# Unit V : Electron Ballistics & Surface Characterization Techniques

## Introduction:

Ballistics is the science of mechanics that deals with the launching, flight, behavior of projectiles under forces generated due to pressure, gravity or air drags. Electron ballistics specifically deals with the trajectories of sub-atomic particles (electrons are considered predominantly in this unit, but the same principles can be applied to other particles of opposite charge polarity) under the influence of electric and magnetic ( $\vec{E}$ & $\vec{B}$ ) fields. Under vacuum, charged particles travel in straight lines and respond readily to changes in the $\vec{E}$ & $\vec{B}$ fields. This sensitivity to changes in $\vec{E}$ & $\vec{B}$ fields can be exploited to precisely control the motion of charged particles for various applications.

In this unit, electrons will be considered as point masses and therefore $\vec{E}$ & $\vec{B}$ forces are large enough to dominate its motion and the gravitational forces and mutual repulsion between the particles can be considered as negligible. Further the derivations in this unit will be treated under the semi-empirical classical Newtonian mechanics formulation.

**Before proceeding with this unit, students are advised to brush up their basic knowledge in electrostatics and kinematics.**

## Motion of electron parallel to Electric Field

When an electron enters a uniform electric field, it experiences a force and gets accelerated. The path of the electron depends upon the angle between the applied field and the initial direction of the electron velocity. The expression for uniform acceleration '$\vec{a}$' for a particle

**Refer to the derivation in Unit-II while deriving for wavelength in matter waves. Substitute $\vec{F}$= m$\vec{a}$ and solve!**

The 1-D kinematic equations are given by:

$$v = v_o + at$$

$$s = v_o + \frac{1}{2}at^2$$

$$v^2 = v_o^2 + 2as$$ ; s here refers to distance and initial velocity $v_0$ is zero

Substituting the value for acceleration, we get:

$$v = at = \frac{eE}{m}t$$

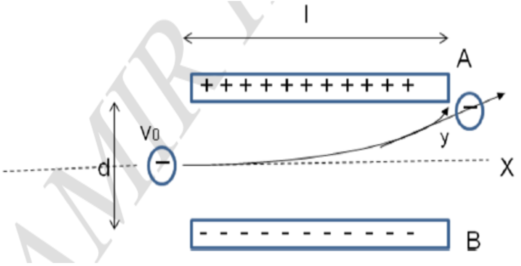
$$s = \frac{1}{2}at^2 = \frac{eEt^2}{2m}$$

$$v^2 = 2as = \frac{2eEs}{m}$$

The kinetic energy attained by an electron after moving a distance s is given by

$$K.E = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{2eE}{m}\right)s = eEs = eV$$

## Motion of Electron Perpendicular (Transverse) to Uniform Electric Field



Consider two parallel metal plates A and B of length ‘l’ oriented horizontally and separated by a distance d. A potential difference V is applied between the plates which produce a vertically acting uniform electric field $\vec{E}$ directed from plate A to B. The strength of electric field acting in the region between the plates is given by

$$\vec{E} = \frac{V}{d} \longrightarrow (1)$$

An electron enters an electric field $\vec{E}$ acting at $90^0$ to the direction of electron propagation, between plates A & B along the positive x-axis with initial velocity $v_0$. While passing through the plates A & B the electron will experience acceleration in the vertical direction along positive y-axis towards positive plate A. After emerging from the field, it will travel along the straight line defined by the deflection. During the electron motion between the plates A and B, its velocity can be resolved along the axial and perpendicular direction. The velocity remains unchanged along the axial direction and represented by $v_0$, but is continuously attracted towards the plate B and attains a final velocity represented by $v_y$ as it leaves the region between the plates. From this point onwards the electron will move in a straight line with a resultant velocity having components along the x and y directions given by $v_0$ & $v_y$.

The electron is attracted upwards (along y-axis) towards the positive plate A due to force generated by the uniform electric field $\vec{E}$, given by

$$\vec{F} = e\vec{E} \longrightarrow (2)$$

Therefore the acceleration along the y-direction is $a_y = \frac{e\vec{E}}{m} = \frac{eV}{md} \longrightarrow (3)$

The displacement of electron along the y-direction in the region of electric field in a given time interval t is given by

$$y = \frac{1}{2}a_y t^2 = \frac{1}{2}\frac{e\vec{E}}{md}t^2 \longrightarrow (4)$$

The displacement along x –axis travelled by the electron in the time interval t depends on the initial velocity and is given by $t = \frac{x}{v_0} \longrightarrow (5)$

Substituting in equation 4, we get

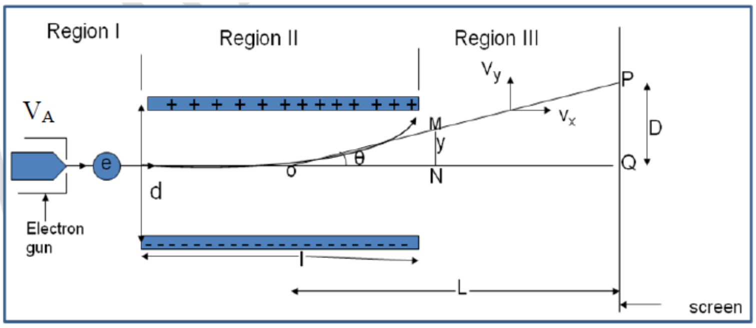
$$y = \frac{1}{2}\frac{e\vec{E}}{md}\left(\frac{x}{v_0}\right)^2 \Rightarrow y = \frac{1e\vec{E}x^2}{2m{v_0}^2}$$

$$\therefore y = kx^2 \xrightarrow{\hspace{3cm}} (6) \text{ Where } k = \frac{1e\vec{E}}{2m{v_0}^2}$$

Equation 6 shows that the path of electron entering a uniform electric field at right angles is a parabola.

## Electrostatic Deflection (Qualitative)

**The deflection of electron beam caused by an electrostatic field is known as electrostatic deflection**



When an electron comes out of the field, no forces act on it and electron travels along a straight line with a velocity v which is a resultant of $v_o$ and $v_y$.

$$v = \sqrt{v_o^2 + v_y^2}$$

Consider fluorescent screen at a distance 'L' from the center 'o' of the parallel plates. In the absence of electric field electron strikes at 'Q'. In the presence of electric field the electron gets deflected and strikes the point 'p'. Thus, PQ represents the linear deflection of the electron. In the triangle OP Q. The accelerating potential of the electron is $V_A$

$$\tan\theta = \frac{PQ}{OQ}$$

$$let PQ = D$$

$$\frac{D}{L} = \tan\theta \text{-------------------------}(1)$$

Referring to the figure, the slope of the curve at x=*l* is given by

$$\tan\theta = \frac{dy}{dx} = \frac{d\left(\frac{eEx_o^2}{2mv_o^2}\right)}{dx}$$

$$\therefore \frac{dy}{dx} = \frac{eEx}{2mv_o^2}$$

$$\therefore \left(\frac{dy}{dx}\right)_{x=l} = \frac{eEl}{2mv_o^2} \text{-----------------------------------}(2)$$

Equating equation (1) and (2), we get

$$\frac{D}{L} = \frac{eEl}{2mv_o^2}$$

$$but$$

$$v_o^2 = \frac{2eV_A}{m}$$

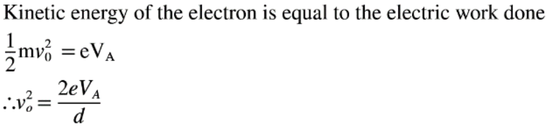
$$\frac{D}{L} = \frac{eEl}{2m}\frac{m}{eV_A} = \frac{El}{2V_A}$$

$$but$$

$$E = \frac{V}{d}$$

$$\frac{D}{L} = \frac{Vl}{2dV_A}$$

$$\therefore D = \frac{VlL}{2dV_A}$$



Kinetic energy of the electron is equal to the electric work done

$$\frac{1}{2}mv_0^2 = eV_A$$

$$\therefore v_o^2 = \frac{2eV_A}{d}$$

The parallel plates are called deflection plates and the deflection of electron beam by an electrostatic field is known as electrostatic deflection.

The deflection caused by one volt of potential difference applied to deflection plates is deflection sensitivity.

$$s = \frac{D}{V} = \frac{lL}{2dV_A}$$

**Electron Projected at an Angle (qualitative)**

The initial velocity of the electron may not be parallel to x- or y-axes. Suppose an electron is projected into a uniform electric field at an angle θ, and with an initial velocity $v_0$. Assuming that the electric field direction is along the positive y-direction, the electron gets accelerated (deflected) along the negative y-direction. This acceleration is constant and is given by

$$a = \frac{eE}{m}$$

The motion of the electron is very similar to that of a projectile in the gravitational field and hence the velocity can now be resolved along x and y direction. The x- component of velocity will remain constant, but the y- component varies along its path of propagation.

The velocity along the x-axis is given by: $v_x = v_0 \cos\theta_0$= constant

The velocity along the y-axis is given by: $v_y = v_{y0} + at = v_0 \sin\theta_0 + at$

∴, the co-ordinates of the electron after time $t$ are $x = v_x t = (v_0 \cos\theta_0)t$

$$y = v_{y0}t + \frac{1}{2}at^2 = (v_0 \sin\theta_0\, t) + \frac{1}{2}at^2$$

Eliminating t from the above equations, we get the equation for the electron motion in the electron field.

**Thus,** $\boldsymbol{y = (\tan\theta_0)x + \left(\frac{a}{2v_0^2 \cos^2\theta_0}\right)x^2;}$
**Which is of the form y=ax + bx$^2$ representing a parabola**

**The trajectory of an electron projected into a uniform electric field is a parabola.**

Similar to projectile in a gravitational field, we can calculate

i) H = $\frac{v_0^2 Sin^2\theta_0}{2a}$ ; Defines the maximum height that electrons attain in a uniform electric field

ii) t = $\frac{v_0 \sin\theta_0}{a}$ ; Time taken by the electrons to reach a maximum height H

iii) T= $\frac{2v_0 \sin\theta_0}{a}$; Time of flight of an electron to return to its initial position along the x-direction

iv) R = $\frac{v_0^2 \sin 2\theta_0}{a}$; Horizontal distance traveled by an electron from the starting position to the point at which it returns to the initial position along x-direction

## Motion of Electron in Uniform Magnetic Field

A static electron does not experience any force in $\vec{B}$ field, but when an electron moving with a velocity $v$ enters a $\vec{B}$ field experiences a magnetic force given by

$$\boldsymbol{F = e(\vec{v} \times \vec{B}) = evB \ \sin\theta}$$

e- Charge of the electron (sometimes it is represented by the letter q)

θ- Angle between the velocity & magnetic induction vector (B).

If electron moves along the field direction, then $\theta = 0^0$, $F = evB \sin\theta = 0$

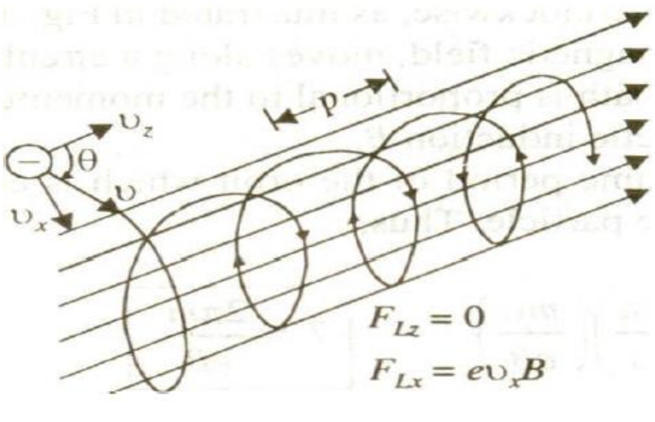
If electron moves opposite to the field direction, then $\theta = 180^0$, $F = evB \sin\theta = 0$

- **The magnetic force is maximum when the angle between $\vec{v}$ *and* $\vec{B}$ is 90$^0$**
- **The electron continues to move without any change in direction or speed**
- **The work done on a charged particle by the magnetic field is zero**

The electron experiences a magnetic force whose direction is given by Fleming’s left-hand rule. Since the force is constant and always acts at right angles to the field, the electron describes a circular path of radius r given by: Magnetic force evB and centripetal force is mv$^2$/r

$$\therefore \frac{mv^2}{r} = evB \ => r = \frac{p}{eB};$$ p- is the momentum given by $p$= m$v$

## Motion of an Electron at an Angle to Uniform Magnetic Field



An electron travelling with a uniform velocity $v$ enters the magnetic field B at an angle θ with respect to field direction $\vec{B}$. The velocity $v$ can be resolved into its corresponding parallel and perpendicular components with respect to the field direction. The motion of the electron is rectilinear in nature (along a straight line and direction of velocity is constant). The horizontal and vertical rectangular components are given by

$v_{parallel} = v\ \cos\theta$ and $v_{perpendicular} = v\ \sin\theta$

i) **Axial velocity component causes uniform transalatory motion:**

The force on the electron in the direction parallel to the magnetic field is zero.

$$F_{parallel} = ev_{parallel}B = 0$$

Therefore, the velocity component $v_{parallel}$ does not undergo a change due to the $\vec{\mathrm{B}}$ field. The electron continues to move along the field direction with the velocity $v_{parallel}$ .

**ii) Perpendicular velocity component causes circular motion:**

The perpendicular force acting on the electron due to the magnetic field is given by

$$F_{perpendicular} = ev_{perpendicular}B$$

The normal force component causes the electron to travel along a circular path around the field direction a with constant speed given by $v_{perpendicular} = v\sin\theta$

**iii) The resultant motion is a helical motion around the magnetic field direction:**

The path traced by the electron is the resultant of the uniform rectilinear motion parallel to the field and a uniform circular motion perpendicular to the field. This superposition of a circular motion on a rectilinear motion creates a helical or spiral path of the electron. Thus, the electron describes a helical path in the magnetic field; the axis of the helix is parallel to the $\vec{\mathrm{B}}$ field. The radius of the circular path of the electron onto the xy plane is given by

$$R = \frac{mv_{perpendicular}}{eB} = \frac{mv\ \sin\theta}{eB}$$

Similarly, the projections onto the xz and yz planes can be represented as sinusoidal waves. The time period 'T' of the revolution along the rectilinear path is given by

$$T = \frac{2\pi R}{v_{perpendicular}}$$

Now substituting the value for radius 'R', we get

$$T = \frac{2\pi R}{v_{perpendicular}} = \frac{2\pi mv \ \sin\theta}{eBv\sin\theta} = \frac{2\pi m}{eB}$$

Pitch is defined as the linear distance covered in one revolution. Pitch of the helix is given by

$p = v_{parallel}T = Tv\cos\theta$ This can be re-written as $p = \frac{2\pi mv\cos\theta}{eB}$

**Lorentz Equation:** The total force experienced by an electron travelling in a region of electric and magnetic fields is the vector sum of $\vec{\mathrm{E}}$ and $\vec{\mathrm{B}}$ field. Therefore, the equation is written by

$$\mathbf{F_L} = \mathbf{e}(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

The above expression is called as the Lorentz equation and the force experienced is called the Lorentz force.

## Application of Crossed $\vec{\mathrm{E}}$ & $\vec{\mathrm{B}}$ Configuration as a Velocity Selector

### Electric & Magnetic field in crossed configuration:

**A uniform $\vec{E}$ and $\vec{B}$ field acting over the same region and perpendicular to each other are said to be in crossed configuration.**

Consider two charged parallel plates that generates a uniform $\vec{\mathrm{E}}$ field along y-direction (vertical) and a uniform $\vec{\mathrm{B}}$ field along the z-direction (out of the plane of the screen). A beam of electrons with initial velocity $v$ enters this crossed field configuration. The electric field deflects the electrons upwards (+ y-direction) and the magnetic field downwards (-y-direction).

The force due to the electric field is given by $F_E = eE$

The force due to the magnetic field is given by $F_B = evB$

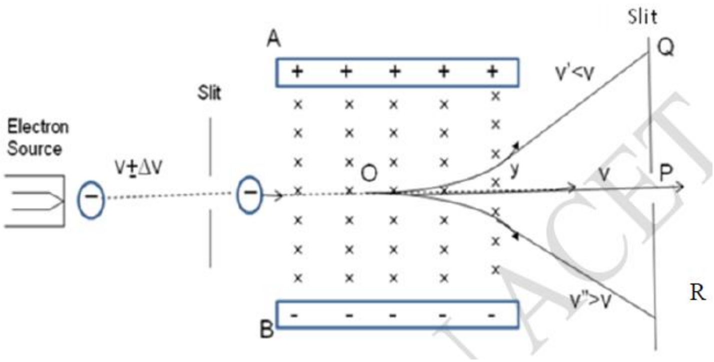
**Case (i):** If $F_E > F_B$, the electron is deflected upwards.

**Case (ii):** If $F_E < F_B$, the electron is deflected downward.

**Case (iii):** When $F_E = F_B$, the net force on the electron beam is zero and

$eE = evB \Rightarrow E = vB \Rightarrow v = \frac{E}{B}$; Where v is the velocity of the electron

**A velocity filter is an electronic device which can select a stream of charged particles with a particular velocity from a beam having a wide range of velocities by employing uniform $\vec{\mathrm{E}}$ and $\vec{\mathrm{B}}$ fields in a crossed configuration.**



A narrow beam of electrons traveling in vacuum enters a region of uniform $\vec{E}$ field and $\vec{B}$ field acting at right angles to each other. The electrons in the beam have velocities in the range of $v_0 \pm \Delta v$ spread around a central value $v_0$. Let the beam enter the crossed field region in a direction normal to both $\vec{E}$ & $\vec{B}$ fields. The electric field produces an upward force on the electrons in the beam, whereas the magnetic field produces a downward force as shown in the figure.

Considering case (iii) from previous discussion and substituting the appropriate values we get the expression for velocity as $v_0 = \frac{E}{B}$; There exists a unique velocity $v_0$ for which the electric and magnetic forces exactly cancel.

Hence, the electrons travelling with velocity $v_0 = \frac{E}{B}$ pass through the region of fields without suffering any deflection. As a result, the electrons pass through the slit P, these electrons are not deflected

Electrons traveling with velocities less than $v_0$, spend more time in the electric field region and are subject to electric force for a longer time and hit the wall at point Q. Similarly, electrons that are traveling with velocities greater than $v_0$ are deflected downwards by the magnetic field and strike the wall at point R.

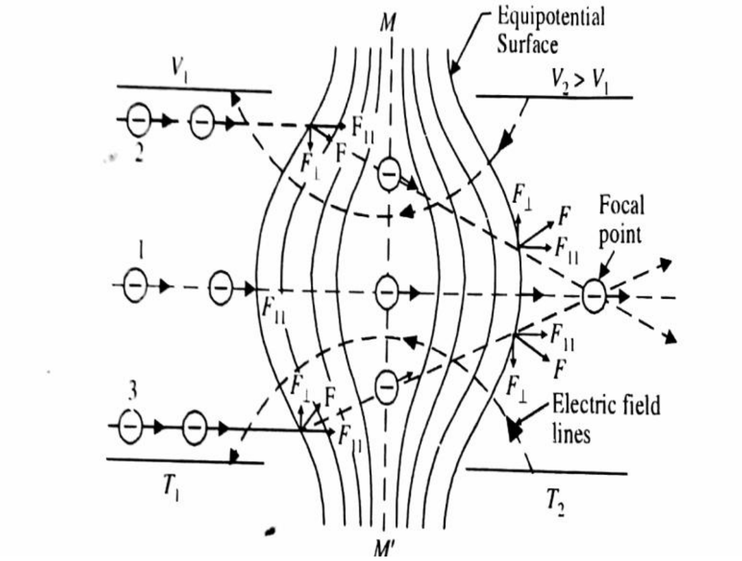
## Electron & Magnetic Lens:

**Analogous to optical lens, an electron lens focuses a beam of electrons at a particular point/ region.**

**Principle:** As evidenced in the previous section, a stream of electron experiences a change in direction of motion when it passes through a non-uniform $\vec{E}$ field. Its path is bent at each equipotential surface in the same way as a light ray is bent at an optical boundary of a lens. By using two co-axial metal tubes maintained at different potentials a beam of electrons can be focused, this in principle is the physics behind electron lens. The geometry of electron lens can vary depending on the application. Classic examples of electron lens geometries are cylindrical, square, or rectangular.

Sometimes a combination of different geometries can also be applied to develop a special type referred to as Einzel lens (combination of cylindrical & rectangular).

**Construction:** A generic electron lens is made of two co-axial short cylindrical metal tubes $T_1$ & $T_2$ separated by an arbitrary distance. The tubes are maintained at different potentials $V_1$ & $V_2$ with $V_2 > V_1$. This creates a non-uniform electric field in the gap between the two tubes.



**Working:** A narrow beam of electron rays enter the lens system through the tube $T_1$ and move to the higher potential region $T_2$. The figure describes the equipotential surfaces in the region between the tubes; electrons labeled 1, are moving along the axis of the system. When the electrons travel through $T_1$, they do not experience any force. As the electrons approach the gap between the cylindrical tubes, they first come across the convex shaped equipotential surface and are directed from tube $T_2$ to $T_1$. At point A, the electric field is along the axis and hence the electrons labeled 1 get accelerated forward along the axis. They travel forward without any deviation from their initial path. Beyond the mid plane MM', the equipotential surfaces are concave shaped but the electric field still acts along the axis in a direction which accelerates the electrons labeled 1. Therefore, these electrons fly forward with increased speed along the axial direction. Electrons labeled 2; on reaching B on the convex shaped equipotential surface, experience an electron force that acts at an angle to the direction of their motion. The force can be resolved into its rectangular components $F_{parallel}$ and $F_{perpendicular}$. Due to the $F_{perpendicular}$, electrons labeled 2 are deflected down toward the axis. Due to the component $F_{parallel}$, they are also accelerated toward tube $T_2$. Hence these electrons are continuously bent downwards till the mid-plane MM' is reached. In the same way, the electrons, labeled 3 on reaching at C on the equipotential surface are continually deflected up towards the axis and are also accelerated forward. Because of cylindrical symmetry, all off-axis electron paths around the lens tend to converge towards a point on the axis.

On crossing the mid-plane MM' of the gap, the electron rays encounter equipotential surfaces of concave shape. In the second half of the gap, the normal component of electric force, $F_{perpendicular}$ is directed away from the axis for all off-axis electron rays and hence causing them to diverge. The $F_{parallel}$ component is directed forward and hence the electrons are accelerated further. Before the electron rays can converge, they are diverged to some extent. However, because the potential is everywhere higher in the second half of the gap, the electrons travel faster in the second half than in the first half of the gap. The electrons spend a greater time in the first half of the gap and the impulse'$F_{parallel}$t' is smaller for the divergence interval. Consequently, the electron rays are less diverged by the second half than converged by the first half of the gap. Therefore, the converging action of the first half of the gap will be stronger than diverging action of the second half of the gap and the electron rays emerge from the tube $T_2$ still sufficiently convergent as shown in the figure. By adjusting the potentials on the tubes approximately, the electron beam can be focused to a suitable required point on the axis.

**Magnetic Lens:** Similar to the electric lens, axially symmetric magnetic fields have a focusing effect on an electron beam passing through them. By using parallel placed short solenoids encased in hollow iron shields the magnetic fields are concentrated and improved focusing action is obtained, such an arrangement is called thin magnetic lenses. This arrangement will develop a non-uniform magnetic field that is symmetrical about the axis OI of the coil. O is the source of electrons, which are focused at the point I due to the magnetic field. The typical focal length of magnetic lens is very small of the order of a few centimeters.

An electron beam can only be converged by magnetic lens. Diverging action is impossible in magnetic lenses. With the adjustment of current through the solenoid and the initial accelerating voltage of the electron, the focal distance of the magnetic field can be adjusted.

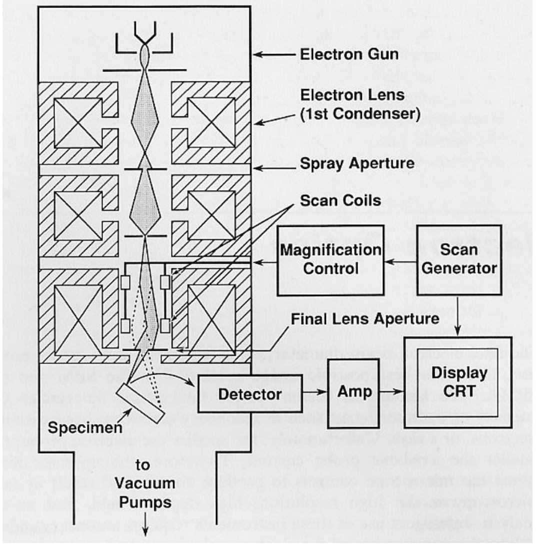
**Scanning Electron Microscope (SEM):** The scanning electron microscope (SEM) is a powerful and frequently used instrument, in both academia and industry for imaging the surfaces of almost any material with a resolution down to about 1 nm. Most scanning electron microscope has magnification ranges from X20 to X100000. SEM images have a characteristic three-dimensional appearance and are useful for adjudging the surface structure of the sample.

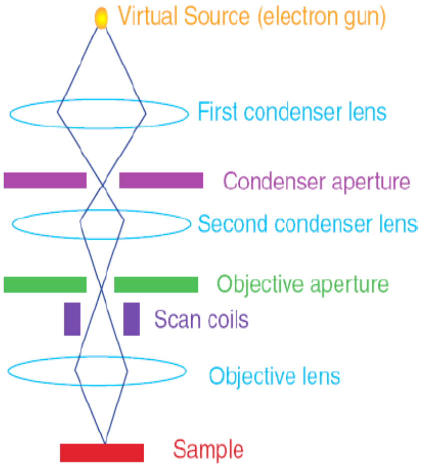
**Principle** :

In the scanning electron microscope (SEM) electrons are made to fall on the sample and the scattered or generated electrons are detected. The SEM is usually operated with an acceleration voltage of 1K V to 40 K V for the electrons. The incoming electrons interact with the sample on a depth of ~1μm. This electron beam generates a number of different types of signals, which are emitted from the area of the specimen where the electron beam is impinging. The induced signals are detected and the intensity of one of the signals (at a time) is amplified and used to as the intensity of a pixel on the image on the computer screen. The electron beam then moves to next position on the sample and the detected intensity gives the intensity in the second pixel and so on. This produces an image with depth-of-field which is usually 300-600 times better than that of an optical microscope, and also enables a three-dimensional image to be obtained.

### Construction and working

A schematic of typical SEM is shown in the above figure. Electrons thermionically emitted from a tungsten filament (cathode) are drawn to an anode and focused by two successive magnetic lenses into a beam with a very fine spot size that is typically 10Å in diameter. Pairs of scanning coils located at the objective (magnetic) lens deflect the beam either linearly or in raster fashion over a rectangular area of the specimen surface. Upon impinging on the specimen, the primary electrons decelerate and several processes such as elastic scattering *viz.,* forward scattering and backscattering of the incoming electrons and inelastic scattering *viz.,* generation of secondary electrons, Auger electrons, bremsstrahlung, characteristic x-rays, electron-hole pairs (in insulators and semiconductors), long-wavelength electromagnetic radiation. A number of different types of signals, which are emitted from the area of the specimen where the electron beam is impinging, is as shown in fig.





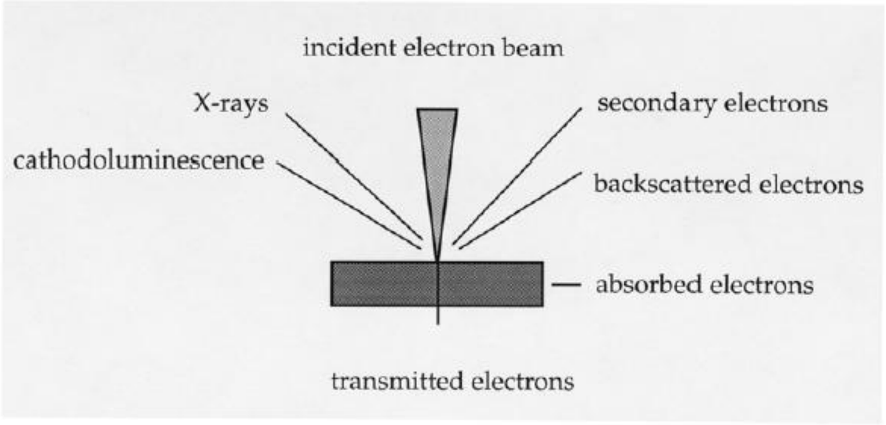


**Fig:** Different types of signals produced when high-energy electron impinges on a material.

Various **SEM** techniques are differentiated on the basis of what is subsequently detected and imaged, and the principle images produced in the **SEM** are of three types:

- Secondary electron images,
- Backscattered electron images and
- Elemental X-ray maps.

The secondary electrons are the electrons which are generated from the surface of the specimen when it is bombarded by high energy primary electrons. These electrons are collected by detector which creates a pattern of light and dark areas in CRT corresponding to the emission of secondary electrons from the specimen. As the number of electrons produced at any given point can be related directly to the topography of the specimen with respect to the detector, the patterns created on the viewing screen represent the surface topography of the specimen.

Backscattered electrons are the high energy electrons that are elastically scattered and essentially possess the same energy as the incident or primary electrons. The probability of backscattering increases with the atomic number of the sample material. Therefore the primary electrons arriving at a given detector position can be used to yield images containing information on both topology and atomic composition.

An additional electron interaction in the SEM is that the primary electron collides with and ejects a core electron from an atom in the sample. The excited atom will decay to its ground state by emitting either a characteristic X-ray photon or an Auger electron. By analyzing energies of characteristic of the x-ray photon the atoms can be identified. Further the concentration of atoms in the specimen can be determined by counting the number of X-rays emitted.

**Applications:**

SEM is used in a wide range of fields as a tool for observing surfaces at nanometer level. It is an indispensable instrument for not only basic research but also for highly integrated semiconductor devices and new advanced materials. The SEM are used in the investigation of surface features of materials (topography), the shape and size of the particle making up object (Morphology), heterogeneity of the materials to visualize various mineral components in their distinct growth forms and their relation in terms of overall micro fabric and texture (composition) and to visualize arrangement of atom in an object (crystallographic information). Besides surface topographic studies the SEM can also be used for determining the chemical composition of a material, its fluorescent properties, and the formation of magnetic domains and so on.

## Scanning Tunneling Microscope:

The scanning tunneling microscope (STM) was developed in the early 80 at the IBM research facility, Switzerland by Gerd Binnig and Heinrich Rohrer and; For their invention the Nobel prize in Physics was awarded to them in 1986. Unlike traditional microscope techniques the radiation that is refracted /reflected off the sample is no longer analyzed. Here, a tiny tip is scanned across the surface and makes use of the tunneling effect. This gives this technique enormous resolution as it is not dependent on the wavelength of the beam! Dimensions as small as the size of an atom can be selectively probed using the STM.

**Working Principle:** A small metal tip is brought close to the surface of a sample typically in the range of 1 nanometer. By applying a small potential on the sample and tip it is possible to cause the electrons to flow (“tunnel”) this gap of 1 nanometer. If a small voltage UT is applied to the sample and the tip, it is possible to generate a tunneling current given by IT. This current is strongly dependent on the distance between the tip and sample surface. The tip can scan the surface either by maintaining constant distance or constant current. What is to be noted is that the surface of any sample is never smooth, hence the variations in the distance between the tip and sample surface cause variations in the tunneling current or the feedback parameters. A suitable analogy is to imagine reading a book using braille language. Though it sounds easy, but in reality, it involved a lot of physics and a solution for many technical problems.

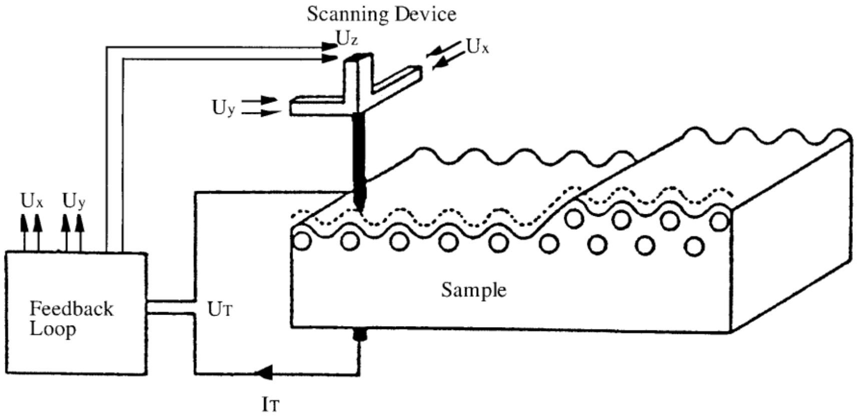
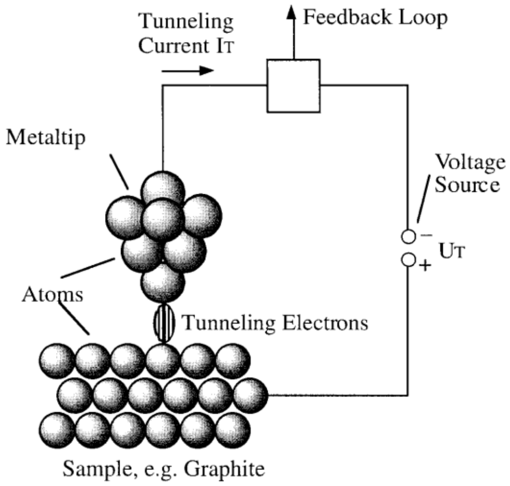


Fig. The principle of the scanning tunneling microscope

A general schematic of tunneling process.



A schematic of the tip and sample surface is illustrated above. The intensity of the tunneling current between the tip and sample is measured in the range of nanoamperes. In order to achieve high precision and resolution, the tip of the sample has to be as small as possible (order f one atomic dimension). Typically, the tip of the probe is comprised of an atom ripped from the sample due to the high electric fields. A downside of this process is that only conductive materials can be examined.

The conducting electrons of a metal are able to move freely inside the metal, but cannot leave it due to the attractive force of the positively charged cores. In order to get the electrons out of the surface, work has to be done using the so called work function (Φ). When we heat a metal red-hot, the kinetic energy of the thermal movement in the material is sufficient to free the electrons (principle behind a filament bulb!). But, at room temperatures an electron cannot escape the surface or gaining sufficient energy just from application of a voltage. Therefore an electron(s) cannot exist in the region between the tip and sample. One important point we have to remember is that the flow of electrons is not just limited from sample to tip; it can flow the other way around too.

If we take a closer look at the relation for the tunneling current, it does not just measure the height of the structures on the sample surface, but also gives information on the electron desnsities of the sample at the measuring position. With STM we can not only see atoms but also the ring shaped maxima of the electron density inside: a standing wave of the probability density of the electrons! In reality, bound electrons are arranged upto a maximum energy. This concept was taught in unit -3 while discussing Fermi energy level. The number of electrons with a given energy may change rapidly with the energy. In a metal only electrons up to a given energy $E_{max}$ are present If electrons with a given energy want to tunnel to the other metal, only as may electrons can do so as the energy distribution of that metal allows. The figure below describes the tunneling process of the electrons at a given energy. The arrows depict tunneling of electrons into the sample.

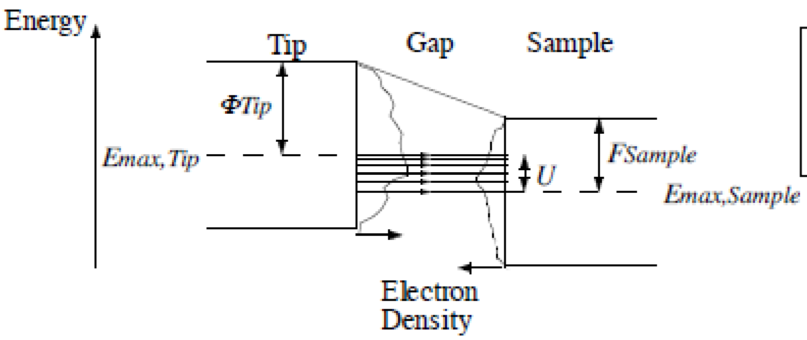


Fig: Tunneling of electrons from tip to sample

If there is a large number of electrons at a given energy present and there are a large number of unoccupied states with this energy in the other metal, the tunneling current will be particularly large. A quantitative estimate of the tunneling current and its dependence on the distance d between the sample and tip:

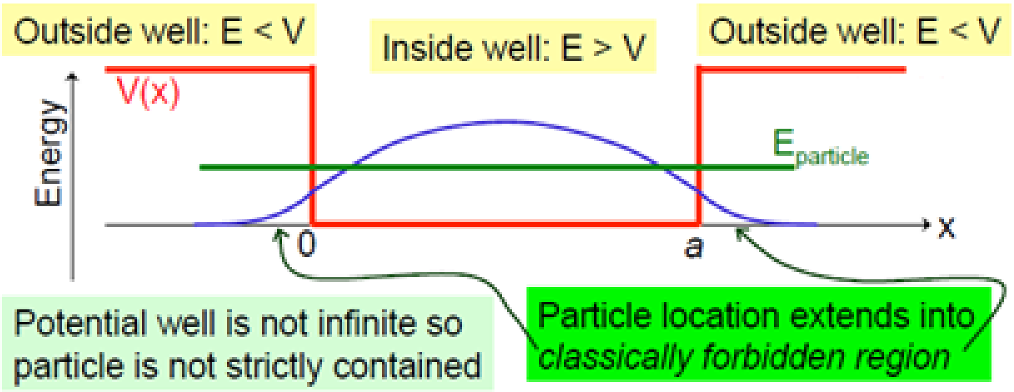
$$I_T = c_1 U_T e^{-c_2\sqrt{\phi}d}$$

The tunneling current decreases exponentially with the distance. The constant c1 in the relation for the tunneling current, therefore, depends on the energy distribution of the electrons. If you change the external voltage, you may gain information on the energy distribution of the electrons inside the sample. It is possible to make visible the electron shell structure of individual atoms.

**How is there a flow of current between the tip and sample if there is a barrier? The electron in the sample is seperated from the metal tip by a potential barrier. Though according to classical mechnaics the electron stays bound, but according to quantum mechanics it can tunnel through this energy barrier.**

We are already familiar with the infinite potential well, where a particle is trapped inside the potential well and cannot escape out. This setting of the tip and sample surface can be explained imagining the potential of the barrier to be a finite value.

The formal derivation of a finite potential well is similar to an infinite well; the difference is that the wave function doesnot dissappear at the boundaries of the well. In fact, what we observe is that the probability of a particle existing in the well does not go to zero but has finite value that is dependant on the height and size of the well. A detailed derivation of the finite well is shown in appendix -A after the unit. The wavefunction of a particle in a finite well is given by the figure

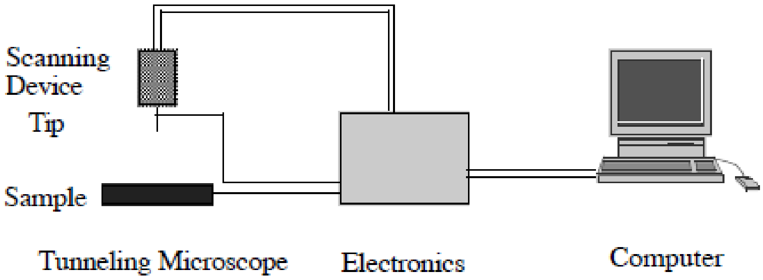


It is clear from the above figure that the wavefunction does not go to zero at the boundaries, but the exponential tail does exist in the classical forbidden region on the either side. If the barrier width and height is small then the particles wavefunction can tunnel through the barrier and appear on the other side. The potential barrier in the case of STM is the air gap between the tip and the sample surface. This is the reason why we need to maintain a distance of a few nanometers.

The STM can be operated in two different modes:

1. Scanning at a constant height: The tip is probing the surface in a straight line. At the same time the tunneling current is recorded.
2. Scanning with a constant current: The tip probes the surface in a way that the tunneling current is kept constant. The change of the tip height is being recorded.

**STM Setup:**



STM Schematic

The electronics and software are very similar to SEM.

**Display Unit and Recording system:** The output in the form of amplified electronic signal is send to the display unit. To form SEM image, scanning is synchronized with electron beam scan and brightness (which depends upon number of secondary electrons emitted) on the display unit appearing on the monitor screen. Previously, CRT (Cathode Ray Tube) was used as a display unit but these days it is replaced by LCD (Liquid – Crystal Display). Extremely fast scan speed is used while focusing for observation and slow speed used for capturing or saving image.There are three main reasons that cause surfaces to be so difficult.

1. Number of particles
2. Cleanliness
3. The arrangement of the surface atoms

> ***"The volume of a solid has been created by God, its surface by the devil"- Wolfgang Pauli***

1. **Number of particles:** The number of atoms in one cubic centimeter volume of a material is given by Avogadro's number (~ $10^{23}$); but while scanning the surface area of one square centimeter there are only about $10^{15}$ atoms.
2. **Cleanliness:** To study surfaces they have to be kept clean. At atmospheric pressure every second $10^{23}$ gas particles hit one centimeter of surface. This means that each atom on the sample surface is hit about $10^{8}$ times per second. Even if only a fraction of the amount of these particles stick to the surface, the time a freshly cleaned surface stays clean is very short. Hence, we need high vacuum conditions to maintain optimum cleanliness. This will give us an idea as to why semiconductor fabrication facility workers wear dresses similar to a space suit!
3. **Arrangement of surface atoms:** An atom in the bulk of a solid is completely surrounded by neighbouring atoms. An atom on the surface however has only other surface atoms and the atoms that are underneath as neighbours. Surface atoms can therefore arrange themselves in a totally different way to those inside the solid. The properties of the surface atoms can therefore very different to those of the bulk.

These are the three primary reasons are responsible for our limited knowledge of the surface as compared to the bulk. Most of the chemical reactions take place on the surface (catalysis and corrosion), a lot of biological processes often take place in areas with large surfaces, and the surface is important in many technical applications (sensors, adhesion, etc.). Therefore the ability to probe the surface and not the bulk of a material is very crucial in developing better and efficient technologies.