Fundamentals of Optical and Scanning Electron Microscopy

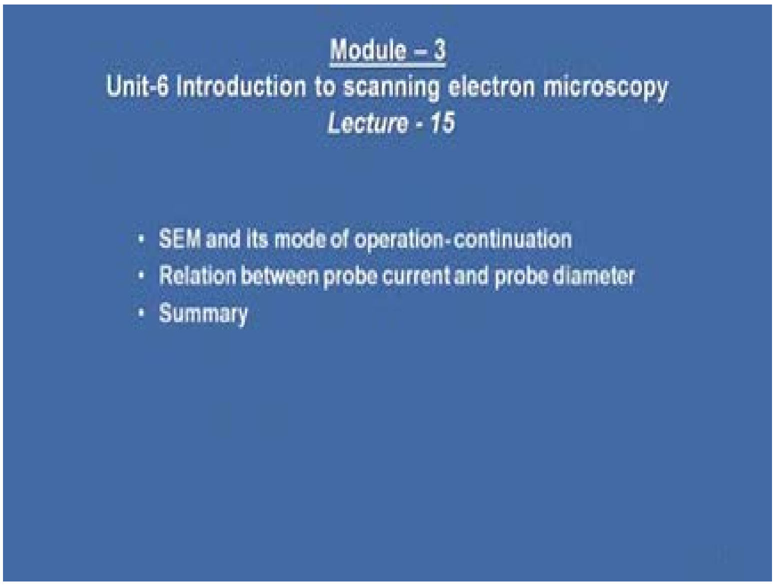
Prof. Dr. S. Sankaran
Department of Metallurgical and Materials Engineering
Indian institute of Technology, Madras

Module - 03

Lecture - 15

Introduction to Scanning electron microscopy

(Refer Slide Time: 00:10)

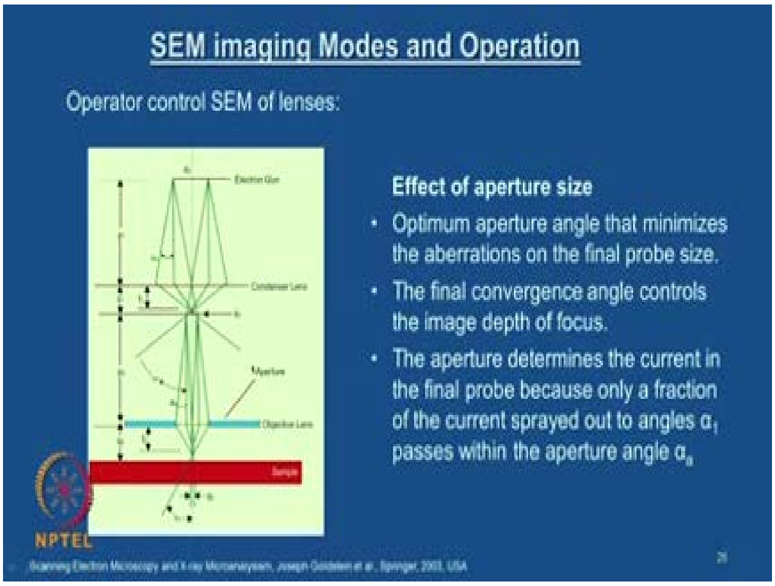


Module – 3
Unit-6 Introduction to scanning electron microscopy
Lecture - 15

- SEM and its mode of operation-continuation
- Relation between probe current and probe diameter
- Summary

Hello everyone, welcome to this material characterization course. In the last class, we just looked at the concept of scanning electron microscopy functions, and this basic instrumentation and its controls and operator controls and so on. We will continue this discussion, and then we will look at much more details about the electron beam specimen interactions and what is that going to affect your ultimate resolution and its effect on main in general imaging.

(Refer Slide Time: 01:08)



SEM imaging Modes and Operation

Operator control SEM of lenses:

Effect of aperture size

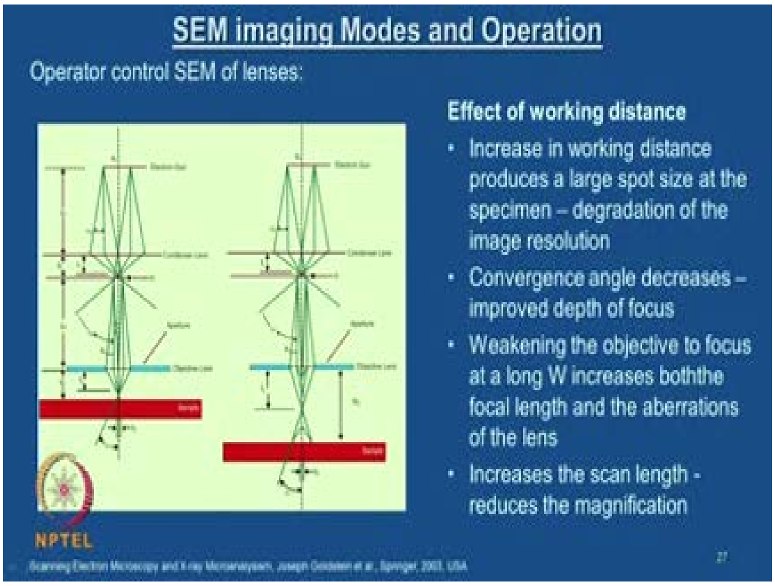
- Optimum aperture angle that minimizes the aberrations on the final probe size.
- The final convergence angle controls the image depth of focus.
- The aperture determines the current in the final probe because only a fraction of the current sprayed out to angles α_1 passes within the aperture angle α_a

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

So, if you look at the control switch I talked about yesterday, we will just quickly review this. We just started looking at the operator control in SEM of lenses, we have three primary parameters one of them is the aperture. So, this schematic clearly shows that if the final aperture which basically controls the probe diameter which finally impinges on the sample by controlling this objective lens. And this is what we just summarized here the optimum aperture angel that minimizes the aberration on the final probe size. The final convergence angle controls the image depth of focus.

The aperture determines the current in the final probe because only a fraction of the current sprayed out to the angles alpha 1 passes within the aperture angle alpha a. So, if you look at this the initial spread of current this what it is mentioned here, the current sprayed in alpha 1, eventually it is controls by this aperture and then it makes alpha a, this aperture angle and eventually it controls the probe size. This is one of the primary parameters, which is in control of the operator.

(Refer Slide Time: 02:56)



SEM imaging Modes and Operation

Operator control SEM of lenses:

Effect of working distance

- Increase in working distance produces a large spot size at the specimen – degradation of the image resolution
- Convergence angle decreases – improved depth of focus
- Weakening the objective to focus at a long W increases boththe focal length and the aberrations of the lens
- Increases the scan length - reduces the magnification

NPTEL

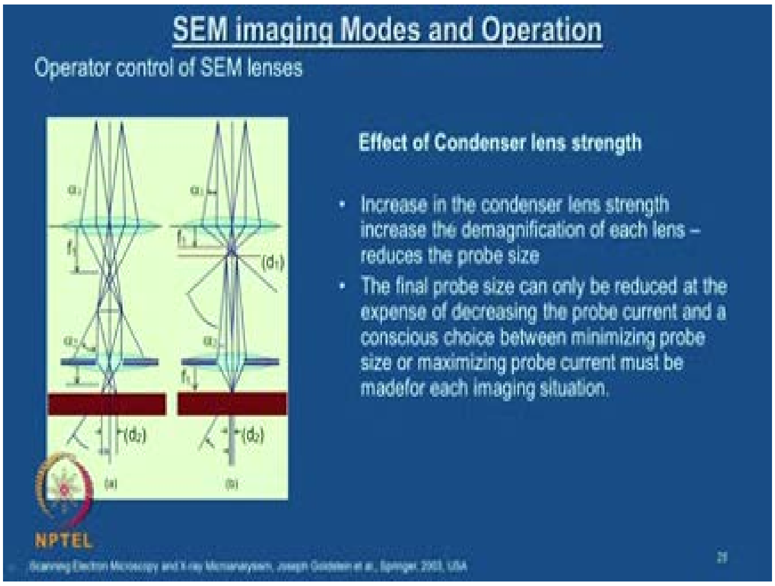
Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

27

And then we can see the next one the working distance. We also define this, what is the working distance; it is the distance between the final aperture and this specimen surface. And you can clearly see this effect of working distance from these two schematics, which is quite evident that if you increase the working distance, you are increasing the probe size. You carefully look at it, you can see that the probe size is increased now and obviously it will have some significant effect on the resolution.

So, we summarize this increase in working distance produces a large part size at this specimen and which will cause the degradation of the image resolution. And also you see that convergence angle decreases which will result in improved depth of focus. And increasing working distance will also cause weakening the objective to focus at a long working distance w, which eventually increases both the focal length and the aberration of the lenses. So, which is very clear it is shown in this schematic, and which also increases the scan length and which will cause reduction in the magnification as well. So, this is again very important parameter which an operator can have a control on this, and then take appropriate decision depending upon what information we are looking at on this specimen surface.

(Refer Slide Time: 04:52)



SEM imaging Modes and Operation

Operator control of SEM lenses

Effect of Condenser lens strength

- Increase in the condenser lens strength increase the demagnification of each lens – reduces the probe size
- The final probe size can only be reduced at the expense of decreasing the probe current and a conscious choice between minimizing probe size or maximizing probe current must be madefor each imaging situation.

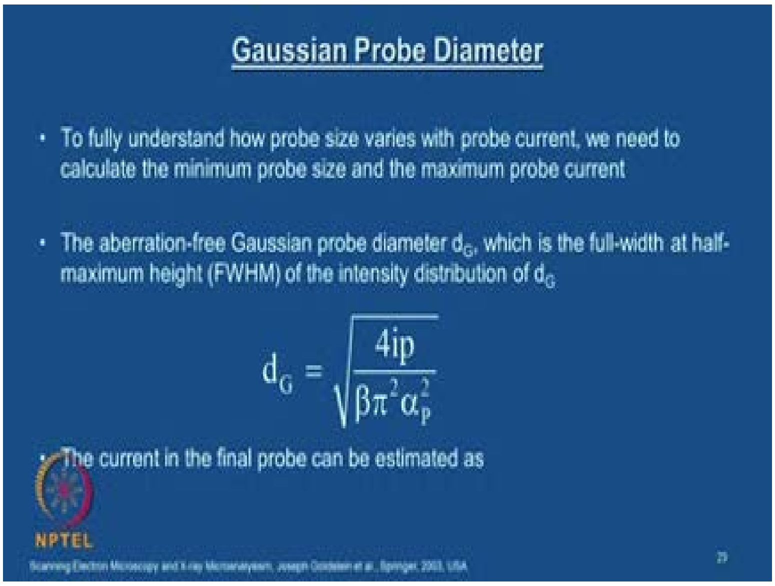
NPTEL

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

The third one is the condenser lens strength, which operator can control, which is also is nicely shown in the schematic. If you increase the condenser length strength, which increases the demagnification of each lens, which will cause again the reduction in the probe size. So, you can see that effect very clearly if on this schematic. So, this is the first schematic is for a given field strength, if you increase it further, you can see that the final probe size is completely reduced.

You can see this, this is the initial probe size with for a given field strength; but if you increases from that, and you see that there is a control of the probe diameter. So, the final probe size can only be reduced at the expense of decreasing the probe current and a conscious choice between minimizing the probe size or maximizing the probe current must be made for each imaging situation. So, this is exactly I was just mentioning that all these parameter controls has to be done as per the requirement for the appropriate information we are looking at from the specimen and it is completely in the user control.

(Refer Slide Time: 06:29)



Gaussian Probe Diameter

- To fully understand how probe size varies with probe current, we need to calculate the minimum probe size and the maximum probe current
- The aberration-free Gaussian probe diameter d_G, which is the full-width at half-maximum height (FWHM) of the intensity distribution of d_G

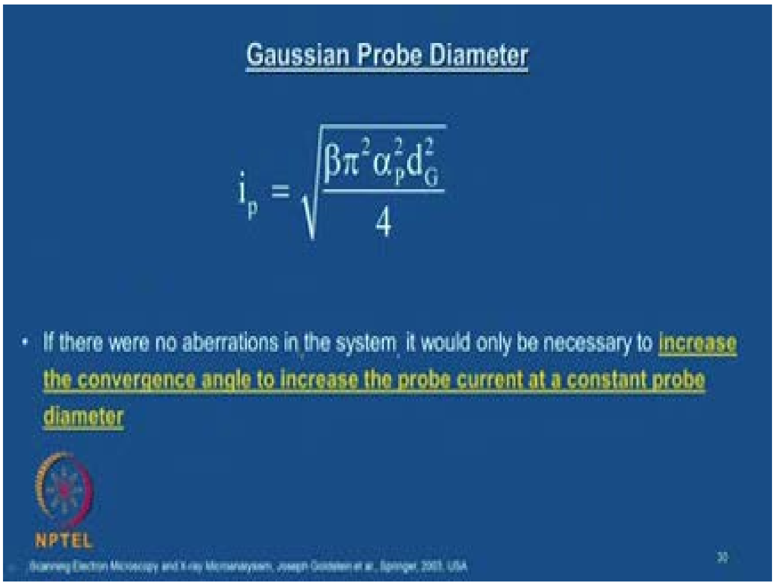
$$d_G = \sqrt{\frac{4ip}{\beta\pi^2\alpha_p^2}}$$

- The current in the final probe can be estimated as

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

So, now we will move onto the probe diameter which yesterday we quickly reviewed. I just want to give an emphasize on the probe diameter again, because whatever we have just seen before ultimately the parameters controls a probe diameter, which results in the complete a resolution as well as and its effects on the imaging process. So, to fully understand how the probe size varies with the probe current, we need to calculate the minimum probe size and the maximum probe current. See in a idealized situation, the aberration-free Gaussian probe diameter d G, which is the full width at half maximum height of the intensity distribution of d G is given by d G is equal to square root of 4 ip divided by beta pi square alpha p square.

(Refer Slide Time: 07:40)



Gaussian Probe Diameter

$$i_p = \sqrt{\frac{\beta \pi^2 \alpha_p^2 d_G^2}{4}}$$

- If there were no aberrations in the system, it would only be necessary to increase the convergence angle to increase the probe current at a constant probe diameter

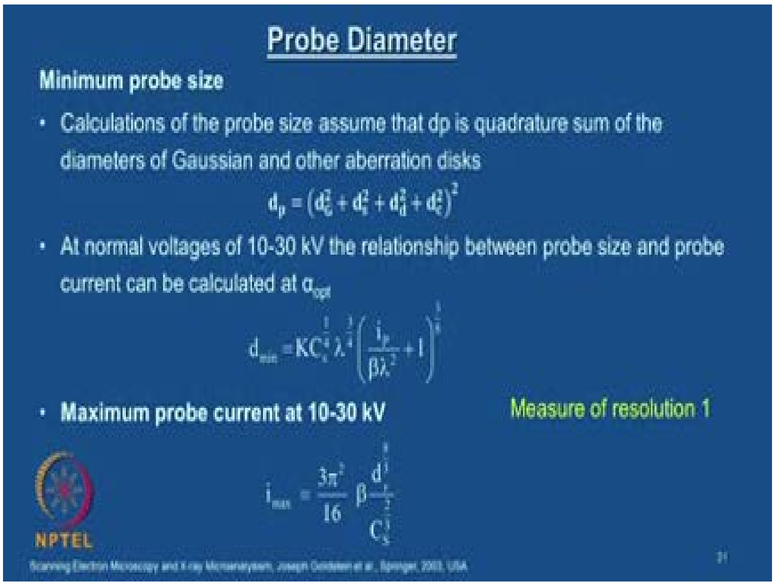
NPTEL

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

30

The current in the final probe can be estimated as i p is equal to square root of beta pi square alpha p square and d G square divided by 4. If there were no aberrations in the system, it would only be necessary to increase the convergence angle to increase the probe current at a constant probe diameter. See, why we talked about this Gaussian probe diameter, because this is the one, which we will start with to mathematically quantify assuming there is no aberration at all. But eventually that is not going to be the case, you are going to have the effect of each aberrations which we talked about in an electron optical system and then we can see how this Gaussian probe diameters modified because of this aberrations that is what we have looking at finally, is a real probe diameter.

(Refer Slide Time: 08:43)



Probe Diameter

Minimum probe size

- Calculations of the probe size assume that dp is quadrature sum of the diameters of Gaussian and other aberration disks

$$d_p = \left(d_G^2 + d_s^2 + d_d^2 + d_c^2\right)^2$$

- At normal voltages of 10-30 kV the relationship between probe size and probe current can be calculated at α_{opt}

$$d_{min} = KC_s^{\frac{1}{4}}\lambda^{\frac{3}{4}}\left(\frac{i_p}{\beta\lambda^2}+1\right)^{\frac{3}{8}}$$

- **Maximum probe current at 10-30 kV**

Measure of resolution 1

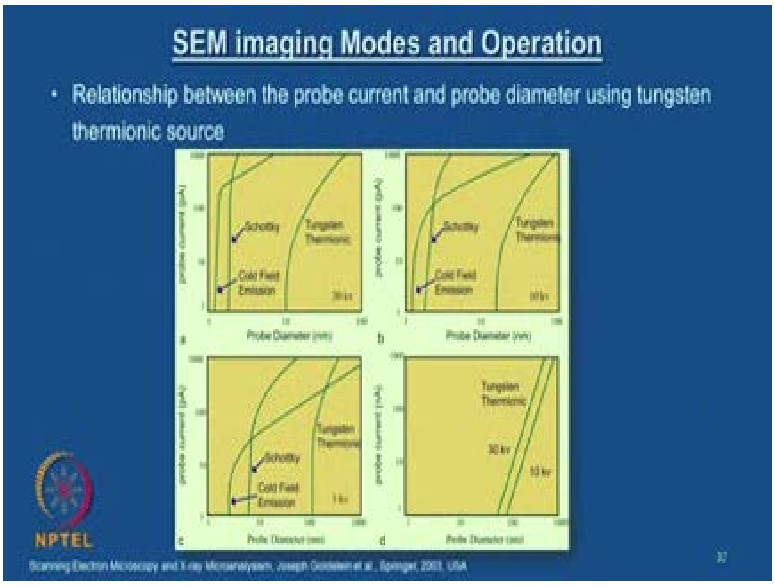
$$i_{max} = \frac{3\pi^2}{16}\beta\frac{d_p^{\frac{8}{3}}}{C_s^{\frac{2}{3}}}$$

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

So, if you look at the minimum probe size, involving all this aberrations. Calculations of the probe size assume that d p is quadrature sum of the diameters of Gaussian and other aberration disks. You look at this expressions, there was a little bit of typo which was there was in the yesterday presentation, I have made the corrections. You see that d p is equal to d G where d G is Gaussian probe diameter and d s square - spherical aberration diameter plus d d square this is a diffraction disk plus d c which is chromatic aberration whole to the power half. At normal voltages, sorry I just did a mistake this is not whole to the power of, it is square. So, d p is equal to d G square plus d s square plus d d square plus d c square whole to the power square.

At normal voltage of 10 to 30 kilo volt, the relationship between the probe size and the probe current can be calculated at alpha optimum which is d minimum is equal to K C s to the power half lambda to the power three by 4 times i p by beta lambda square plus 1 whole to the power 3 by 8, where C s is the spherical aberration coefficient. Here only considering this aberration, this expression is valid. It is assumed that other aberrations do not have a significant influence on that circumstances this expression is valid. Maximum probe current at 10 to 30 kilo volt, you have the i max equal to 3 pi square by 16 times beta into d p to the power 8 by 3 divided by C s to the power 2 by 3. So, it is a kind of maximum resolution one can obtain in the presence of other aberration effects.

(Refer Slide Time: 11:03)



SEM imaging Modes and Operation

- Relationship between the probe current and probe diameter using tungsten thermionic source

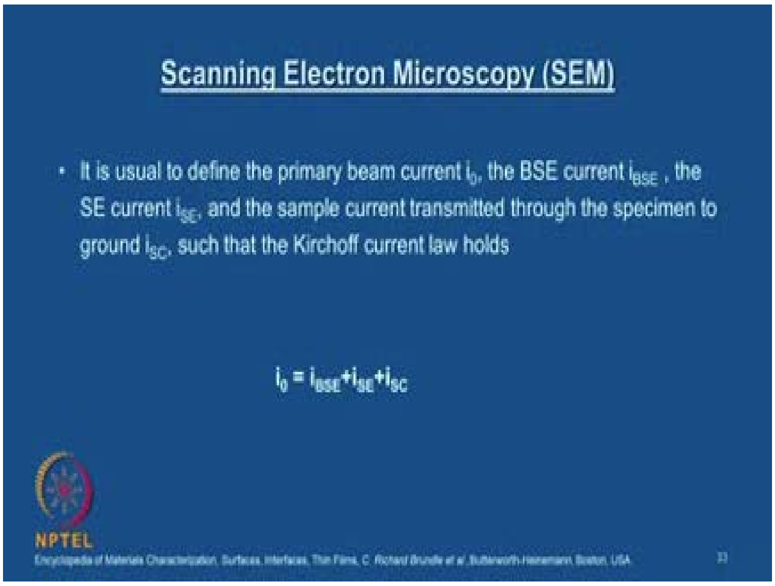
Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

Now, we will look at the plots where the relationship between the probe current and the probe diameter using tungsten thermionic source. You see in the beginning, we just looked at all the electron gun sources I just mentioned, there are two types one is thermionic source, and another is field emission source. So, this how this probe current and probe diameter varies with the tungsten thermionic source versus the field emission source is shown in all this four plots. You can carefully look at this the probe diameter, which is varying from 1 to 100 nano meters versus probe current which is a normal imaging condition. Ynd you can see that you have these thermionic field I mean thermionic source and as well as you have the field emission source.

Obviously, we can see that field emission source exhibit a superior probe diameter for at the given 30 kilo volt, this is a normal imaging. And then you have another low kv imaging; you can see that similar lots are obtained. And the lot c, shows very low voltage imaging, where you can see that how the probe current varies with the probe diameter. And this is kind of a plot, where mostly this kind of situation is used for the chemical analysis. And you can see most of this plots shows that the field emission gun source exhibit superior diameter compare to the thermionic source.

And then it also varies with the as a function of operating voltage. Just to give you an idea how this electron sources controls a probe diameter as a function of operating voltage, we will look at this aspect in the imaging and its resolution and so on in the due course.

(Refer Slide Time: 13:40)



Scanning Electron Microscopy (SEM)

- It is usual to define the primary beam current i_0, the BSE current i_{BSE} , the SE current i_{SE}, and the sample current transmitted through the specimen to ground i_{SC}, such that the Kirchoff current law holds

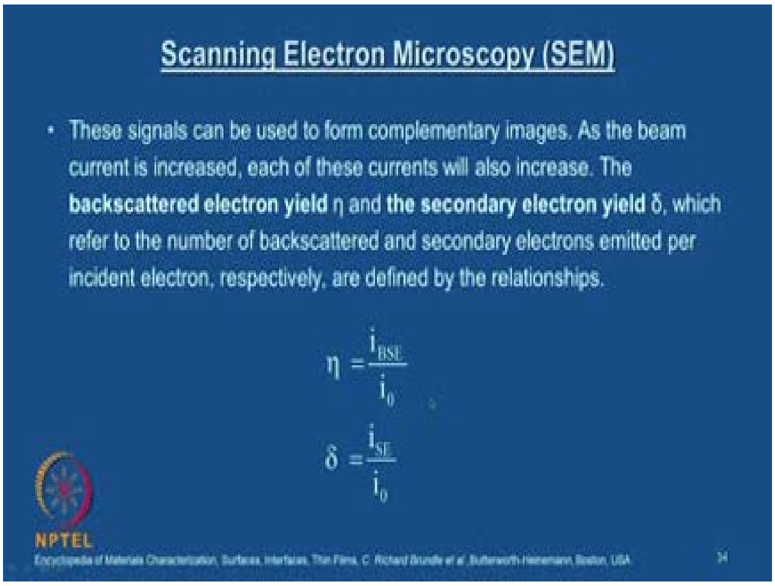
$$i_0 = i_{BSE}+i_{SE}+i_{SC}$$

NPTEL

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al. Butterworth-Heinemann, Boston, USA

So, now we will look at the much more detail about this the probing current and so on. It is usual to define the primary beam current i naught, the back scattered electron current i BSE, the SE current is i SE, and the sample current transmitted through the specimen to the ground is i SC such that the Kirchhoff current law holds. So, the primary beam current can be as can be represented as a summation of i BSE plus i SE plus I SC.

(Refer Slide Time: 14:26)



Scanning Electron Microscopy (SEM)

- These signals can be used to form complementary images. As the beam current is increased, each of these currents will also increase. The **backscattered electron yield** η and **the secondary electron yield** δ, which refer to the number of backscattered and secondary electrons emitted per incident electron, respectively, are defined by the relationships.

$$\eta = \frac{i_{BSE}}{i_0}$$

$$\delta = \frac{i_{SE}}{i_0}$$

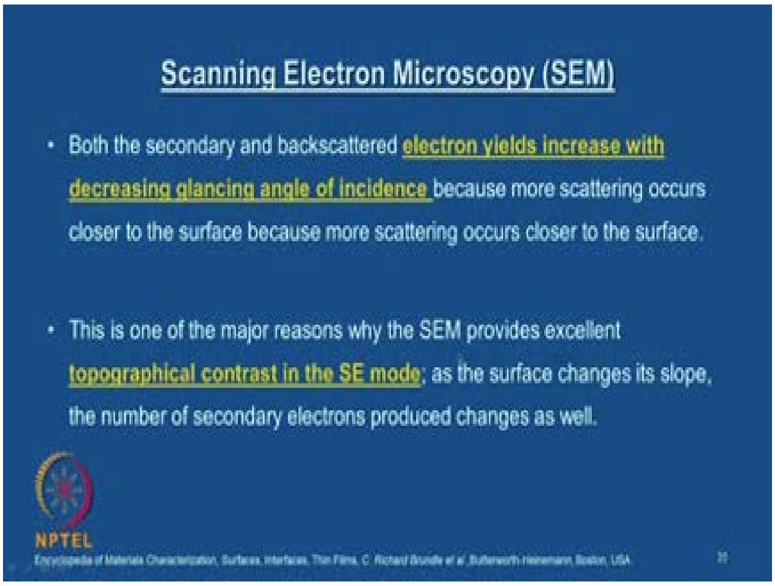
NPTEL

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al. Butterworth-Heinemann, Boston, USA

And we are interested the signals which is coming out of the samples. So, basically how they are quantified, we know that a secondary electron signal and the back scattered electron signals are going to come out from the sample and how they are quantified this is what is about we will see. So, these signals can be used to form complementary images.

As the beam current is increased, each of these currents will also increase. The back scattered electron yield eta and the secondary electron yield delta, which refer to the number of back scattered and secondary electrons emitted where incident electron respectively are defined by the relationships. Where eta is equal to i BSE that is the back scattered electron current divided by i naught. Similarly, the secondary electron yield delta is i SE divided by i naught.

(Refer Slide Time: 15:39)



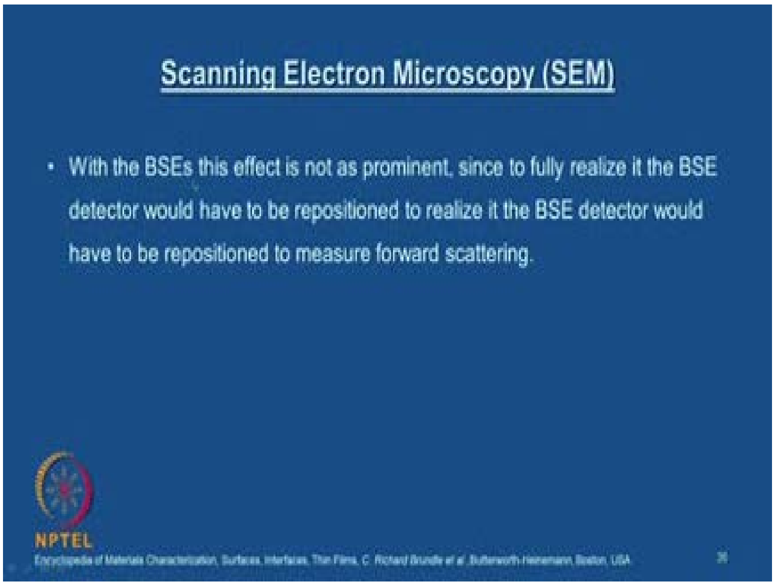
Scanning Electron Microscopy (SEM)

- Both the secondary and backscattered electron yields increase with decreasing glancing angle of incidence because more scattering occurs closer to the surface because more scattering occurs closer to the surface.
- This is one of the major reasons why the SEM provides excellent topographical contrast in the SE mode; as the surface changes its slope, the number of secondary electrons produced changes as well.

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al, Butterworth-Heinemann, Boston, USA

Both the secondary and backscattered electron yields increase with decreasing glancing angle of the incidence, because more scattering occurs closer to the surface because more scattering occurs closer to the surface. This is one of the major reasons why the SEM provides an excellent topographical contrast in the SE mode; as the surface changes its slope, the number of secondary electrons produced changes as well. This point we just discussed in the introduction of the SEM class as well; I just mentioned why only these two signals BSE and SE for widely use in SEM that is because only these two signals vary as a surface modulation or surface slope changes very sensitive to the surface unevenness.

(Refer Slide Time: 16:46)



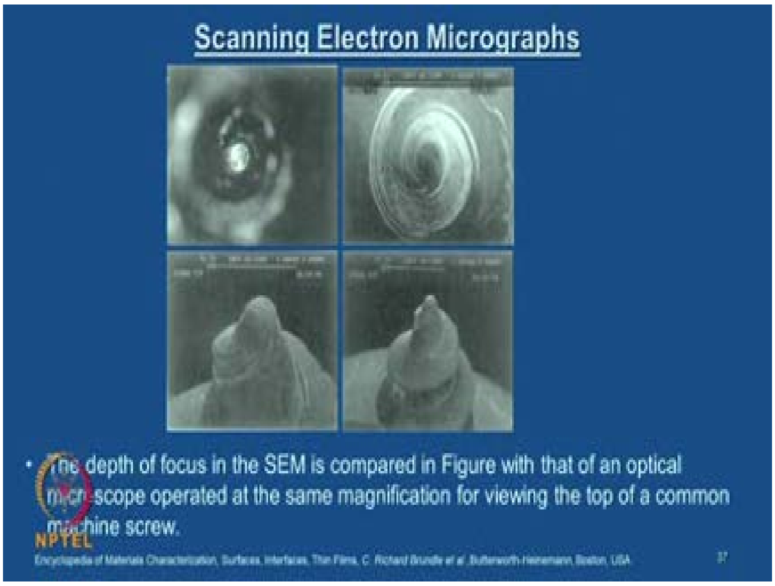
Scanning Electron Microscopy (SEM)

- With the BSEs this effect is not as prominent, since to fully realize it the BSE detector would have to be repositioned to realize it the BSE detector would have to be repositioned to measure forward scattering.

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al, Butterworth-Heinemann, Boston, USA

With the backscattered electrons this effect is not as prominent, since to fully realize it the back scattered electron detector would have to be repositioned to realize it the backscattered detector would have to be repositioned to measure the forward scattering. This is an operation detail for detecting the signal; we will see how it is being actually done in the lab.

(Refer Slide Time: 17:13)



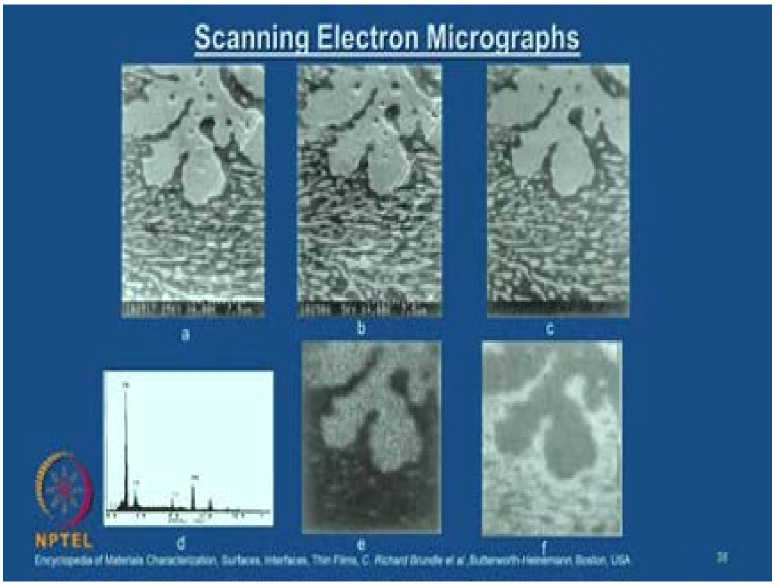
Scanning Electron Micrographs

- The depth of focus in the SEM is compared in Figure with that of an optical microscope operated at the same magnification for viewing the top of a common machine screw.

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al, Butterworth-Heinemann, Boston, USA

Another important aspect of this SEM we mentioned is a depth of focus. And this set of micro graph clearly illustrates that aspect. So, what you see here is this is the machine screw viewed at under the optical microscope; and this is under scanning electron microscope. You can see that in an optical microscope, you do not see any of this detail, when you look at this screw from the top. You can see the all the other the circular details of this screw. And the c and d are taken with the sides of the screw; you can see that the much more clear details are obtained using scanning electron microscope. This is just to illustrate that effect. You have very high depth of focus, and by now you know that why we get very good depth of focus.

(Refer Slide Time: 18:32)



Scanning Electron Micrographs

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al ,Butterworth-Heinemann, Boston, USA

Another set of micrographs illustrates the effect of both secondary electrons as well as backscattered electrons. What you are seeing is it is a led tin alloy surface; it is what we are seeing as bright as an eutectic led tin eutectic. People who do not understand this metallurgy of this, you can assume that there are two phases. And you can clearly see that this particular micrograph is obtained at 25 kv, and this micrograph the same region is obtained at 5 kv. And these two are obtained using secondary electrons, and the same region was imaged using backscattered electron in this image c. So, I would like you to look at these 3 images little more carefully.

And what is the difference, you are seeing. And if you are able to figure out the differences then that means, you have clearly understood the previous information what we have discussed. And if you are not able to catch that difference I will help you.

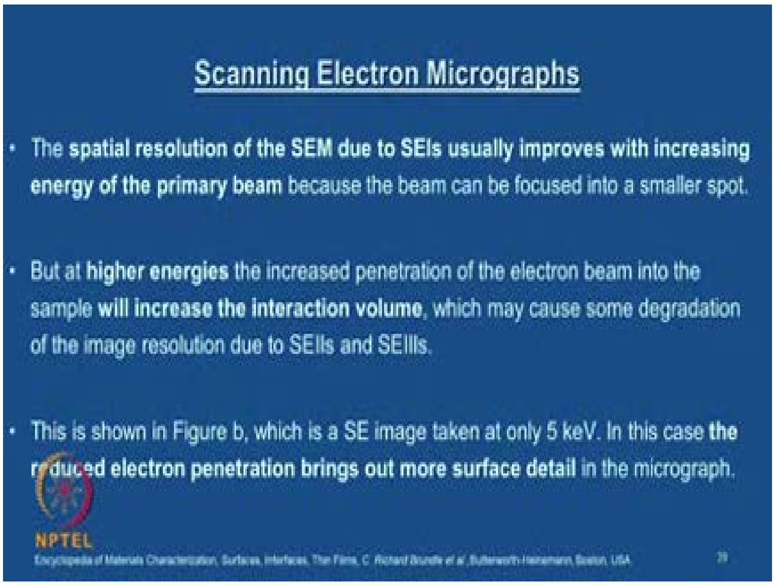
You look at this the scratch here, scratch mark here. And look at this scratch mark here, so you see that these two are even though they are obtained using these secondary electron signals, there is a small difference. And also you see that this scratch is not at all visible as clearly as in the micrographs obtained by secondary electron signals, so that clearly indicates that your secondary electrons are much more sensitive to the surface unevenness. And the difference between this a and b is because of further complications because of the electron specimen interaction. What is that you see that this micrograph is obtained at lower kv, high kv and this is obtained at 25 kv.

So, if you recall, we just discussed in the beginning of this lecture probably yesterday or day before yesterday, I had mentioned that the higher the operating voltage the severe will be the being specimen interaction. And then you also produce SE 1, SE 2 and SE 3 and these signals will get produced more if the electron beam specimen interaction is intense.

And when this SE 2 and SE 3 signals, they are not going to promote the topological details in fact, even they come out of this specimen they are going to interfere and reduce the resolution that is what is happening here. You can see that the scratch details are not as clear as what you see in the image b. So, it is not that if you keep on increasing the operating voltage you are not you are going to obtain much more clear image. There is an optimum voltage and other parameters under which circumstances you get the much clearer picture. So, this is just to explain that phenomenon.

And what you see in other images I mean this figure d is an EDS spectrum. And e and f are maps elemental analysis maps. And these particular about the spectra scoping details we will discuss later in a separate lecture series; right now, my focus is only on the SEM imaging. We will talk about this elemental analysis and how it is done and what are the limitations with the existing spectrometer and so on, we will discuss in a separate lecture series.

(Refer Slide Time: 23:30)



Scanning Electron Micrographs

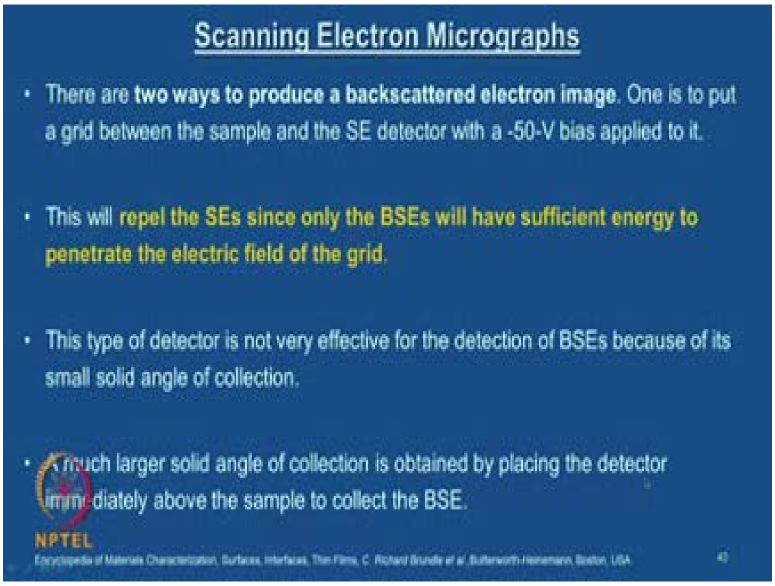
- The **spatial resolution of the SEM due to SEIs usually improves with increasing energy of the primary beam** because the beam can be focused into a smaller spot.
- But at **higher energies** the increased penetration of the electron beam into the sample **will increase the interaction volume**, which may cause some degradation of the image resolution due to SEIIs and SEIIIs.
- This is shown in Figure b, which is a SE image taken at only 5 keV. In this case **the reduced electron penetration brings out more surface detail** in the micrograph.

NPTEL

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al.,Butterworth-Heinemann, Boston, USA

Now, we will just summarize what we have just looked at in the previous slide. The spatial resolution of the SEM due to SE 1 usually improves with increasing energy of the primary beam because the beam can be focused into a smaller spot. But at higher energies the increased penetration of the electron beam into the sample will increase the interaction volume, we will quickly see in few minutes what is this interaction volume about, which may cause some degradation of the image resolution due to SE 2s and SE 3's. This is shown in figure b, which is a secondary electron image taken at only 5 kilo electron volt. In this case, the reduced electron penetration brings out more surface detail in the micrograph.

(Refer Slide Time: 24:29)



Scanning Electron Micrographs

- There are **two ways to produce a backscattered electron image**. One is to put a grid between the sample and the SE detector with a -50-V bias applied to it.
- This will **repel the SEs since only the BSEs will have sufficient energy to penetrate the electric field of the grid.**
- This type of detector is not very effective for the detection of BSEs because of its small solid angle of collection.
- A much larger solid angle of collection is obtained by placing the detector immediately above the sample to collect the BSE.

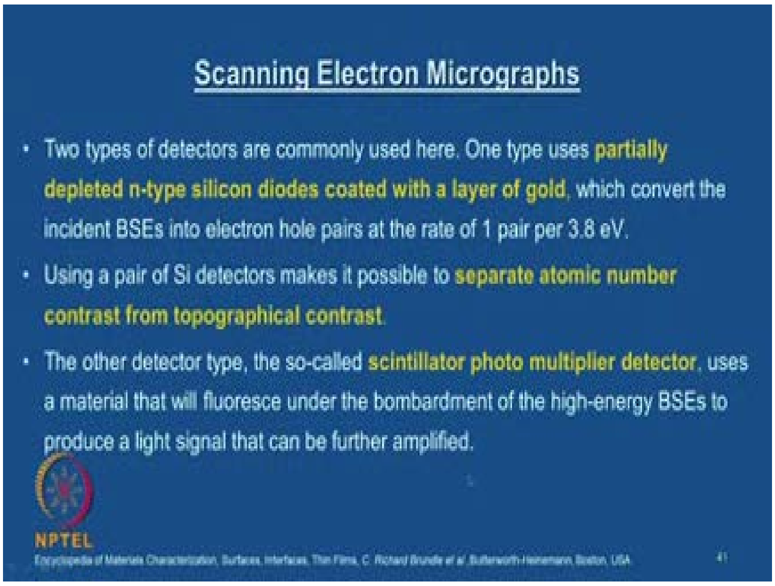
NPTEL

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al. Butterworth-Heinemann, Boston, USA

And if you look at the method of producing the backscattered electron image, there are two ways to produce BSE image. One is to put a grid between the sample and the secondary electron detector with a negative voltage that is minus 50-volt bias applied to it. If you recall when I just introduce the instrumentation schematic where I said that if you put positive voltage, it will collect both BSE and SE; if you put negative voltage, it will ripple and then it will collect only one, so similar thing, so that is the bias. This will ripple the SEs since only the BSEs will have sufficient energy to penetrate the electric field of the grid.

This type of detector is not very effective for the detection of BSEs because of its small solid angle of the collection. We will look at the detector system and it is details little more as we go long; and this right now we are does discussing about how this signals are collected, and how what are the immediate effect of these two individual signals on its image formation. A much larger solid angle of collection is obtained by placing the detector immediately above the sample to collect the BSE.

(Refer Slide Time: 26:07)



Scanning Electron Micrographs

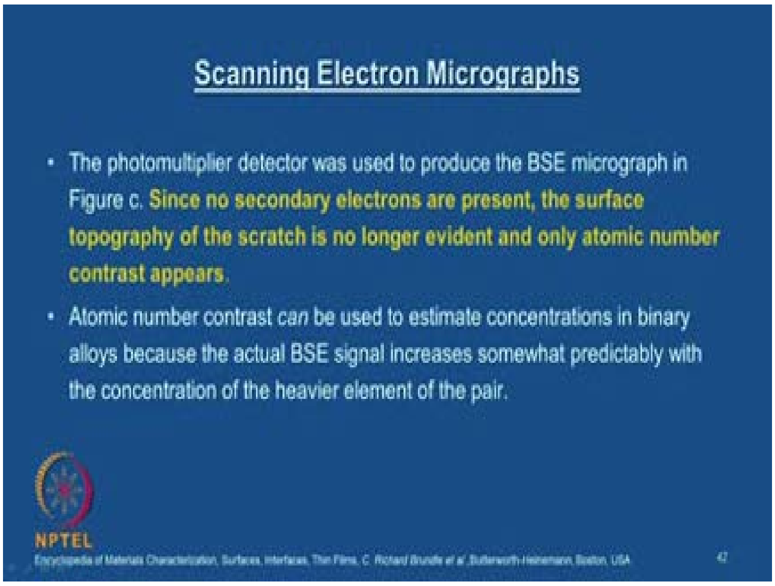
- Two types of detectors are commonly used here. One type uses **partially depleted n-type silicon diodes coated with a layer of gold**, which convert the incident BSEs into electron hole pairs at the rate of 1 pair per 3.8 eV.
- Using a pair of Si detectors makes it possible to **separate atomic number contrast from topographical contrast**.
- The other detector type, the so-called **scintillator photo multiplier detector**, uses a material that will fluoresce under the bombardment of the high-energy BSEs to produce a light signal that can be further amplified.

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al. Butterworth-Heinemann, Boston, USA

Two types of detectors are commonly used here. One type uses partially depleted n-type silicon diodes coated with a layer of gold, which convert the incident BSEs into electron hole pairs at the rate of 1 pair per - 3.8 electron volt. Using a pair of silicon detectors makes it possible to separate the atomic number contrast from topographical contrast.

The other detector type the so-called scintillator photo multiplier detector, uses a material that will fluoresce under the bombardment of the high-energy BSEs to the produce a light signal that can further amplified. So, these are all some of the specific operations of the type of detectors, which eventually give the image in CRT. We will look at these detectors separately, and we will talk about all the functions much more detail in the due course.

(Refer Slide Time: 27:17)



Scanning Electron Micrographs

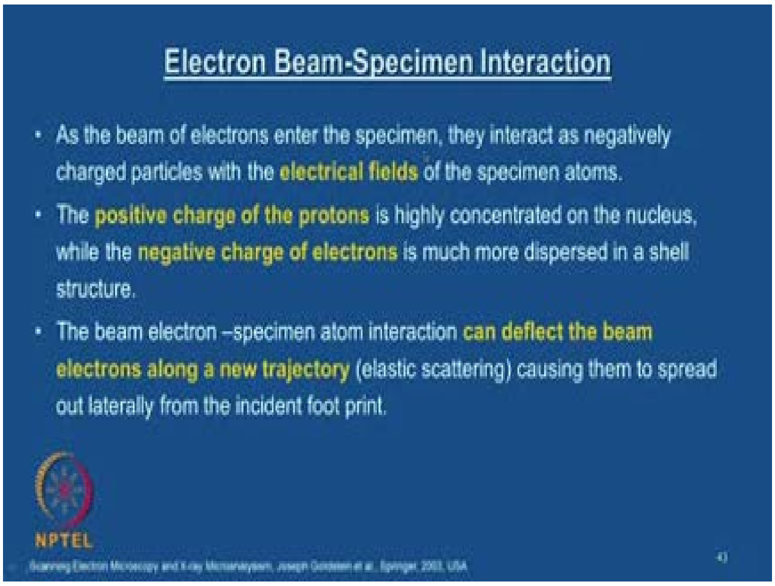
- The photomultiplier detector was used to produce the BSE micrograph in Figure c. Since no secondary electrons are present, the surface topography of the scratch is no longer evident and only atomic number contrast appears.
- Atomic number contrast *can* be used to estimate concentrations in binary alloys because the actual BSE signal increases somewhat predictably with the concentration of the heavier element of the pair.

Encyclopedia of Materials Characterization, Surfaces, Interfaces, Thin Films, C. Richard Brundle et al, Butterworth-Heinemann, Boston, USA

The photomultiplier detector was used to produce the BSE micrograph in figure c. What we have just seen in two slides before, since no secondary electrons are present, the surface topography of this scratch is no longer evident and only in atomic number contrast appears. Atomic number contrast can be used to estimate the concentrations in binary alloys because the actual BSE signal increases somewhat predictably with the concentration of the heavier element of the pair. So, this point is about the material detail. And what you have to understand is BSE is a sensitive to atomic number that we will anyway talk about much more detail when we discuss the image contrast and contrast mechanisms and so on.

Now we will divert our focus to very important aspect of imaging that is electron beam specimen interaction, in it involves lot of physics as scattering physics, we need to understand this clearly then only you will be able to interpret all the images which we are going to see. So, I would like to request all of you to pay much more attention to look at this particular section, this is more fundamental. It may be very difficult to understand in the beginning, but if you look at them again and again, and if you are finding it difficult to follow this, I request you to go through some of the basic physic book about these scattering phenomenon and then come back to the section then things will be all right.

(Refer Slide Time: 29:27)



Electron Beam-Specimen Interaction

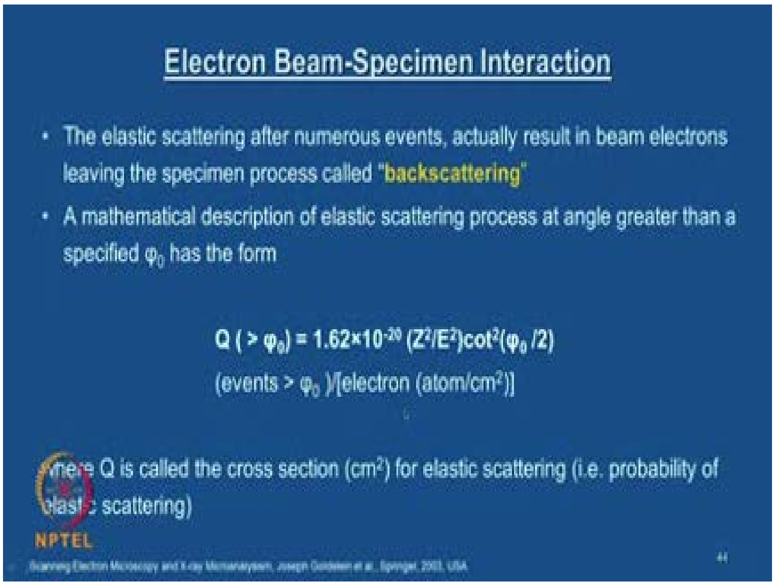
- As the beam of electrons enter the specimen, they interact as negatively charged particles with the **electrical fields** of the specimen atoms.
- The **positive charge of the protons** is highly concentrated on the nucleus, while the **negative charge of electrons** is much more dispersed in a shell structure.
- The beam electron –specimen atom interaction **can deflect the beam electrons along a new trajectory** (elastic scattering) causing them to spread out laterally from the incident foot print.

NPTEL

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

So, as the beam of electron enters the specimen, they interact as negatively charged particles with the electrical fields of the specimen atoms. The positive charge of the protons is highly concentrated on the nucleus, while the negative charge of electrons is much more dispersed in a shell structure. The beam electron-specimen atom interaction can deflect the beam electrons along a new trajectory which is considered elastic scattering causing them to spread out laterally from the incident foot print. I am going to show you some of the schematic regarding this, to understand the point three what we are now talking about.

(Refer Slide Time: 30:24)



Electron Beam-Specimen Interaction

- The elastic scattering after numerous events, actually result in beam electrons leaving the specimen process called "**backscattering**"
- A mathematical description of elastic scattering process at angle greater than a specified φ_0 has the form

$$Q(>\varphi_0) = 1.62\times10^{-20}\,(Z^2/E^2)\cot^2(\varphi_0/2)$$

(events > φ_0)/[electron (atom/cm^2)]

where Q is called the cross section (cm^2) for elastic scattering (i.e. probability of elastic scattering)

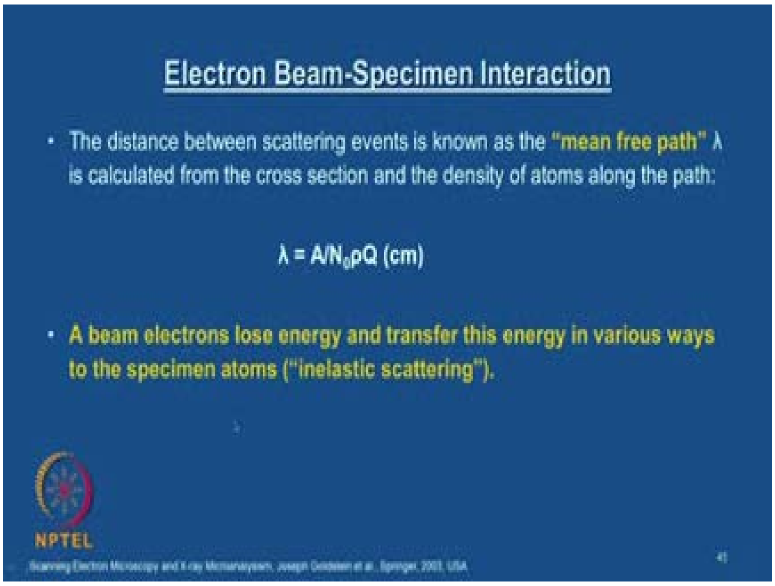
NPTEL

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

So, the elastic scattering after numerous events, actually result in beam electrons leaving the specimen process called backscattering. It gives a kind of a definition for back scattering that is the elastic scattering after numerous events actually result in beam electrons leaving the specimen.

A mathematical description of elastic scattering process at angle greater than a specified phi naught has the form Q which is greater than phi naught is equal to 1.62 into 10 to the power minus 20 times z square by E square cot square phi naught by 2. So, this is events - scattering events greater than phi naught divided by the electron which is atoms per centimeter square; where Q is called the cross section which is in centimeter squared for elastic scattering that is probability of elastic scattering which is given in this form.

(Refer Slide Time: 31:45)



Electron Beam-Specimen Interaction

- The distance between scattering events is known as the **"mean free path"** λ is calculated from the cross section and the density of atoms along the path:

$$\lambda = A/N_0\rho Q \text{ (cm)}$$

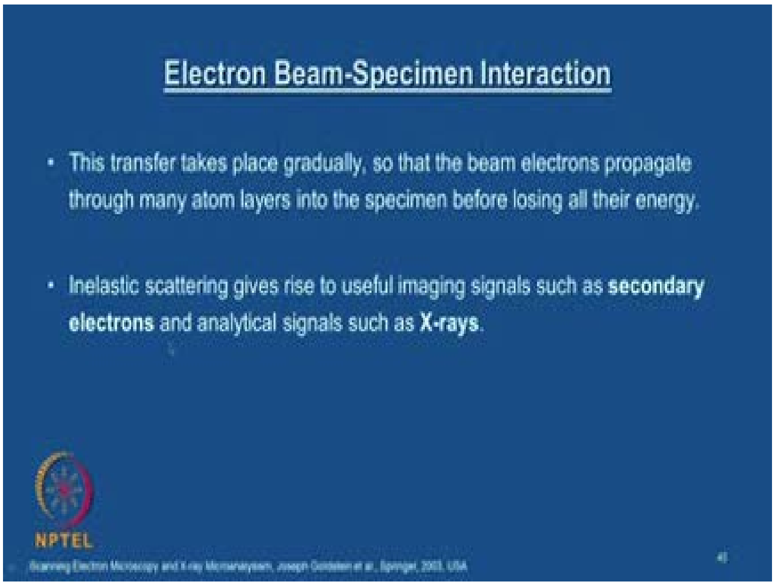
- **A beam electrons lose energy and transfer this energy in various ways to the specimen atoms ("inelastic scattering").**

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

The distance between scattering events is known as the mean free path lambda is calculated from the cross section and the density of atoms along the path. The lambda is equal to A divided by N naught rho Q, which is in centimeter. Beam electrons lose energy and transfer this energy in various ways to the specimen atoms which is nothing but inelastic scattering.

See, you see in a SEM, we get the characteristic x-rays for a chemical analysis like we discussed in the beginning, and the basic fundamental physics of that event is what we are now discussing. The beam of electron loses the energy and transfers this energy in various ways. See, one of the ways is like know you are getting a characteristics rays and you have SEs, BSEs and all this signals, so all basically inelastic scattering.

(Refer Slide Time: 32:57)



Electron Beam-Specimen Interaction

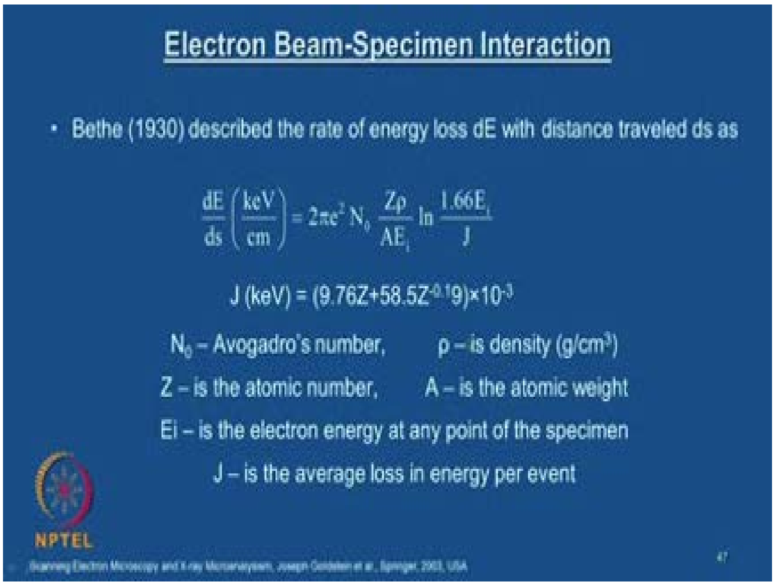
- This transfer takes place gradually, so that the beam electrons propagate through many atom layers into the specimen before losing all their energy.
- Inelastic scattering gives rise to useful imaging signals such as **secondary electrons** and analytical signals such as **X-rays**.

NPTEL

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

This transfer takes place gradually, so that the beam electrons propagate through many atom layers into the specimen before losing all their energy. So, this the loss of energy of the electron beam is not going to be instantaneous, so it will be more I mean you can see that how some of the models are being made, for this how the electron beam is losing energy which I will show you in few minutes. From that, we will get an idea how the electron beam after impinging on the specimen surface looses energy gradually as a function of interaction volume. Inelastic scattering gives rise to useful imaging signals such as secondary electrons and analytical signals such as X-rays.

(Refer Slide Time: 33:59)



Electron Beam-Specimen Interaction

- Bethe (1930) described the rate of energy loss dE with distance traveled ds as

$$\frac{dE}{ds}\left(\frac{keV}{cm}\right) = 2\pi e^2 N_0 \frac{Z\rho}{AE_i} \ln \frac{1.66E_i}{J}$$

$$J\,(keV) = (9.76Z + 58.5Z^{-0.19}) \times 10^{-3}$$

N_0 – Avogadro's number, ρ – is density (g/cm^3)

Z – is the atomic number, A – is the atomic weight

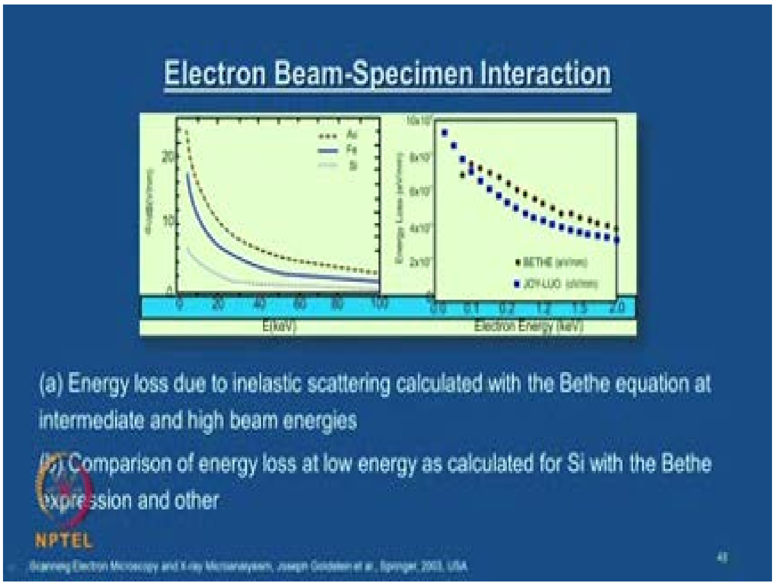
Ei – is the electron energy at any point of the specimen

J – is the average loss in energy per event

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

Bethe described in 1930, the rate of energy loss dE with the distance traveled ds as dE by d s, the energy is given an kilo electron volt and the distance is centimeter, which is equal to 2 pi e square N naught into X rho divided by A E i ln 1.66 E i by J; where the J is equal to 9.76 Z plus 58.5 Z to the power minus 0.19 into 9 into 10 to the power minus 3. Where N naught is equal Avogadro number, the rho is density, Z is the atomic number, A is the atomic weight, E i is the electron energy at any point of the specimen, J is the average loss in energy per event. It is just this expression simply tells you how this energy loss takes place, and how we can visualize quantitatively with all this variables. I just want you to appreciate that point rather than getting into the details at this mode.

(Refer Slide Time: 35:24)



Electron Beam-Specimen Interaction

(a) Energy loss due to inelastic scattering calculated with the Bethe equation at intermediate and high beam energies

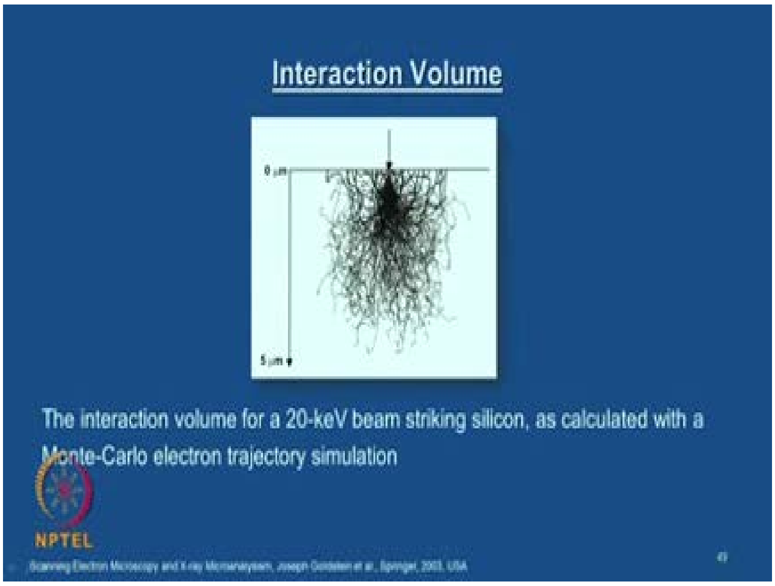
(b) Comparison of energy loss at low energy as calculated for Si with the Bethe expression and other

NPTEL

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

So, you can see that two plots which are based on this Bethe equation, how the energy loss due to inelastic scattering is calculated. You can see that plot a is energy loss due to inelastic scattering calculated with the Bethe equation at intermediate and high beam energies for all this elements. And the plot b is the comparison of energy loss at low energy as calculated for silicon with the Bethe expression and others; so how this energy loss occurs as the function of electron volt.

(Refer Slide Time: 36:14)



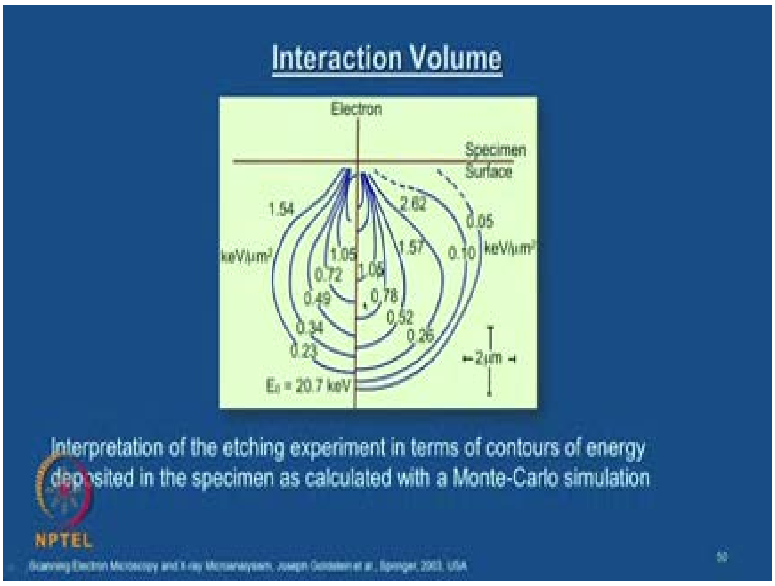
Interaction Volume

The interaction volume for a 20-keV beam striking silicon, as calculated with a Monte-Carlo electron trajectory simulation

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

Now what you are going to see is we will look at what is this interaction volume and the electron beam comes and interacts with the specimen surface. And what you are now seeing is the a simulation is the interaction volume for a 20 kilo electron volt beam striking the silicon as calculated with a Monte Carlo electron trajectory simulation, it is a numerical simulation. And what you see is you know you see that know there are there are thick black line and then very light black lines which just getting inside this specimen to the order of about few microns. So, this is happening in a three-dimensional. So, let us try to understand how this happens.

(Refer Slide Time: 37:26)



Interaction Volume

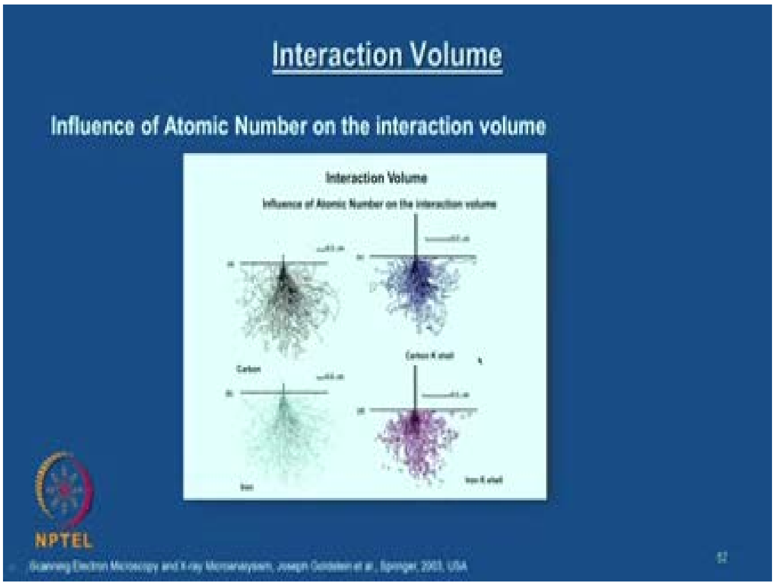
Interpretation of the etching experiment in terms of contours of energy deposited in the specimen as calculated with a Monte-Carlo simulation

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

This is you can see that this another schematic showing that this kind of interaction volume is interpreted through any etching experiment in terms of contours of the energy deposited in the specimen as calculated with the Monte Carlo simulation. So, the left hand side is how the energy varies as a function of depth using any etching experiment. What is this etching experiment people have taken some of the low atomic number of materials like poly methyl metha related kind of a specimen, and then they just do an etching experiment within a bombardment of electron, how it just I mean damage this molecular and polymeric molecules, and then how it the intensity of a damage decreases from the surface to the core. And that is done with that model that is called etching experiment.

And then the left hand side is the experimental measurement, how the energy varies from the surface to the core in a three-dimension. And the right hand side is the same thing is done numerically through Monte Carlo simulation, and then you get some kind of very close agreement with this. So, the important point to appreciate here is you get a kind of an idea what is an interaction volume is and how it occurs three-dimensionally and what are its dimensions. So, it gives you a kind of a basic outline about an interaction volume. And please remember whatever we have now just showing is only a static image, and actually it is happening dynamically between the interactions between electron beam in the surface.

(Refer Slide Time: 39:39)



Interaction Volume

Influence of Atomic Number on the interaction volume

Scanning Electron Microscopy and X-ray Microanalysis, Joseph Goldstein et al., Springer, 2003, USA

And I will just show you few more schematic which you have the, just excuse me, it mean. So, I would like to show this as a function of electron beam energy versus interaction volume. Actually, what you will see that the as the electron energy increases, the interaction volume also will increase, and somehow this simulation is not working right now. So, you can see that the same effect of atomic number also you can see, influence of atomic number on the interaction volume you can see it for different material.

Here, it is a carbon, and this is for a carbon k shell, and then you have the iron, and then you have the iron k shell. You can also see that as the atomic number increases, the linear dimension decreases that are very much understandable that is because you are scattering cross section varies as the atomic number increases. So, you can see that the linear dimension also decreases in accordance with that number.

And you can see that a similar another system same effect for a silver, silver 1 shell, and then you have uranium and uranium m shell and so on. So, what I try to tell here is depending upon the atomic number as well as the energy of the electron beam which is impinging on these sample, you are interaction volume is going to change. And the scattering physics involved is little more complicated, and this has got a significant influence on your image resolution; and the kind of details one can get from the specimen surface that is all I just want to emphasize here.

And then we will look at the scanning action how this electron beam is scanning the surface and how exactly the image is formed, all those details we will see it in the next class.

Thank you.