation of the scan coils and not on the excitation of the objective lens. Once the objective lens is adjusted in strength to focus the image at high magnification, low magnification of the same region remain in focus as the scan strength is increased to a scan larger area. And another important point is lack of image rotation. For operation at a fixed working distance with the constant objective lens strength the image does not rotate as the magnification is changed. At a fixed working distance your image is not going to rotate.

Absolute value of the magnification; of course, if somebody is interested in this aspect if accurate measurements are to be made the magnification should be verified by means of an external standard. For example, if you want to do very sensitive measurements, very accurate measurements like; then let us use some kind of a standard, a scale or something or grating under which you calibrate the distance as you do it with a different magnification you generate a calibration chart and then you use that values rather than a simple reading a marker on the display which comes along with the images in the SEM.

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Image Formation and Interpretation

Picture Element (Pixel) Size

The picture element is the size of the area on the specimen from which information is collected and transferred to the CRT image or computer memory.

Usually the PE is considered as a circle ot square, described by a linear measure of diameter or edge length. Considering the rectilinear scan to be divided into equal-sized square boxes filling all of the scan frame,

The linear dimension D_{PE} of the picture element is given by the expression

$$D_{PE} = L_{spec}/N_{PE}$$

Where L_{spec} is the length of the scan on the specimen and N_{PE} is the number of discrete locations along the scan line

Table 4.2. Size of the Picture Element as a Function of Magnification. ∝

Magnification	Edge dimension of picture element
10X	10 µm
100X	1 µm
1000X	0.1 µm (100 nm)
10,000X	0.01 µm (10nm)
100,000X	0.001 µm (1nm)

∝ Assumptions: 1000 pixel x 1000 pixel scan matrix, 10 cm X 10 cm display CRT

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So, the next important aspect is Picture Element Size, a Pixel Size. The picture element is the size of the area on the specimen from which information is collected and transferred to CRT image or computer memory. Usually the Picture Element is considered as a circle or square, described by a linear measure of diameter or edge length. Considering the rectilinear scan to be divided into equal sized square boxes filling all of the scan frame, the linear dimension D pixel of the picture element is given by the expression. D PE equal to L specimen divided by N PE. Where, L spec is the length of the scan on the specimen and N PE is the number of discrete location along the scan line.

So you can see that the size of the picture element as a function of magnification. So, you have this magnification 10x, 100x, 10000x and so on. You have the corresponding edge dimension of the picture element, given as 10 micron, 1 micron, 0.1 micron and so on.

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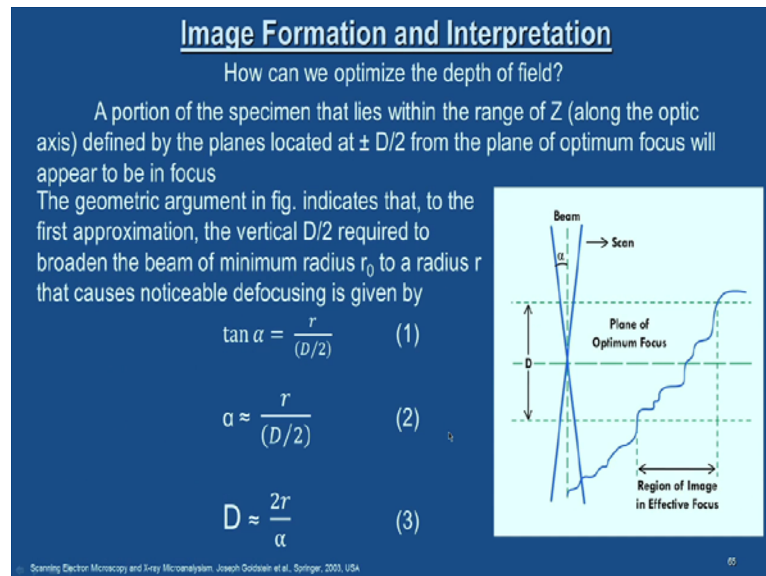

As we all know that in SEM the very important feature is the depth of field. We discussed in the beginning as well as in some of theory involved, the depth of field in SEM is the important feature. So, how can we optimize the depth of field?

So let us look at this schematic. This is the a specimen surface where the beam is falling on this, and suppose if you assume this is the plane of optimum focus where the beam converges and this is your alpha, and let us assume that this is a kind of a fracture surface which is having lot of uneven ups and downs or lot of inclinations. With this figure in mind let us look at the remarks, a portion of the specimen that lies within the range of Z along the optic axis defined by the planes located at plus or minus D by 2 from the plane of optimum focus will appear to be in focus.

So let us assume this is the plane of optimum focus. So, this distance is D by 2. From the geometry, argument in the figure indicates that to the first approximation, the vertical D by 2 required to broaden the beam of minimum radius r naught to a radius r that causes

noticeable defocusing is given by, tan alpha is equal to r by D by 2. So, with this geometry, it valid's; where, the minimum radius r naught from there it opens to r. Where, alpha is the glancing angle which is approximated to r by D by 2 where d is equal to 2 r by alpha.

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Image Formation and Interpretation

How can we optimize the depth of field?

On a high resolution CRT display where the spot size = 0.1 mm, most observers will find that defocusing becomes detectable when two pixels are fully overlapped, that is, when the condition in figure and eqn. (3) has been reached with r =1 pixel.

The pixel size refrred to the specimen space is given by 0.1 mm/M, where M is the magnification. Substituting r = 0.1/M into eqn. (3) gives a practical expression for the depth of field

$$D \approx 2(0.1mm/M)/\alpha = 0.2\ mm/\alpha M \quad (4)$$

Eqn. (4) indicates that to increase the depth of focus D, the microscopist can choose to reduce either M or α. The divergence angle is adjusted by the section of the final beam defining aperture. For aperture with, located at the scan crossover in the exit of the objective lens and working distancradius R_{ap} e, D_W we find

$$\alpha = R_{Ap}/D_W \quad (5)$$

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So, on a high resolution CRT display where the spot size is 0.1 mm, most observe will find that defocusing becomes detectable when the 2 pixels are fully overlapped, that is when the condition in figure and the equation 3 has been reached with r is equal to 1 pixel. The pixel size referred to the specimen space is given by 0.1 mm by M, where M is the magnification. Substituting r is equal to 0.1 divided by M into the equation 3 gives a practical expression for the depth of field. That is, D is approximately equal to 2 times 0.1 mm by M divided by alpha which is equal to 0.2 mm divided by alpha M.

This equation 4 indicates that to increase the depth of focus D, the microscopist can choose to reduce either M or alpha. Normally we are interested in higher magnification. So, the divergence angle is adjusted by the section of the final beam defining aperture. For aperture with, located at the scan crossover in the exits of the objective lens and working distance radius R ap, and D w, we find that alpha is equal to R AP divided by D

w. So, from this expression you can see that how one can optimize the depth of field in a SEM.

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Now, we will move on to some of the characteristics of detectors. As I mentioned that the detectors a play very important role in obtaining the quality images, and we just look at the characteristic of the detectors and then we will move on to the actual details.

Where is the detector relative to the beam and the specimen? That is under the pole piece, where exactly your detector is kept and where exactly your specimen is placed. So, if you recall in the laboratory demonstration the specimen is placed just below the pole piece, and for a detectors are kept in the particular angle in the side, one of the sides. How large is the detector? And how efficient is the detector for converting radiation which strikes the collection area into signal? And what is the bandwidth of the detector or amplification system? So, here is a schematic which clearly shows. So the detector is kept at an angle, I would see the take of angle psi, the angle between specimen surface and the line connecting the center of the detector is psi, and the how large is a detector which is a defined by the solid angle omega, which is equal to area of the detector divided by the radial distance r square, which is defined by the solid angle.

You can understand this by a sphere has got the solid angle of 4 pi. How efficient is the detector for converting radiation which strikes the collection area into signal? You see you the signal which is coming out of the specimen have got a wide range of signals with varying energies.

How efficient the detector can convert this into the useful signal is also an important aspect, we will just see that; some of the examples how we can understand this. What is the bandwidth of the detector or amplification system? So, each detector will have a set of bandwidth. For example, if you are scanning a very fine details and then your signal frequency will be very very high, in fact your signal is converted into time domain that is a high frequency so that means, each detector will have a frequency cut off beyond which the detector will not collect that signal and then you will lose that information. So this, the bandwidth of the detector is also an important aspect of the detectors. So, the signal which is being collected from the specimen it is primarily depend upon the type of detectors and it is efficiency which depends upon this four parameters what we have discussed.

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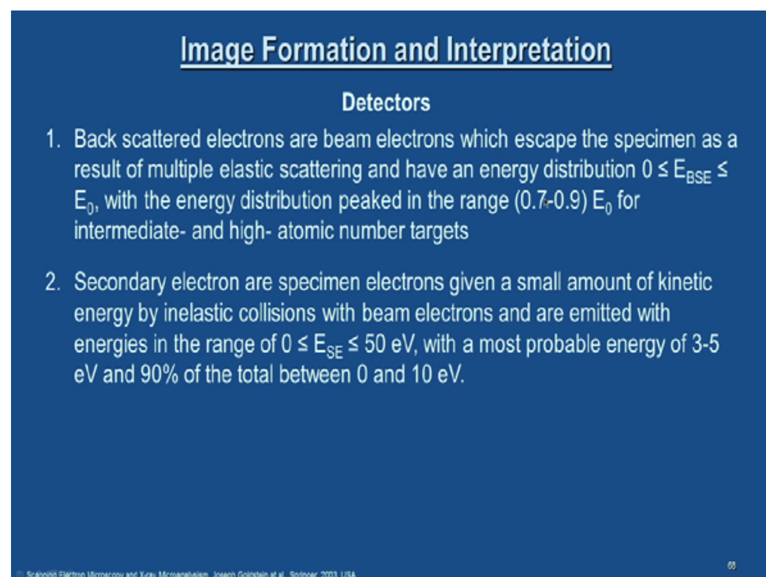

So, when we talk about detectors we have already classified this signals, let us recollect those. Back scattered electrons are beam electrons which escape the specimen as a result

of multiple elastic scattering and they have an energy distribution between 0 less than or equal to BSE less than or equal to E naught, with the energy distribution peaked in the range 0.7 to 0.9 E naught for a intermediate- and high- atomic number targets. This is the kind of characteristic of BSE's.

Secondary electron are specimen electrons given a small amount of kinetic energy by inelastic collisions with the beam electrons and are emitted with energies in the range of that is they are between 0 and 50 electron volts, with a most probable energy of 3 to 5 electron volts and 90 percent of the total signals between 0 and 10 electron volts. So, this is about the primary signals.

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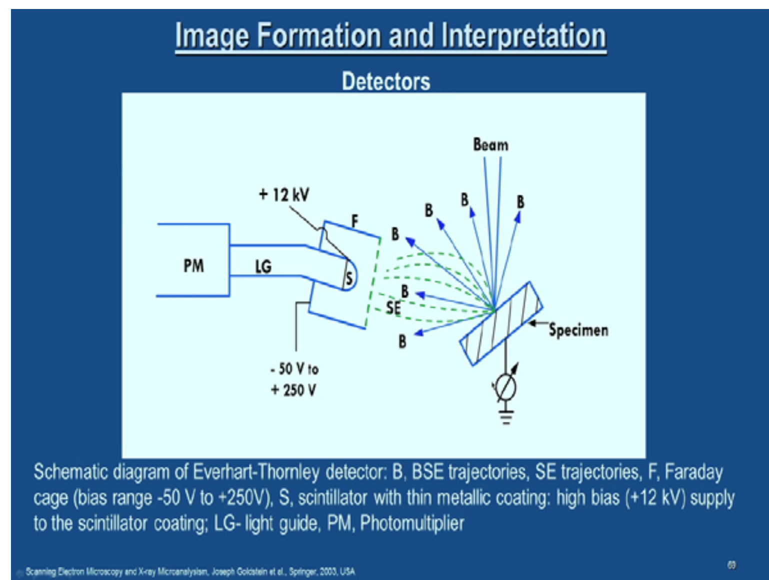

And what I am just showing the detector in the schematic is a very a popular detector called Everhart-Thornley detector. In 1960’s these detectors were invented from a Cambridge group, and almost all the SEM’s will have this E-T detectors, so called ETD, E-T detectors. And this detector is capable of capturing both secondary electrons as well as back scattered electrons, and as we have already seen this is the faraday cage and this is a scintillator and this can be operated with the biased voltages either minus 50 volt to plus 250 volt depending upon what kind of signal we want to collect.

What you are now see here is, a signals are coming from the specimens, the solid lines are back scattered electrons, a broken lines are secondary electrons which is coming from the specimen. And that is how it is given in this description, image description. So, you have back scattered electron trajectories, secondary electron trajectories, a F' s of faraday cage which is this and you can give the bias voltage in the range of minus 50 to volt to plus 250 volts. S is scintillator with the thin metallic coating, high bias plus 12 kilo volt supply to the scintillator coating, LG is light guide and PM, is a Photomultiplier. So, this is a typical detector schematic, ETD which is primarily used in most of the SEM's.

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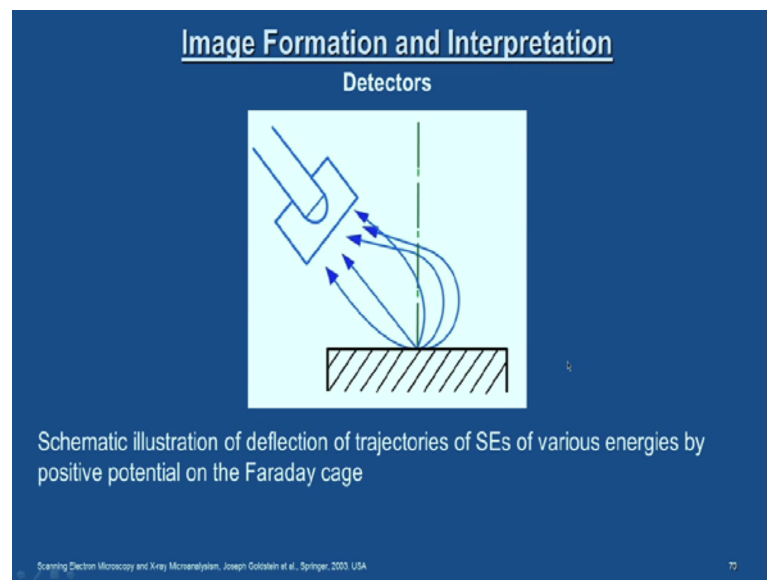

This is the schematic illustration of deflection trajectories of secondary electrons of various energies by positive potential on the faraday cage. You see in the ETD also which is capable of collecting both secondary electrons as well as a back scattered electrons. So, depending upon how we energize the detector or how it is biased for example, the detector has the positive potential on the faraday cage it will deflect the trajectories of secondary electrons like this. If it is a negative potential it will collect only the back scattered electrons.

So, you can go back and then see the one more important point what you can understand from this. You see the back scattered electrons the trajectories are quite straight line, just to indicate that they are all high energy electrons as compare to secondary electrons. We will just look at the collection details of this, with respect to the specimen geometry in due course.

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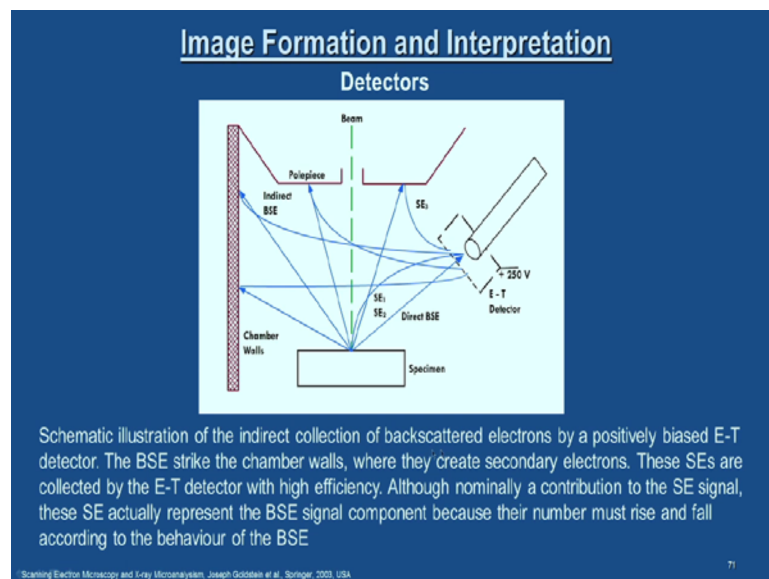

See, another important information about the detector is shown in the schematic. What you are now seeing in this schematic illustration of the indirect collection of back scattered electrons by a positively biased E-T detector. What you see here is this is a pole piece and this is the electron beam which is coming and falling on the specimen surface and then you get signals coming out of the specimen surface like BSE and SE’s.

What you are now seeing here is, you have this E-T detector a positively biased so that means it can collect both BSE as well as SE. The important information which you have to observe in this schematic is, you see all this back scattered electron which are shown to the a solid line which hits the bottom surface of the pole piece as well as the chamber walls. In that interaction they lose lot of energy in that process it produces SE 2 and SE 3 of varying energies, and then they are being collected by the E-T detector.

So we have being telling that, SE secondary electrons contribute to the image contrast. We will see what this SE 2 and SE 3 will represent in terms of image contrast and so on in the coming slides. So, what you have to appreciate from this schematic is, the BSE strike the chamber walls, where they create a secondary electrons, that is conversion of BSE to SE. These secondary electrons are collected by the E-T detector with high efficiency although nominally a contribution to the secondary electron signal, these secondary electron actually represent the BSE signal component because their number must rise and fall according to the behavior of the BSE. We will see why we talk about the number of these electrons is important.

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Image Formation and Interpretation

Contrast

Contrast can be influenced by a complex mix of the characteristics of the beam – specimen interaction, the properties of the specimen, the nature of the signal carriers and the position, size and the response of the detector. There are three different ways the contrast can be measured:

- ***Number component*** – different number of electrons leaving the specimen at different beam locations in response to changes in the specimen characteristics at those locations
- ***Trajectory component*** – The trajectory component refers to contrast effects resulting from the paths the electrons travel after leaving the specimen
- ***Energy component*** – The energy component arises when the contrast is carried by a certain portion of the BSE energy distribution. Typically, the high-energy backscattered electrons are the most useful for imaging contrast mechanisms

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So, now we will come to the important aspect of this lecture is on Contrast. Everybody is interested in a good contrast images, and we have already seen the basic definition of a contrast when we looked at the fundamentals. So, you know the definition of the contrast. In SEM, contrast can be influenced by a complex mix of characteristics of beam- specimen interaction, the properties of the specimen, the nature of the signal carries and the position, size and the response of the detector. You see n number of variables now come in to contribute or influence the image contrast. There are three different ways the contrast can be measured: one is Number component and second is Trajectory component and third is Energy component.

So, the Number component, what is that, different number of electrons leaving the specimen at the different beam location in response to changes in the specimen characteristics at those locations. So it is that, how many electrons are coming out of this specimen surface is also an important aspect. And then you have Trajectory component- The trajectory component refers to a contrast effects resulting from the paths the electrons travel after leaving the specimen. You see the electrons are coming out of the specimen surface, as I shown in the previous slide you can see that the electron travels in a very arbitrary path ways depending upon the energy it has, if it is having a high energy, if it is a BSE the trajectories are almost straight.

If it is a secondary electron that is low energy electrons the trajectories are quite arbitrary. And even when the BSE goes and hits on the pole piece or a chamber walls then it becomes again loses energy and becomes a SE 2 and SE 3 and then they are trajectories are also quite arbitrary. So, the trajectory is very important. The energy component- The energy component arises when the contrast is carried by a certain portion of the BSE energy distribution. Typically, the high energy back scattered electrons are the most useful for imaging contrast mechanisms.

So, what you have to appreciate here is, when it comes to the contrast of the imaging these three components have an important role to play whether you get an secondary electron image or a back scattered electron image. So, we will see one by one how these three components a play a crucial role in the case of contrast types. What are the contrast types we talk about, we talk about a composition contrast or atomic number contrast or z contrast, and they are all same. And then second type is a topographic contrast. There are two primary contrast types we will look at those contrast types and it details. Then how these three components contributes to each type under what conditions and then what is the contribution from the detectors and it is location and geometry and so on in the next class.

Thank you.