Therefore, in scanning electron microscopy, depth of field is inversely proportional to aperture size and directly proportional to the distance between the final lens and the specimen (Table 2-2, Fig. 2-14).

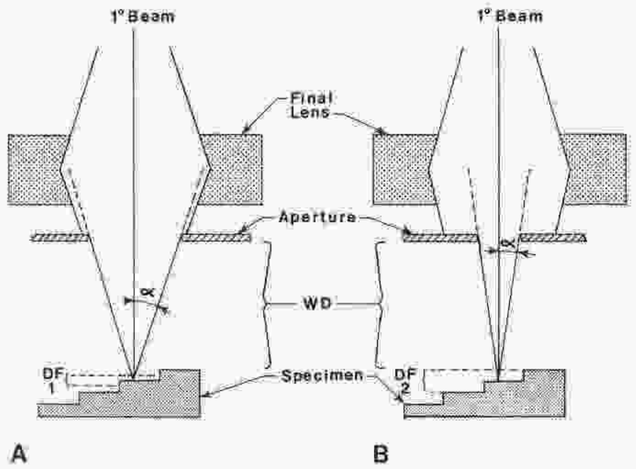
Table 2-1
WORKING DISTANCE AND IMAGE QUALITY

Working Distance (mm)	5	10	15	30
Depth of field	Shallow	----------	----------	Deep
Resolution	High	----------	----------	Low

Table 2-2
FINAL LENS APERTURE AND IMAGE QUALITY

Final lens aperture diameter (μm)	400	300	200	100
Depth of Field	Shallow	----------	----------	Deep
Specimen Current	Large	----------	----------	Small

VACUUM SYSTEMS. The operation of a scanning electron microscope requires that the column be under high vacuum. A vacuum is necessary for several reasons. First, a hot tungsten filament will oxidize and burn out in the presence of air. Second, the column must be kept clean if the beam is to be well-focused: moisture in the air will cause corrosion, dust particles in the beam path can block the beam or may become charged and deflect the beam. Third, air molecules will scatter electrons. The mean free path (MFP) of electrons in the beam—the

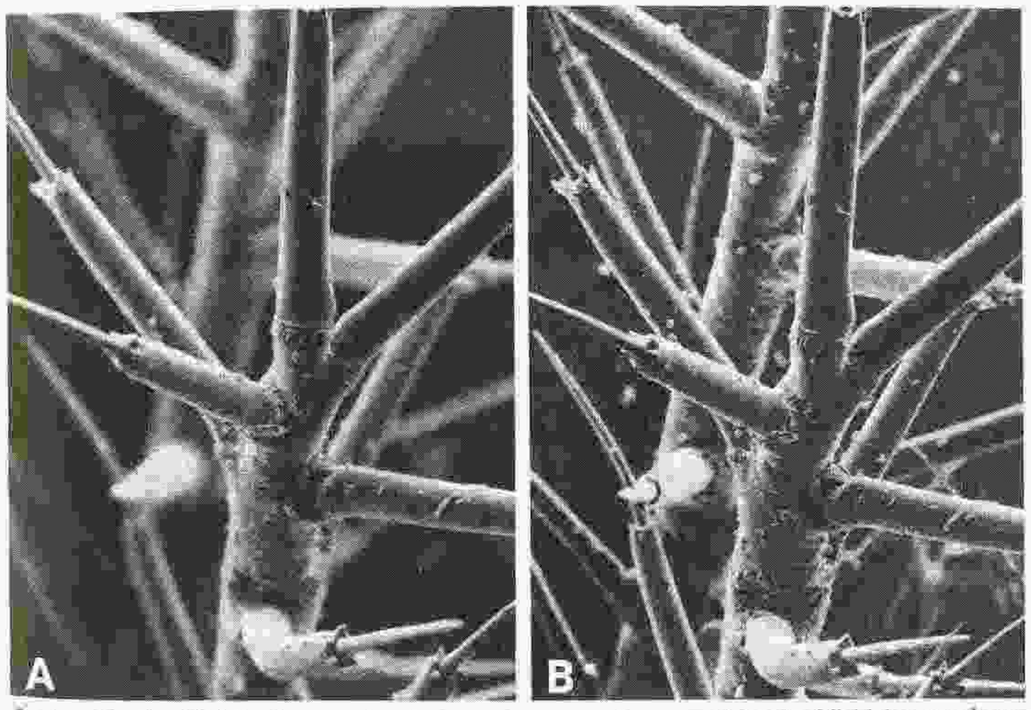


2-13. Enhancement of depth of field by reduction in the size of the final lens aperture. (A) Large aperture. (B) Small aperture.

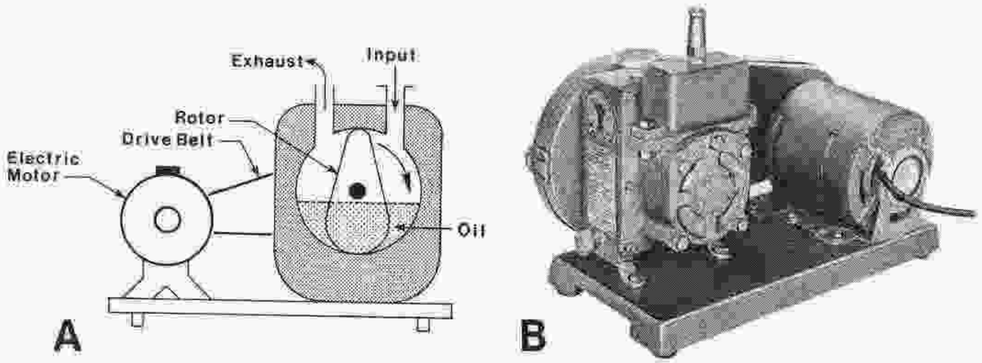
average distance that an electron travels before it collides with an air molecule—must be longer than the length of the microscope column. For most microscopes, the column is about 1 meter long and an air pressure of less than 1×10^{-4} mm Hg (1×10^{-4} torr) is needed. Normal working vacuum for a scanning electron microscope using a tungsten filament is better than 5×10^{-5} mm Hg. This compares with atmospheric pressure that is approximately 760 mm Hg. A comparison of modern nomenclature for vacuum terminology is 760 mm Hg (torr) is equal to 101325 Pa (pascals) or N/m^2 or equal to 1 atmosphere (24).

Attaining the vacuum necessary for the operation of a scanning electron microscope requires the use of more than one type of vacuum pump. The pumping system generally utilizes a mechanical pump in conjunction with either a diffusion pump or a diffusion pump-assisted ion pump.

Mechanical Pumps. The design of mechanical pumps varies somewhat from one manufacturer to another, but essentially they consist of a motor driven, eccentrically-shaped or mounted rotor. This rotor rotates through an oil bath which acts as a lubricant and vacuum seal. As shown in Figure 2-15, air enters the pump through the inlet that is connected to the apparatus to be evacuated. The eccentric rotation of the rotor compresses the air and, with continued rotation, forces it through the outlet. With continued pumping, the air pressure will be lowered. In some designs, spring-loaded vanes are used to increase the pumping efficiency. Mechanical pumps are classified according to their initial pumping rates. Rates of 500 to 1000 liters per minute are typical. The efficiency of mechanical pumps decreases rapidly as vacuum improves and while the



2-14. Depth of field in the scanning electron microscope. Increase of depth of field due to a change in objective aperture size. (A) 300 μm. (B) 100 μm.

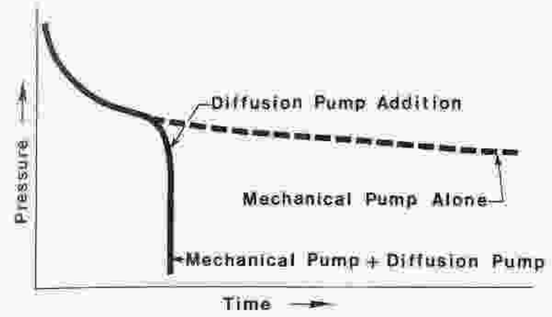


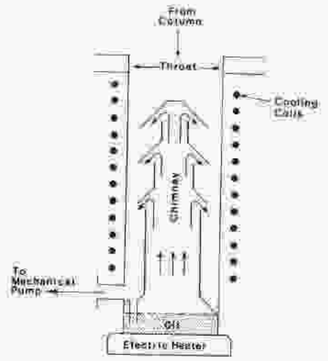
2-15. Mechanical pump for a scanning electron microscope. (A) Schematic representation. (B) Photograph (Courtesy of Ladd Research Industries, Inc.).

mechanical pumps commonly used for a scanning electron microscope can achieve a pressure of better than 5×10^{-5} torr, they are inefficient at pressures lower than 1×10^{-2} torr resulting in exceptionally long pump down times (Fig. 2-16). Because of this, the diffusion pump is used in conjunction with the mechanical pump on most scanning electron microscopes.

Diffusion Pumps. The diffusion pump, as its name implies, operates by means of air diffusion into the pump. It is composed of a heating element, oil, and a distribution system (Fig. 2-17). As the oil is heated, it circulates through the distribution system termed a chimney. The oil vapor moves up the chimney and is directed onto the underside of several vanes and it then flows back down the side of the pump's walls. Cooling coils containing circulating chilled water are wrapped around the diffusion pump to cool and condense the oil as it flows to the bottom of the pump. As the oil circulates through the system, the oil vapor transports air molecules from the top of the pump to the bottom. A pressure gradient is thus established, with lower air pressure at the top of the pump than at the bottom. By attaching a foreline from the bottom of the diffusion pump to a mechanical pump, the higher pressure at the base of the pump is relieved and the vacuum in the diffusion pump can be increased. The top of the diffusion pump is connected to the microscope column and can rapidly achieve pressures of 5×10^{-5} torr or less. The efficiency of a diffusion pump is largely determined by the size of its throat. For this reason, throat size is a very common means of classifying diffusion pumps. In contrast to a mechanical pump, a diffusion pump is theoretically capable of 500 to 1000 liters per *second* pumping rate at a pressure of about 1×10^{-5} mm Hg.

Unfortunately, the diffusion pump cannot be used at pressures greater than 1×10^{-2} torr. At this pressure, many heated hydrocarbon-base oils will oxidize (crack) and be converted to a vapor phase, which is removed from the diffusion pump by the mechanical pump, and a solid phase (tar) which coats the inside of the diffusion pump. The cracking of diffusion pump oil can be reduced or eliminated by the use of a fluid which is more stable at higher temperatures and pressures. Several alternative diffusion pump oils are available (including silicon and perfluoropolyester based) each with its own advantages and disadvantages





2-16. Graphic demonstration of qualitative pumping rates for mechanical pump—diffusion pump system. Stippled line indicates the inefficiency of the mechanical pump alone.

2-17. Schematic representation of an oil diffusion pump.

(24). The type of diffusion pump oil used will generally be determined by the microscope manufacturer to suit the needs of each particular application.

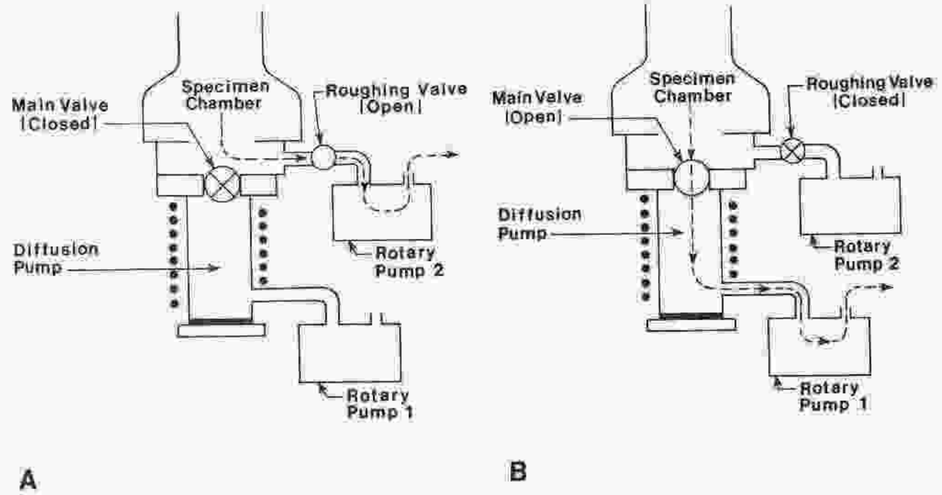
The general vacuum system of a standard scanning electron microscope, illustrated in Figure 2-18, is composed of two mechanical pumps and one diffusion pump. One mechanical pump (backing) always works in conjunction with the diffusion pump to continually relieve the pressure gradient. The second mechanical pump (roughing) acts to evacuate the column or specimen chamber from atmosphere to the point where the diffusion pump can be used.

Ion Pumps. The vacuum level attainable in the typical diffusion pumped system is approximately 1×10^{-6} torr. An even higher vacuum can be obtained through the use of an ion pump. With an ion pump, ultrafine particles of a very reactive metal are released into a chamber near the filament by a process termed "sputtering" (see Chapter 5). The air molecules react with the metal to form stable, solid compounds. Thus, air is removed from the system and the pressure drops. Vacuum levels as great as 10^{-11} torr are possible with an ion pump (19, 20). As with diffusion pumps, ion pumps cannot be used from atmospheric pressures. Thus, the microscope must be rough pumped to an acceptable vacuum, then the ion pump turned on.

In dealing with higher vacuum levels (10^{-7} to 10^{-11} torr), additional factors must be taken into consideration. For example, some specimens may react adversely to higher vacuum by out-gassing into the column. This may cause deformation of the specimen surface or contribute to a higher pressure in the column that will interfere with microscope operation. One approach to this problem has been to utilize differentially pumped systems which maintain conventional pressure (10^{-5} or 10^{-6} torr) at the specimen with ultra-high vacuum (10^{-10} or 10^{-11} torr) at the gun.

IMAGE FORMATION

SIGNAL GENERATION. The interaction of a primary electron beam with a specimen creates a volume of primary excitation within the specimen (Fig. 2-19)

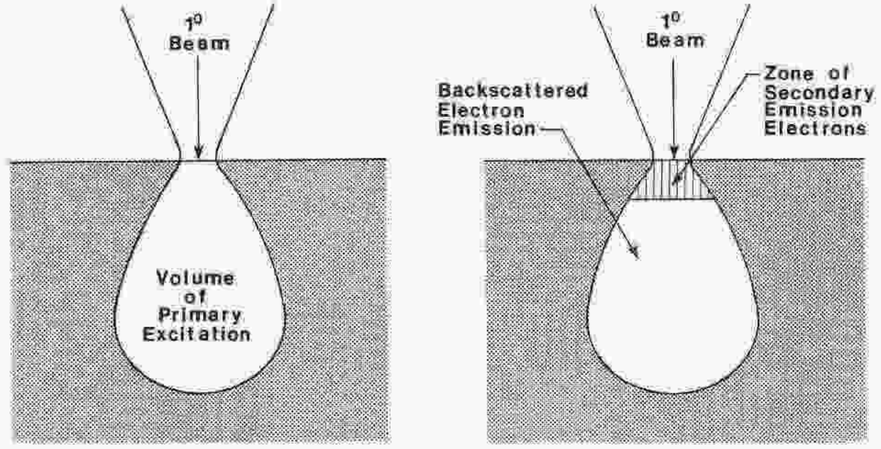


2-18. Diagram of the evacuating system of a scanning electron microscope. (A) Roughing of the specimen chamber by rotary pump 2. (B) High vacuum operation.

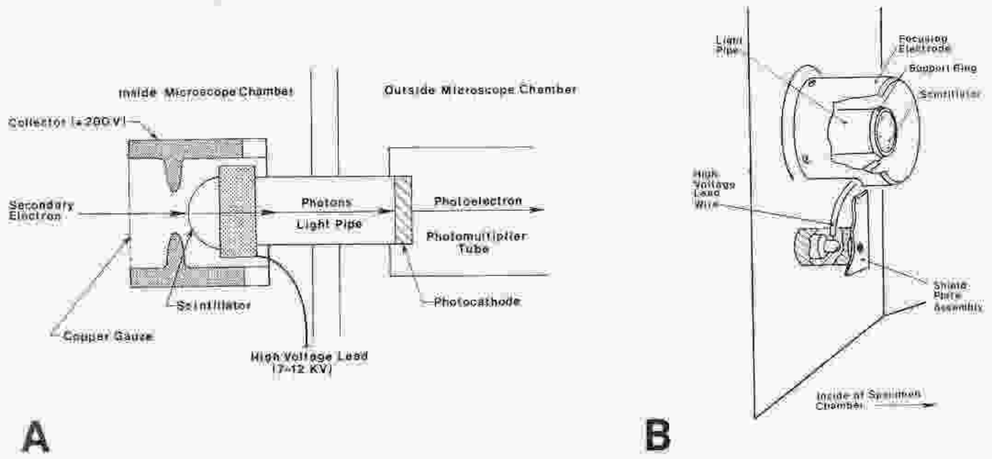
in which electrons are scattered (34). This scattering may be divided into two types: elastic and inelastic (35). In elastic interactions, the electrons involved retain virtually all of their energy. The resulting high energy electrons are termed backscattered electrons if they are emitted back from the specimen surface. In inelastic interactions, the electrons involved lose much of their energy and hence are of low energy. Those electrons of less than 50 electron volts may be termed secondary electrons (other signals generated are discussed in Chapter 3).

Secondary electrons are created throughout the volume of primary excitation. Due to their low energy, most of them are absorbed by adjacent atoms in the specimen. As a result, only those secondary electrons created near the surface of the specimen are able to escape. However, in contrast to secondary electrons, backscattered electrons can escape from greater depths within the specimen because of their higher energy (Fig. 2-19b).

Secondary and backscattered electrons are emitted outward from the specimen surface in all directions. The electrons may be detected by a system in the microscope column composed of a collector, scintillator, light pipe, and photomultiplier tube (13, 14) as shown in Figure 2-20. The collector has a positive bias that draws the electrons to the scintillator. The scintillator is a thin plastic disc (which in the original design was hemispherical) coated with a special phosphor for greater efficiency in transferring the energy of electrons to photons. The scintillator is also coated with approximately 10 nm of aluminum which serves as a mirror to direct the photons toward the photomultiplier (4). A positive bias is applied to a ring around the scintillator and is referred to as the anode or collector. This positive bias accelerates the low energy secondary electrons toward the detector, but does not influence the higher energy backscattered electrons (Fig. 2-21). Therefore, the resulting "secondary electron image" is actually formed by a combination of the backscattered electrons emitted toward the detector and almost all of the collected secondary electrons.



2-19. Interaction of the electron beam with the specimen. (A) Description of the volume of primary beam excitation. (B) Zones of secondary and backscattered electron emission.



2-20. Secondary electron detection system. (A) Image collection system for secondary electrons (after Everhart and Thornley, 1960). (B) Secondary electron detector as used in the Hitachi S-500 scanning electron microscope (Courtesy of Hitachi, Ltd.).

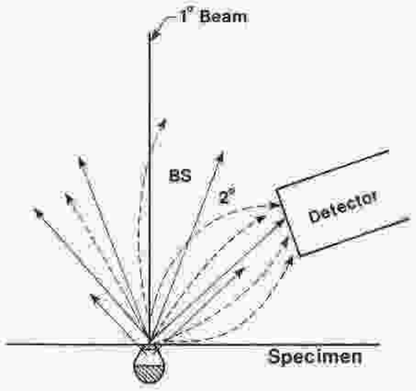
Electrons biased to the detector strike the scintillator after being accelerated by the anode. The scintillator contains phosphors that will produce small flashes of light (photons) when struck by electrons. Theoretically, several photons are emitted for each incoming electron (one photon for each 3.3 eV), but scintillator efficiency is far lower than this figure (36). To be of use for the scanning electron microscope, the phosphors must have a rapid decay time; that is, the flash of light must be immediate and short-lived.

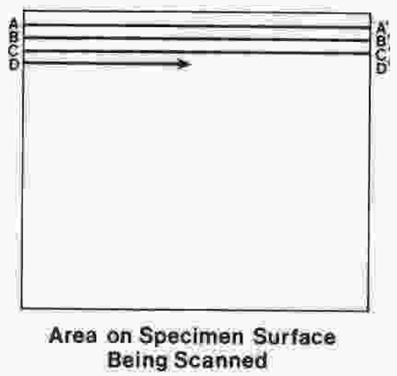
The flash of light produced by the scintillator is transported through a light pipe from the evacuated microscope column. Light pipes vary in composition

from one microscope to another but are generally made of plexiglass or polished quartz. The photons carried by the light pipe are converted outside the microscope column to an amplified electronic signal through the use of a photocathode and photomultiplier tube. The signal can then be displayed on a cathode ray tube on the display console with the brightness on the screen proportional to the number of secondary electrons emitted from the specimen (amplitude contrast). The amplification of the signal with the photomultiplier is far less efficient than that of the scintillation disk, in that noise is greatly amplified with the photomultiplier (36).

Scanning Coils. For scanning electron microscopy, as its name implies, the specimen is traversed by an electron beam. This movement is achieved by scanning (raster) coils in the microscope column controlled by a scan generator. The primary beam is electromagnetically deflected across a given area of the specimen. As shown in Figure 2-22, the beam starts at point A and moves across to point A′, then from B to B′, C to C′, and so forth; thereby, building up an image line by line. When the beam reaches the right-hand side, it is deflected back to the left and starts on the next line. The raster pattern of the primary electron beam is synchronized with the scanning pattern of the cathode ray tube (CRT) yielding a point-by-point translation.

IMAGE DISPLAY. Scanning electron microscopes generally are equipped with at least two cathode ray tubes for the visualization and recording of the specimen image. The cathode ray tube is much like a television picture tube where the deflection coils are coupled to the scanning coils of the microscope, thus producing a one-to-one representation of the area scanned (Fig. 2-23). One cathode ray tube is used for the display of the specimen image to the microscope operator. This visual display unit is equipped with a persistent





2-21. Detection of the electrons generated by the interaction of the primary (1°) beam with the specimen. Secondary (2°) electrons are described by dotted lines while backscattered electrons (BS) are described by solid lines. Note that the secondary electron image is formed by both the secondary electrons and the backscattered electrons that reach the detector.

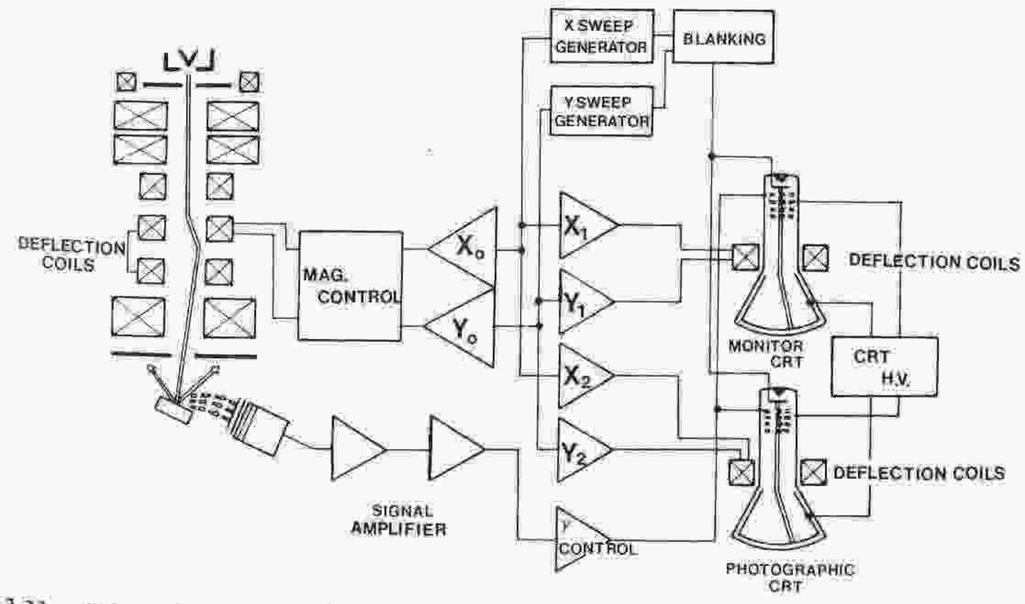
2-22. Illustration of the raster pattern produced by the deflection of the primary electron beam by the scanning coils.

phosphor screen. The persistence of the phosphor facilitates specimen focusing and selection. The second cathode ray tube is used for photography only. This screen has short persistence phosphors to avoid fogging of the photographic film due to afterglow (4).

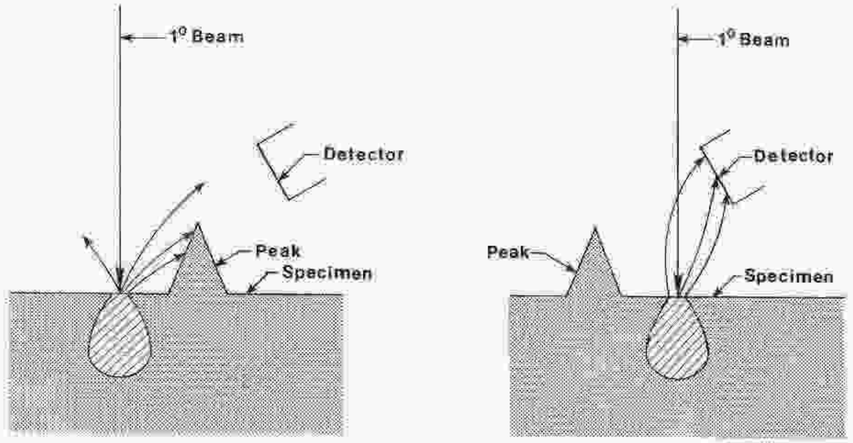
If we define the brightness of the image viewed on the cathode ray tube by the number of secondary electrons reaching the detector (as the primary beam scans the specimen), then the factors which control the emission and path of secondary electrons as they escape from the specimen surface will determine the amplitude contrast seen in the cathode ray tube image. The two most important factors are specimen composition and surface topography.

Specimen composition. The number of secondary electrons produced by a specimen is partly dependent upon the density of electrons in the specimen. As a result, the number of secondary electrons emitted increases with increasing atomic number (secondary electron coefficient).

Specimen topography. The secondary electron detection mode (like the other detection modes) of the scanning electron microscope is affected by specimen topography. The effect of topography on the image is the result of the position of the detector to one side of the specimen (as opposed to its being directly above). Given a peak on the specimen (Fig. 2-24), many of the electrons emitted from the specimen surface facing away from the detector will be blocked (from the detector) by the peak. Those electrons emitted from the surface facing toward the detector will not be obstructed. This shadowing effect gives the impression that a light is shining on the specimen from one side. The bias on the detector is capable of drawing some secondary electrons from that shaded side and, as a result, the shadowing effect is not absolute. If the



2-23. Schematic representation of selected electronic components of the scanning electron microscope showing the coupling of the deflection coils found in the column with those found in the cathode ray tube.



2-24. Illustration demonstrating the effect of topography and detector position upon the secondary electron image. Note that some of the secondary electrons from the far side of the topographic irregularity will reach the detector while others will be blocked.

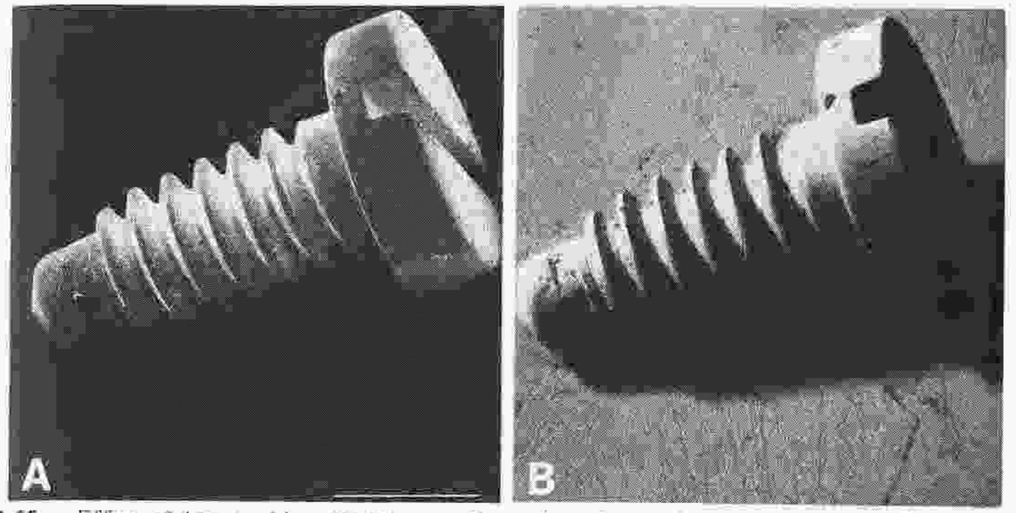
bias on the detector were removed, only those secondary electrons and backscattered electrons that were emitted toward the detector would reach the scintillation disk. In such a case, only those specimen surfaces which face toward the detector would be illuminated on the cathode ray tube (Fig. 2-25).

Topography is also important for another reason. A peak tip emits electrons more efficiently than the rest of the specimen; in effect, the tip acts as a sort of reverse lightning rod. As a result, fine structure commonly appears brighter than the rest of the specimen (Fig. 2-26). This is termed "enhanced emission."

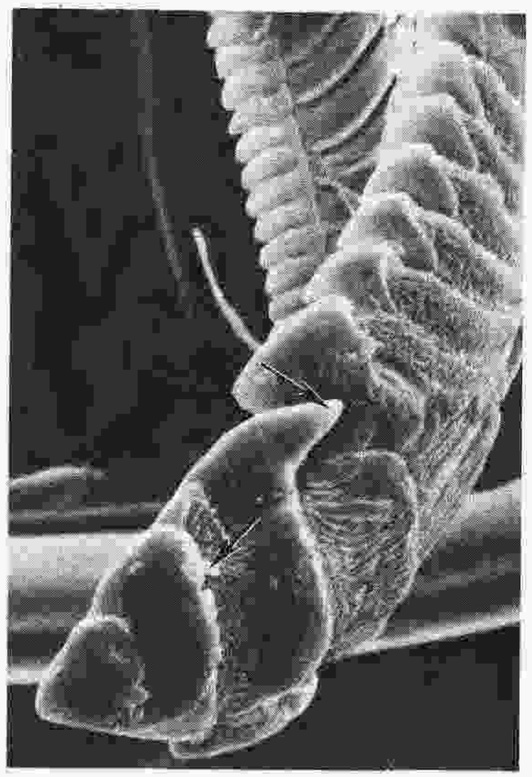
Tilting of the specimen may greatly affect the SEM image, not only by changing the area excited but also by altering the zone of secondary electron emission. The size of this zone varies with the angle at which the primary electron beam strikes the specimen (Fig. 2-26). When the specimen surface is perpendicular to the beam, the zone from which secondary electrons are emitted is smaller than when the specimen surface is tilted. Since more secondary electrons are emitted from each point the beam passes, the tilted surface yields a brighter CRT image (Fig. 2-27).

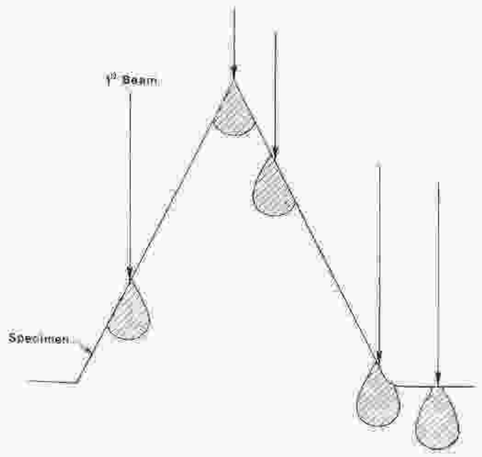
From the discussion in the preceding pages, it is apparent that the final image produced by an SEM is dependent upon a large number of variables. The contrast, brightness and resolution may be changed by alterations in the filament/gridcap assembly, electromagnetic lenses, apertures, or detection system, and is affected by changes in specimen composition, topography, and tilt.

Magnification. Magnification in the SEM is the ratio of a line of the cathode ray tube image to a comparable line scanned on the specimen. A change in magnification is thus a change in the size of the area scanned. In addition to changes produced by the raster coils, magnification can be changed by varying the working distance (the distance from the objective lens pole piece to the top



2-25. Effect of detector bias. (A) Bias on—Secondary electron image of a screw. Image is composed of secondary electrons and backscattered electrons. (B) Bias off—Backscattered electron image of the same specimen. Line scale is equal to 500 μm.





2-26. Effect of topography on the zone of primary excitation. Note how as the angle and topography change the amount of secondary electron generation also changes. This is termed enhanced emission.

2-27. Enhanced emission as seen on the scanning electron micrograph of the stylet tip of *Tetyra bipunctata*. Arrows indicate some of the areas of enhancement (Micrograph courtesy of R. A. Goyer). Line scale is equal to 20 μm.