Seeing with Electrons

A K Raychaudhuri

In this article we briefly review the application of electrons in the field of microscopy. Two types of microscopes are discussed, the electron microscope and the tunneling microscope. It is emphasized that in both the applications the electron behaves as a quantum mechanical object.

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Introduction

The last five years of the nineteenth century saw some of the important developments in experimental physics which shaped the world and the development of human civilization in the next century. The discovery of the electron by J J Thomson in 1897 (measurement of the charge to mass ratio of the particles of the cathode rays – to be precise) is definitely one such discovery (see Thomson in the *Classics* section of this issue). This triggered some of the landmark discoveries that changed the way we understand the microscopic world today. Importantly it also led to new tools to 'see' the micro-cosmos. In this article we will explore the world of microscopy with electrons.

Trying to go beyond the reach of the normal eye has always fascinated mankind. It may be the sky and the heavenly objects above or the tip of a tiny grass blade below. Early in the 17th century, Galileo Galilei arranged two glass lenses in a cylinder. A curious discoverer and inventor that he was – he happened to look at an insect with the new instrument. He was stunned to find the geometric patterns of the tiny eyes of the insect. Galileo thus made the first recorded observation with a microscope. About half a century after that Robert Hooke (of elasticity fame) was the first to observe the cellular structure in thinly sliced pieces of cork from a mature tree. Given the simplicity of these instruments it is amazing that the pioneers in microscopy saw as

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much as they did. In fact Anton van Leeuwenhoek, a Dutch amateur microscopist with sharp vision even saw a single bacterium! The rest of the world had to wait for two more centuries before they could image a bacterium in a routine way using a scanning electron microscope (SEM). In the 20th century the progress of science and the associated technology took place at a rapid rate. After 50 years of discovery of the transmission electron microscope (TEM) by E Ruska (in 1931) the world could see individual atoms of a solid in yet another new type of electron microscope. This new microscope called the scanning tunneling microscope (STM) was invented by Binnig and Rohrer and within a decade of the invention it has become a 'household' name in laboratories around the world.

Microscopy is commonly done using light (optical microscope), electrons (electron microscope), acoustic waves and even X-rays. All these microscopes (except the STM and SEM to be discussed later on) use the phenomena of diffraction of the waves from the sample to be studied. The 'optics' of the microscope then reconstructs the diffracted wavefront to create the image. The wave phenomenon is thus at the heart of these microscopies. The invention of the field of electron diffraction and electron microscopy thus evolved from a very fundamental physical principle – the de Broglie hypothesis and its subsequent experimental demonstration of diffraction of electron waves. The field of STM depends on another property of electron waves – that it can 'tunnel' into a classically forbidden region. It should be appreciated that it is the electron as a quantum mechanical object that gives us the modern microscopes. This is quantum mechanics in action.

Wave-particle Duality and Electron Diffraction

In 1919, two scientists of Bell Telephone Laboratories in USA had started a project to study the effect of electron bombardment on solid surfaces (see Darrow in Suggested Reading). The work was motivated by general scientific curiosity and the apparatus they used was simple. It was an evacuated glass tube much like the glorified and special radio tubes which were at the heart of electronics in those days. Little did they realize that they would end up doing an experiment which would experimentally verify a landmark hypothesis on which the future modern science would rest. They found that the electrons (with energy $E < 100$eV) are scattered from a Ni crystal surface with preference for a definite angle. (Interestingly the experiment of electron diffraction was independently done by G P Thomson, son of J J Thomson, across the Atlantic at the same time.) This observation was later correlated with the new hypothesis of Louis Victor de Broglie (see de Broglie in Suggested Reading): "For both matter and radiation, light in particular, it is necessary to introduce the corpuscle concept and the wave concept at the same time." The famous hypothesis assigns a wavelength λ to the momentum p of the electron through the relation:

"For both matter and radiation, light in particular, it is necessary to introduce the corpuscle concept and the wave concept at the same time"
– de Broglie's hypothesis.

$$\lambda = \frac{h}{p} \qquad (1)$$

In the electron scattering experiment the diffracted intensity peaks in the directions where the Bragg condition is satisfied. The Bragg condition for observing a peak in the diffracted intensity at an angle θ was originally proposed for X-rays and is defined as:

$$2d \sin\theta = n\lambda \qquad (2)$$

where λ is the wavelength which is diffracted from the periodic array with a lattice spacing d and n is an integer. For diffraction of a wave from a periodic structure this is the condition that gives constructive interference of the diffracted waves.

From Diffraction to Transmission Electron Microscope

The discovery of electron diffraction immediately raised the possibility of a microscope in which the electron waves replace

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light waves. Obviously this needed new optics for the electrons. H Busch soon showed mathematically that a beam of electrons travelling around an axis can be brought to a focus by a magnetic coil just like a glass lens focussing the light waves (see Busch in Suggested Reading). Busch unfortunately could not demonstrate this electron focussing due to lack of proper experimental facility. But his work triggered experimental activities to build lenses for electrons and build an electron microscope. In 1931 E Ruska of Germany showed the first results of a transmission electron microscope at the Cranz colloquium in Berlin (see Knoll and Ruska in Suggested Reading). The microscope had a modest magnification. But it was an invention that would soon change the way we see the microscopic world – mainly to break the micron barrier for resolution which was set by the wavelength of visible light. In fact within a year Ruska and coworkers increased the resolution to start the era of what we call *ultramicroscopy*.

The information obtained from the electron microscope is derived from the scattering process that takes place when the *e-beam* travels through the specimen. The electrons can get scattered elastically by the effective potential of the nuclei in which it loses no energy but the direction of the electron suffers a change. Electrons can also get scattered inelastically by losing energies to other excitations or electrons or through emission of secondary electrons from the atoms at the surface of a solid. For electron diffraction and transmission electron microscope, one utilizes the elastic scattering of electrons from the periodic arrays of lattice planes. The main reason for using an electron for microscopy is its high resolution. The resolution of an electron microscope (R), like any other microscope is given by the Rayleigh formula which is derived by considering the maximum angle of diffracted electrons (α) which can pass through the objective of the lens, and the electron wavelength λ:

$$R = \frac{0.61\lambda}{\alpha} \tag{3}$$

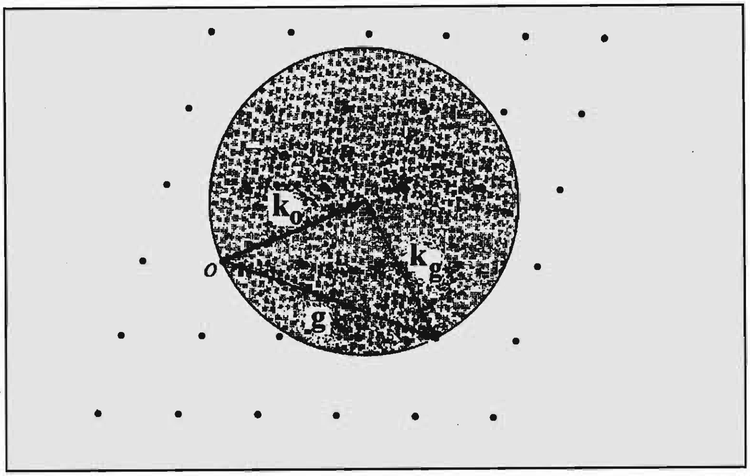


Figure 1. Ewald construction to show the diffraction phenomena.

For a typical microscope operating at 100KeV the wavelength is $\lambda \approx 0.004$ nm. For electron diffraction the Bragg condition should be satisfied. For most solids lattice spacing $d \approx 0.15$ nm. The ratio λ/d being very small the angle α is typically in the milli-radian range. The resolution R achievable is then less than 1nm. In a real system this resolution , however, gets reduced due to aberrations in the magnetic lens system.

The electron diffraction pattern, like the X-ray diffraction pattern, actually is a Fourier transform of the real space arrangements of the atoms. This happens because one has to satisfy the Bragg condition to obtain a peak in the scattered intensity. In *Figure 1* a pictorial representation is shown which is popularly known as the Ewald construction in the field of X-ray diffraction (see Ashcroft and Mermin in Suggested Reading). This figure shows vectorially the wave vector of the incident electron ($\vec{k}_0$) and the scattered electron ($\vec{k}_g$) along with the reciprocal lattice and the reciprocal lattice vector $\vec{g}$ which satisfies the Bragg condition which can be written also as $\vec{k}_g + \vec{k}_0 = \vec{g}$ What distinguishes electron diffraction from X-ray diffraction is that in the latter $k \approx g$ and in the former $k >> g$. As a result the diffraction pattern is almost a planar section of the reciprocal space. When electron diffraction is used to obtain a TEM picture a different geometry known as the Laue geometry is

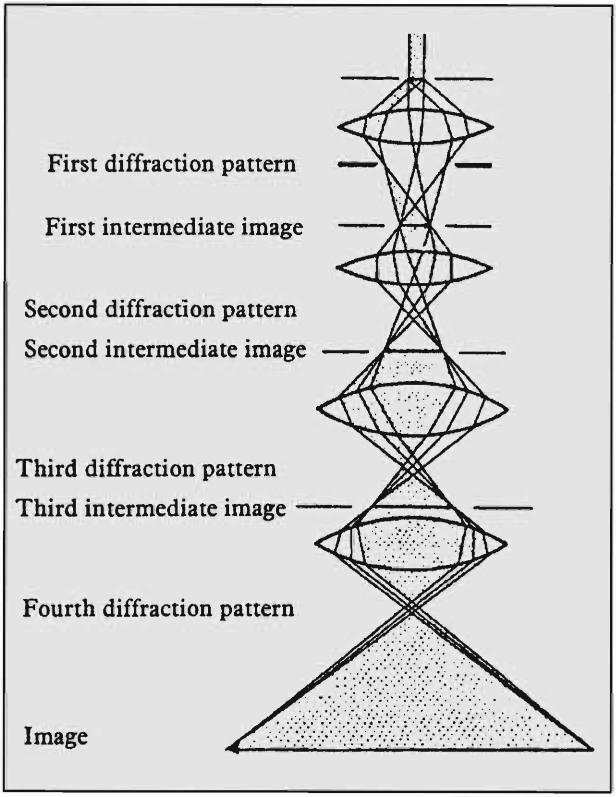


Figure 2. Image formation by TEM.

used. (This geometry is also borrowed from X-ray diffraction). In this geometry the sample is in the form of a thin foil and as shown in the figure the transmitted and the diffracted beams traverse the foil and the interference pattern is formed at the back face of the foil. The interference patterns for crystalline specimens are 2-d arrays of spots showing the symmetry of the reciprocal space and hence that of the lattice.

A high resolution TEM forms an image of the lattice from this diffraction pattern. This is schematically shown in *Figure 2*. Since the electron has to pass through the sample it is necessary to have a thin sample. For TEM studies the sample thickness is typically less than 300 nm and for high resolution microscopy it can be even as thin as 10 nm. Thus in TEM the sample preparation is an important part of the microscopy. The diffraction pattern at the back surface of the sample (or the object) can be considered as being a planar assembly of spherical wavelets. The interference between these wavelets generates the diffracted beams in the case of crystalline specimens and produces a diffraction pattern in the back focal plane of the objective lens. The diffraction pattern can to a good approximation be thought of as a Fraunhofer diffraction pattern of conventional optics (*Figure 3*). This again is a consequence of the fact that in electron diffraction the Bragg angle is often very small for the short wavelength of the electron beams compared to the spacing of the atoms in the solid. The diffraction amplitude is then a Fourier transform of the specimen transfer function for the electrons. This pattern is then collected by an objective lens. The resulting pattern at the back focal plane acts as a source of the Huyghens spherical wavelets which then interfere to produce the enlarged image of the transmission function of the object (or specimen). This image is again a Fourier transform of the diffraction pattern.

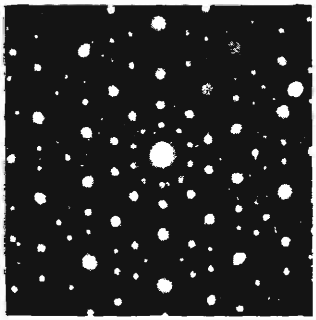


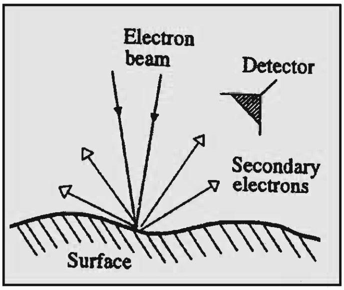
Figure 3. Example of a diffraction pattern formed in an electron microscope.

A modern high resolution electron microscope (HREM) has a number of diffraction stages and it has to overcome a number of different types of aberrations as in a good quality optical microscope. The magnification obtained in a top of the line HREM operating at high voltage can be in excess of 300,000.

Scanning Electron Microscope (SEM)

The concept of making a scanning microscope using electrons which can scan the surface goes back to the early 1930's. Shortly after the invention of TEM M Knoll in Germany invented the first SEM (see Knoll in Suggested Reading). When a beam of electrons hits the surface of a solid, the loosely bound outer electrons from the atoms in the sample are emitted as secondary electrons. These are collected and used for a different kind of microscopy called scanning electron microscopy or SEM. This form of microscopy is extensively used to image the surface feature of any object. We have schematically shown in *Figure 4* an electron beam falling on the surface of an object The beam can be focussed to a spot size smaller than a micron. The intensity of secondary electrons emitted from the surface (I) is a function of the angle (θ) between the local normal and the incident beam. Typically $I \propto \sec(\theta)$. As a result when the beam is focussed on a different spot on the surface the intensity of the secondary electrons will vary because the topography is different in the new spot leading to a different value of θ. If one can scan the surface one can generate an 'image' of the topographic features of the surface scanned from the point to point variation of the intensity of the secondary electrons. In SEM the secondary electron is collected by a detector and a map of the intensity as a function of the spot position on the surface is generated.

Figure 4. Schematic of a Scanning Electron Microscope (SEM).



It is this that gives an 'image' of the sample in SEM It has to be contrasted to imaging in a TEM which is based on the diffraction phenomena much like in an optical microscope. The magnification obtained in SEM can be well in excess of 50,000.

Tunneling Through a Barrier – Wonder of Quantum Mechanics

For any particle of mass m with a total energy E moving in a region with potential energy V, the kinetic energy $T=E-V$. The corresponding de Broglie wavelength of the particle is $\lambda=h/(2mT)^{1/2}$. For the particle to exist in this region classically $T>0$ and λ should have a real value. If $T<0$ the particle is classically forbidden in this region. Quantum mechanics however has a wonder in store. It does not forbid the particle totally from this 'classically forbidden' regime and gives a finite probability for the particle to penetrate into this terrain. This basic principle of quantum mechanics gives us a new phenomenon called 'tunneling'. This phenomenon has no classical particle analogue and is a manifestation of the wave nature of electrons.

In *Figure 5* we show an electron inside a solid. The electron cannot escape the solid because to do so it needs an energy called *work function* (ϕ). The potential barrier seen by the electron at the surface is sketched. Classically the electron will not leave the

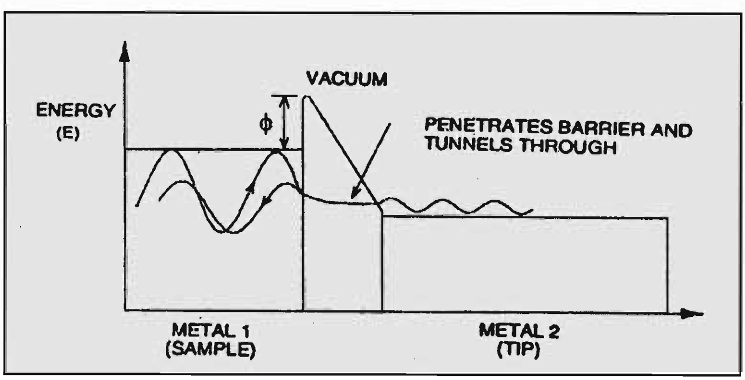


Figure 5. Potential barrier seen by an electron in a solid.

solid till it gets enough energy to overcome this potential barrier. In the region inside the solid the electron has a real wavelength and is described by a quantum mechanical wave function which represents a propagating wave. Beyond the solid, say in the vacuum region the wavelength being imaginary the electron cannot be described by a propagating wave, but the probability of finding the electron beyond the sample surface will decay exponentially with the decay constant being determined by the modulus of the imaginary wavelength. Since this is a finite length there is a finite probability of finding the electron beyond the sample surface although the probability decreases rapidly as one moves away from the surface. This phenomenon is known as *tunneling*.

In 1982, two scientists in Switzerland, G Binnig and H Rohrer invented a super-resolution microscope using tunneling as a probe and combining it with the basic concept of scanning (see Binnig and Rohrer in Suggested Reading). This microscope known as the scanning tunneling microscope (STM) could achieve atomic resolution. This invention was a major break through in surface science and it soon gave rise to a whole new family of scanning probe microscopes (SPM) which can not only image the surface with nanometer level resolution using different physical probes but can also modify the surface. It can thus be considered as a tool for surface engineering.

When a sharp metal tip is brought close to a metal surface within a nanometer then there is a finite probability for an electron to tunnel through the classically forbidden gap between the tip and the surface. If a bias is established between the tip and the substrate then a current can be made to flow through the 'tunnel resistor' formed by the tip and the substrate. This tunnel resistor has quite a different dependence on the separation (δ) between the tip and the substrate. In an ordinary solid resistor the resistance between two electrodes is a linear function of δ. But in a tunnel resistor, since the current transport depends on tunneling the resistance is an exponential function of δ! As a

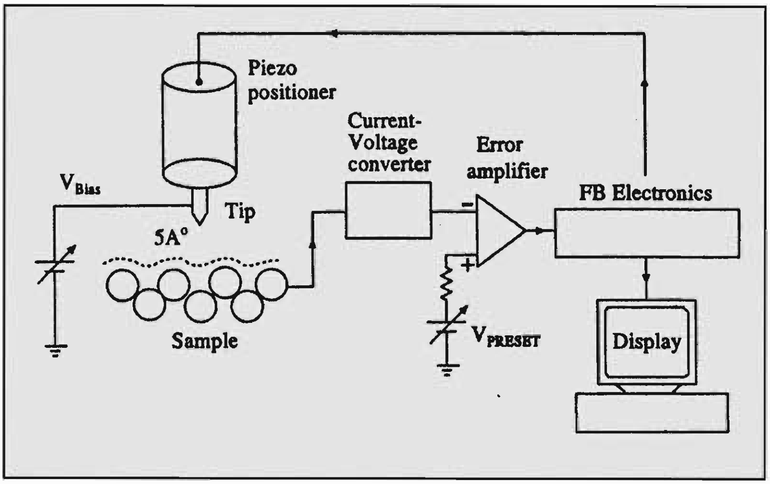


Figure 6. Schematic of a Scanning Tunneling Microscope (STM).

result for a given bias the current through the tunnel resistor decreases exponentially as the separation between the tip and the substrate increases. An STM uses this sensitive dependence of the tunnel current between the tip and the substrate to achieve the super resolution.

In *Figure 6* we show the schematic diagram of an STM. The operation of the STM depends on two things. First, the sharp metal tip (formed by mechanical means or by electrochemical methods) has to be kept within a nanometer of the surface and second, it has to be scanned over the surface with positioning precision better than a nanometer to create an image of the surface using tunneling current as the probe. We use the schematic diagram to first understand the method of topographic image formation. Generally the tunnel current is fixed to a preset value. This ensures that the distance δ is fixed at some finite value. Typically $\delta \approx 1$nm. The tip is generally scanned over the surface by using piezoelectric scanners, and during the scan the value of δ is maintained at the preset value by using a feed back loop which adjusts the distance δ by using another piezoelectric positioner which carries the tip. In the region where there is a 'hill' on the surface the tip is pulled back by the feed back loop which gives a voltage to the piezo-positioner to move the tip back.

Suggested Reading

- J J Thomson. *Philos. Mag.* Vol. 44. p. 293, 1897.
- L de Broglie. *Ann. Phys.* Vol. 10. p. 22, 1925.
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- A nice and readable account of the experiments of Davisson and Germer is given by K K Darrow. *Sci. Am.* Vol. 178. p. 51, 1948.
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- G Binnig, H Rohrer, Ch. Gerber and E Weibel. *Phys. Rev. Lett.* Vol.49, p.57, 1982.

When the tip sees a 'valley' the feed back loop gives a proper voltage to the piezo-positioner which moves the tip forward to keep δ at the preset value. Thus the feed back voltage to the piezo-positioner becomes a measure of the movement of the tip across the hills and valleys of the surface. A map of the voltage as a function of position then gives us an 'image' of the topography.

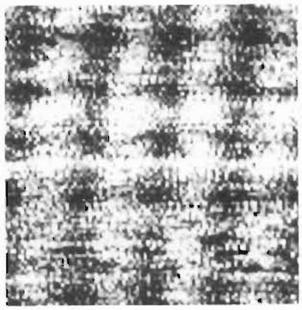

Figure 7. Atomic resolution image seen in an STM.

For imaging atoms on the surface it is not correct to think of the hills and valleys. Instead one needs to use the quantum mechanics proper and one has to bring in the concept of the wave function. The tunnel current depends on the overlap of the electronic wave functions at the tip and at the surface just below the tip . The overlap being exponentially dependent on the distance between the tip and the surface it gets the largest contribution from the region just below the tip. If an atom is present at a site just below the tip the overlap of wave functions will be more and the current will be more. Absence of an atom on the surface just below the tip will give very small tunnel current. So when the tip moves from site to site it can map the surface density of electronic states. The image formed in STM is thus a map of the surface density of electronic states convoluted with the density of electronic states at the tip. In *Figure 7* we show an atomic resolution image of a graphite surface taken by an STM. The symmetry of the surface can be clearly seen.

Conclusion

J J Thomson started with the aim to measure the *e/m* ratio of cathode ray particles. It was a modest aim but the result was one of the greatest discoveries of modern physics. In recent years the applications of electrons in microscopy have reached a level of sophistication that was unheard of even a few decades back. Thanks to the advances in computers, electronics and other associated techniques, some brave minds have scaled new heights of achievement.

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