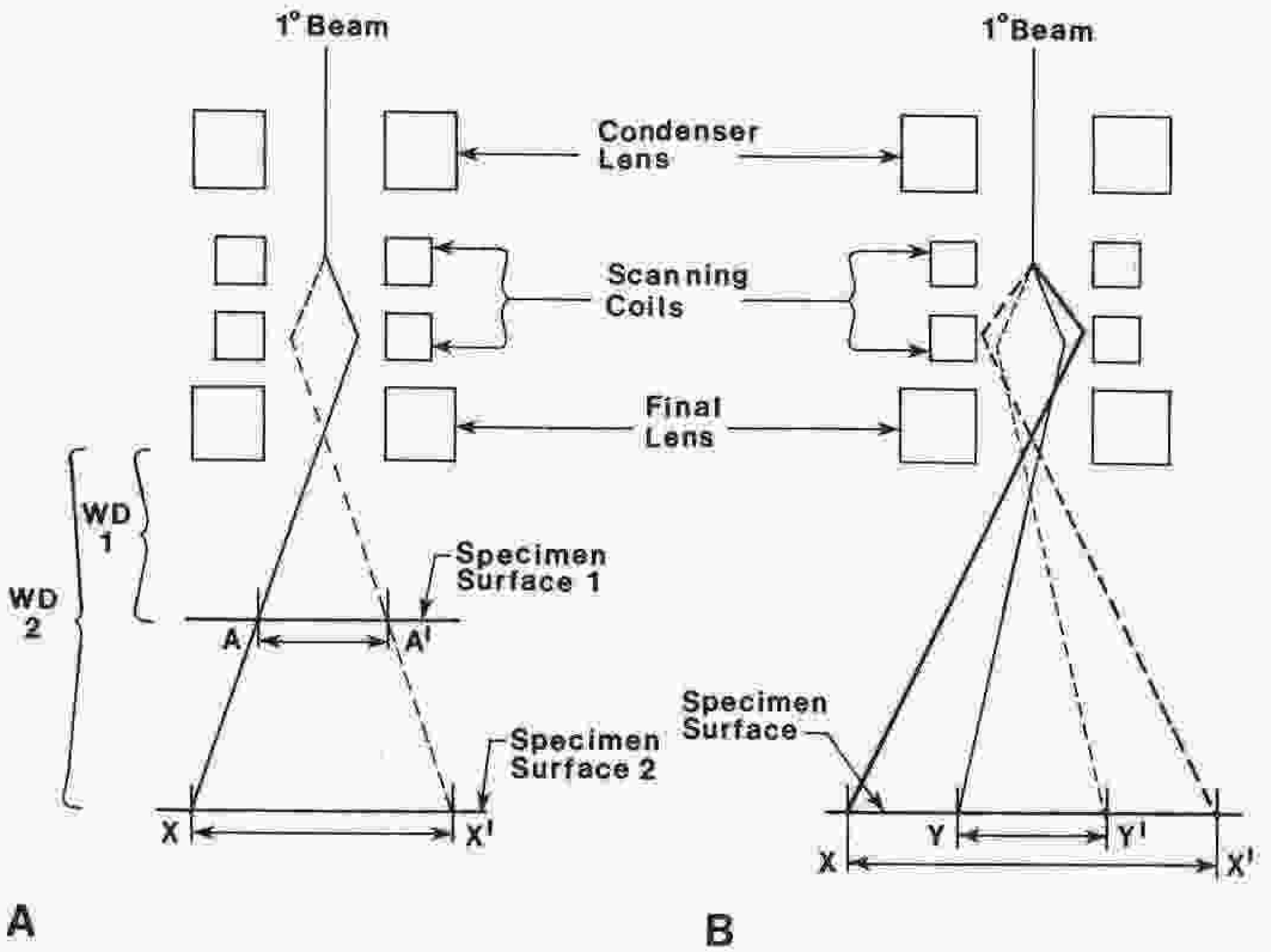
of the specimen) or by varying the accelerating potential of the electron beam (this is compensated for in newer microscopes). Magnification is increased by decreasing the working distance or by increasing the accelerating potential. This fact is illustrated in Figure 2-28. These figures demonstrate that the raster coils deflect the beam in a precise pattern. As the specimen is moved closer to the final lens pole piece, the electron beam scans a smaller area (Fig. 2-28a). Thus, magnification is increased with this decrease in working distance. Conversely, by increasing the accelerating voltage, the beam is deflected less by the electromagnetic field created by the scanning coils (Fig. 2-28b). Thus, an increase in accelerating voltage will increase the magnification of the microscope image. Because specimen height can vary and the accelerating voltage and specimen position can be changed, care should be taken when determining the magnification from a gauge on the microscope console. In many microscopes, the magnification gauge is only able to relate to changes produced in the scan generator.

SPECIAL MODIFICATIONS

The preceding sections describe the components of a standard "vanilla" scanning electron microscope. A number of modifications have become commercially available which improve the operation, optimum resolution and



2-28. Variables affecting magnification in the scanning electron microscope. (A) Alteration in working distance. As the specimen is moved toward the objective lens, the magnification is increased. (B) Alteration of accelerating potential. Increase in the acceleration potential results in higher magnification.

signal manipulation capabilities of this instrument. These improvements can be separated into two basic categories: those which deal with filament design and their associated modifications and those dealing with signal processing.

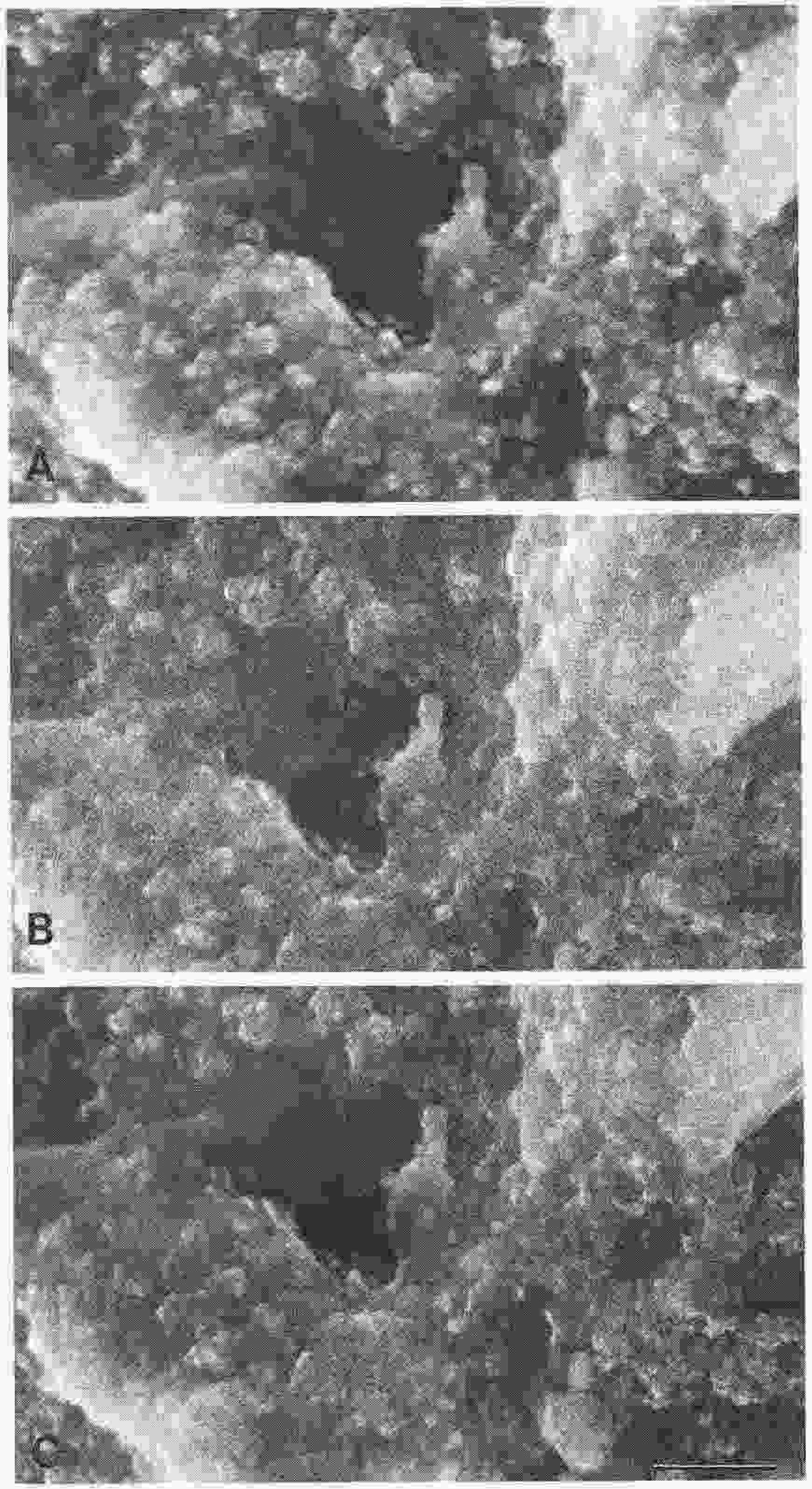
ELECTRON GUN IMPROVEMENTS. The image quality of the scanning electron microscope is limited by the beam spot size and the ratio of the signal (S) produced by the electron beam to the noise (N) imparted by the electronics of the instrument in the displaying of this signal (S/N). Noise pulses are a result of microscope operating parameters such as beam brightness, condenser lens setting or detector gain and may impart a salt-and-pepper (grainy) appearance to the recorded image (Fig. 2-29). Changes in these settings result in a compromise situation and should be considered as such. To obtain a higher resolution image, image brightness suffers and, conversely, a bright image may not be as high in resolution. An appropriate image optimizes the compromises in these situations. The concept of S/N ratio has been carefully covered by Oatley (35); Wells (40); and Goldstein and Yakowitz (17). The image in a scanning electron microscope, and hence its S/N, is improved as the total number of electrons recorded per picture point is increased (Fig. 2-29c). Unfortunately, certain limitations are imposed upon the use of a tungsten hairpin filament in the pursuit of an image with an acceptable signal-to-noise ratio.

Tungsten emitters characteristically have low yields of electrons resulting in a low brightness image. In addition, as the beam passes down the column, much of it interacts with and is excluded by apertures and other column components. At high resolution condenser lens settings, the quantity of electrons reaching the specimen—to interact with that specimen—is quite low. Therefore, secondary electron production within the specimen is low. This requires that high current be applied to the photomultiplier system in order to produce an image. Such a procedure introduces substantial noise into the system resulting in an unfavorable signal-to-noise ratio.

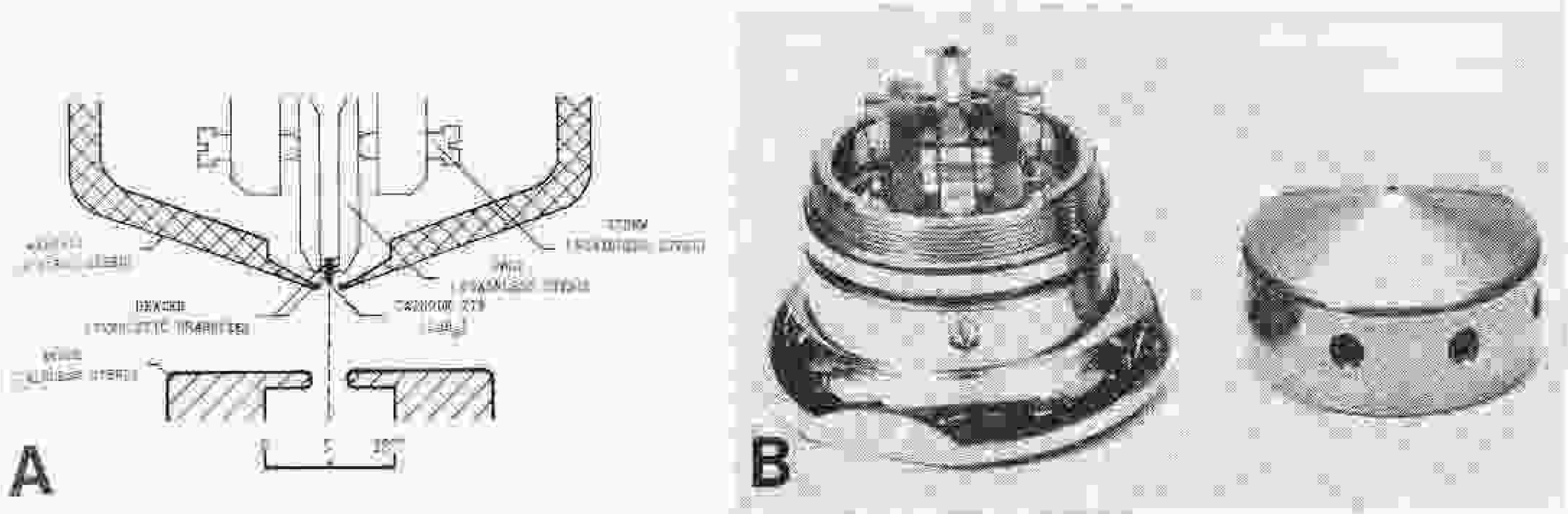
Pointed tungsten hairpin filaments have been used to help increase electron emission and resolution of the scanning electron microscope. These filaments improve unfavorable signal-to-noise ratios, but they are still limited by the characteristically low electron emission of the tungsten and have some instability (21). In an effort to improve the signal-to-noise ratio, brighter sources have been developed. Two specific types of modifications are common: lanthanum hexaboride (LaB_6) and field emission.

Lanthanum hexaboride (LaB_6). The lanthanum hexaboride gun contains a fine-tipped filament composed of a boride of the rare earth lanthanum (LaB_6). In the Broers design (5), the cathode is composed of a 1 mm solid rod of LaB_6. The end from which the electron emission originates is ground to a fine point. One commercial design for this type of filament is shown in Figure 2-30.

Initially, the lanthanum hexaboride electron gun was placed directly into conventional scanning electron microscopes in place of the standard tungsten filament (15). This modification increased filament brightness at least ten fold, but filament life was low. In order to decrease cathode contamination and increase filament life, higher vacuum, in the realm of 10^{-6} to 10^{-7} torr, is necessary. More recent designs have utilized ion pumped gun chambers in



2-29. Effect of alteration of the signal-to-noise ratio. (A) Normal image with acceptable signal-to-noise ratio. (B) Unacceptable signal-to-noise ratio obtained by reducing beam intensity (signal reduction) and increasing photomultiplier tube amplification (noise increase). (C) Improvement of recorded image (as in B) by slower scan speed, thus increasing the number of electrons recorded. Line scale is equal to 2 μm.



2-30. Lanthanum hexaboride emitter for a JEOL JSM-35 scanning electron microscope. (A) Labeled diagram. (B) Photograph (Courtesy of JEOL, USA).

order to maintain the necessary ultra-clean environment around the cathode.

The design, operation and characteristics of the lanthanum hexaboride gun have been adequately covered by several authors (1,2,6,23,27,28,39) and, therefore, further discussion will be limited. It should be pointed out that several advantages can be realized by the use of an LaB_6 cathode (Table 2-3). Not only does the use of a lanthanum hexaboride filament provide an increase in brightness over a tungsten filament, but also the effective source size is much smaller. As a result, the spot size is much smaller. Another advantage of the LaB_6 gun is that its energy spread (chromacity) is far less than a tungsten filament, thus reducing chromatic aberration. The combined effect, as demonstrated by Nakagawa and Yanaka (28), has been to improve resolution to a 4 nm range with a far more favorable signal-to-noise ratio. Presently, the use of LaB_6 guns is limited due to costs associated with fabrication of large, single LaB_6 crystals and the initial cost and maintenance of the necessary high vacuum systems (7).

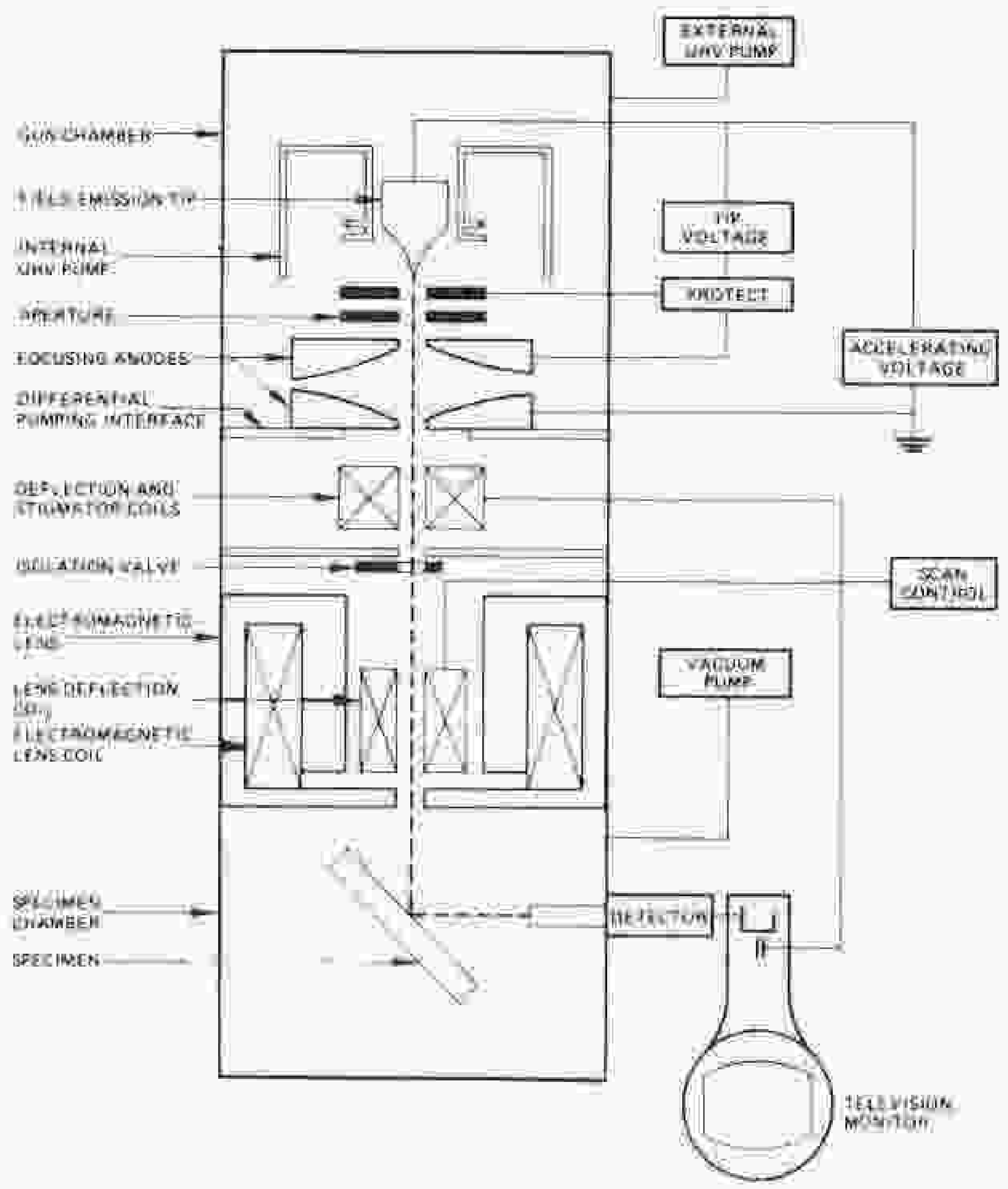
Field Emission. The field emission concept was originally described by B. W. Wood in 1897 and, subsequently, has been discussed by numerous authors (8,9,10,11,18,22,38,41,42). Field emission sources are fundamentally different from thermionic sources (i.e., conventional tungsten and LaB_6 filaments). In thermionic emission, the electrons are liberated from the filament tip by heating the filament; essentially, the electrons are "boiled off". However, in field emission systems, electrons are drawn by an electrical field from a precisely oriented, finely-pointed tungsten crystal. Since filament heating is not the controlling factor in electron generation, these sources are sometimes referred to as "cold sources" (41). Figure 2-31 illustrates the design of a field emission scanning electron microscope.

The field emission source is a short piece of specifically oriented, single crystal tungsten wire electrolytically etched to a very sharp point. An axis of the tungsten crystal is oriented to coincide with the optical axis of the microscope. The planes of most intense electron emission are perpendicular to the ⟨310⟩ and ⟨111⟩ crystallographic indices (Fig. 2-32). In such a source, electrons are thought to originate from a point source on the filament which may be less than 5 nm in diameter. This is a much finer source than even that of the lanthanum hexaboride tip.

Table 2-3

COMPARISON OF ELECTRON SOURCES (AFTER WELTER, 1975)

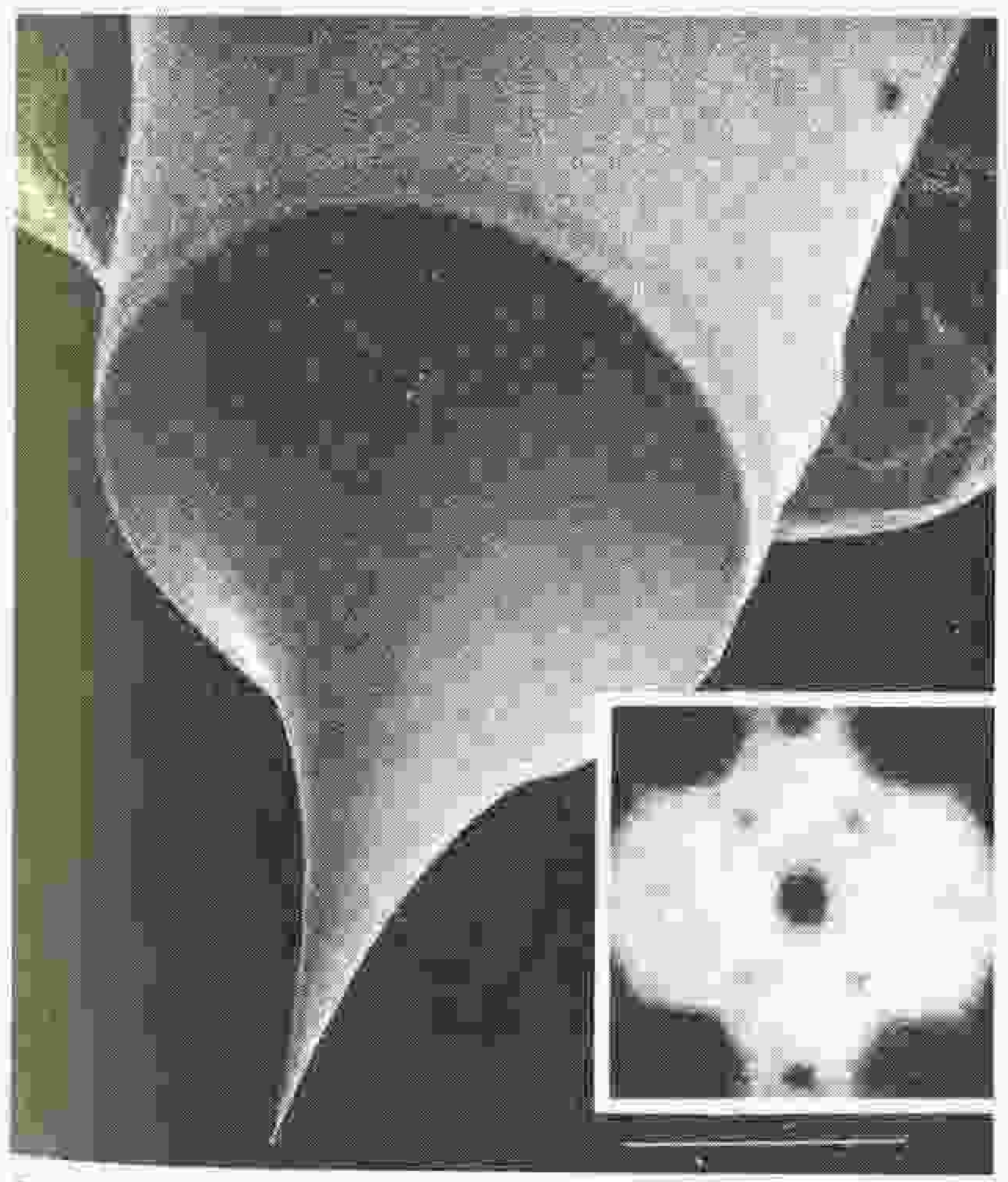
	Tungsten Filament	Lanthanum Hexaboride	Field Emission
Type of Emission	Thermionic	Thermionic	Field
Operating vacuum (torr)	10^{-4} - 10^{-5}	10^{-6} - 10^{-7}	10^{-9} - 10^{-10}
Brightness ($A/cm^2 \bullet ster$)	10^4 - 10^5	10^5 - 10^6	10^7 - 10^9
Source Size (Å)	1×10^6	2×10^5	$<1 \times 10^2$
Energy Spread (eV)	1-5	0.5-3	0.2-0.3
Probe Current Stability (% per minute)	0.1-1.0	0.2-2.0	2-10
Operating Life (hrs.)	>20	>100	>300

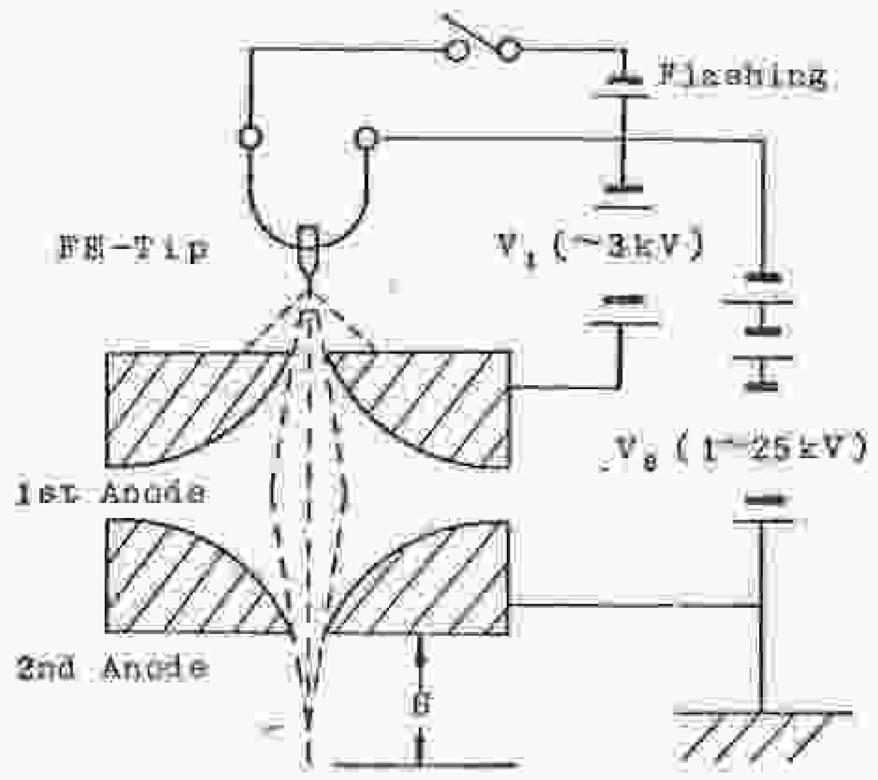


2-31. A schematic view of the column of a field emission scanning electron microscope. (Courtesy of Coates and Welter, Corp.).

In one design (Fig. 2-33), the field emission gun consists of the cathode and two anodes. To the field emission tip and the first anode an emission voltage (V_1) of 3 to 6 KV is applied. Electrons emitted from the tip pass through the first anode and are accelerated by the second anode voltage (Vo). In this design, the two anodes act as an electrostatic lens to form the electron beam. Subsequently, electromagnetic lenses provide further demagnification and control over beam current. The extremely fine source of the field emission system enables the attainment of higher resolution. The curves represented in Figure 2-34 demonstrate that probe diameters of better than 2 nm are possible with a field emission source while the theoretical limit imposed upon conventional therminoic sources is 4 to 8 nm. The actual resolution of any system will be poorer than the spot diameter of the beam because the primary beam generates secondary electrons from a teardrop shaped region in the specimen (Fig. 2-19) and not a single point. The size of the teardrop is related to several factors covered in Chapter 3. Therefore, the smaller probe facilitates the production of a higher resolution image (Figs. 2-35 and 2-36). This fact makes these microscopes and their capabilities unique. Further advantages presented by a field emission system have been reported (41) with two specific ones being paramount: increased brightness and increased depth of field.

Field emission results in enhanced electron emission relative to thermionic sources (1×10^{-3} amp as opposed to approximately 1×10^{-6} amps for a conventional tungsten filament). It also has phenomenally low electron spread





2-32. The field emission tip. Scanning electron micrograph of a field emission tip (line scale is equal to 50 μm). Inset shows the planes of most intense electron emission (Courtesy of Hitachi, Ltd.).

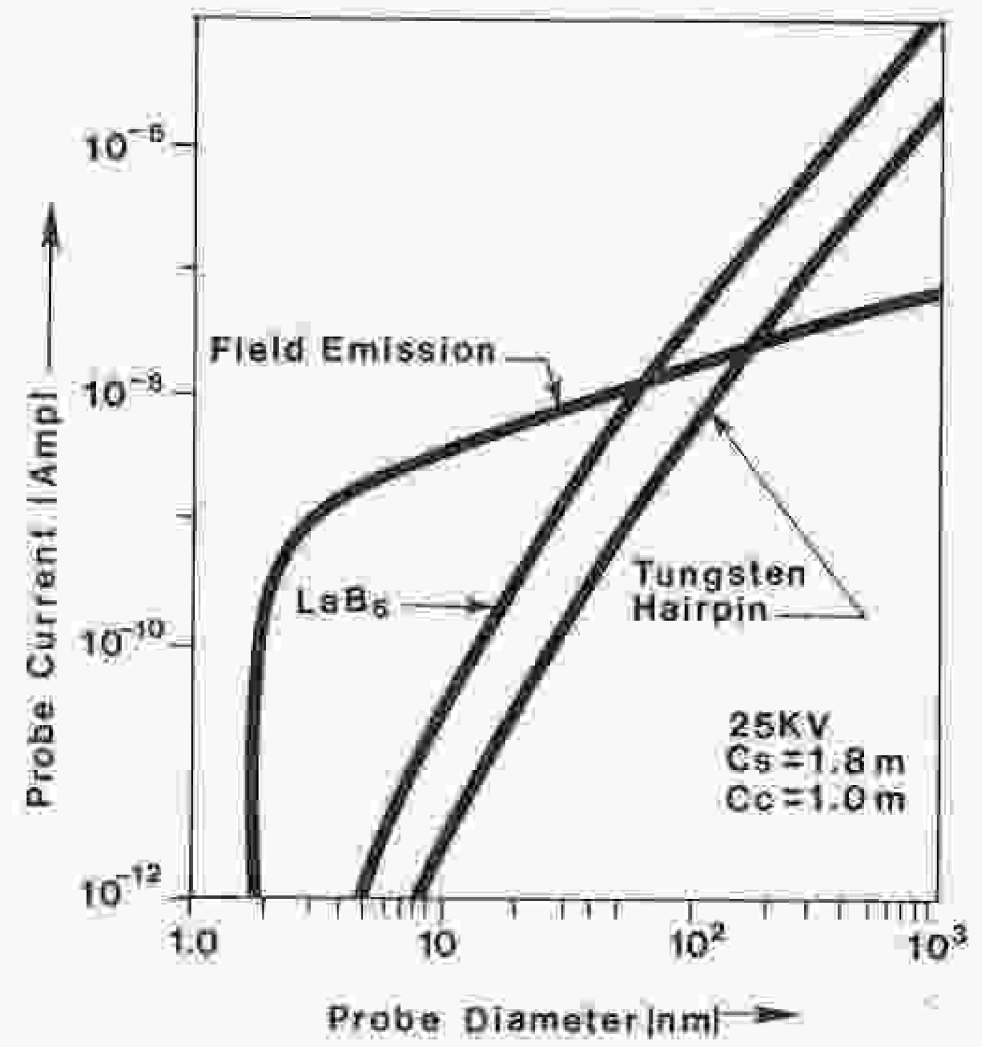
2-33. The construction of a field emission gun (Courtesy of Hitachi, Ltd.).

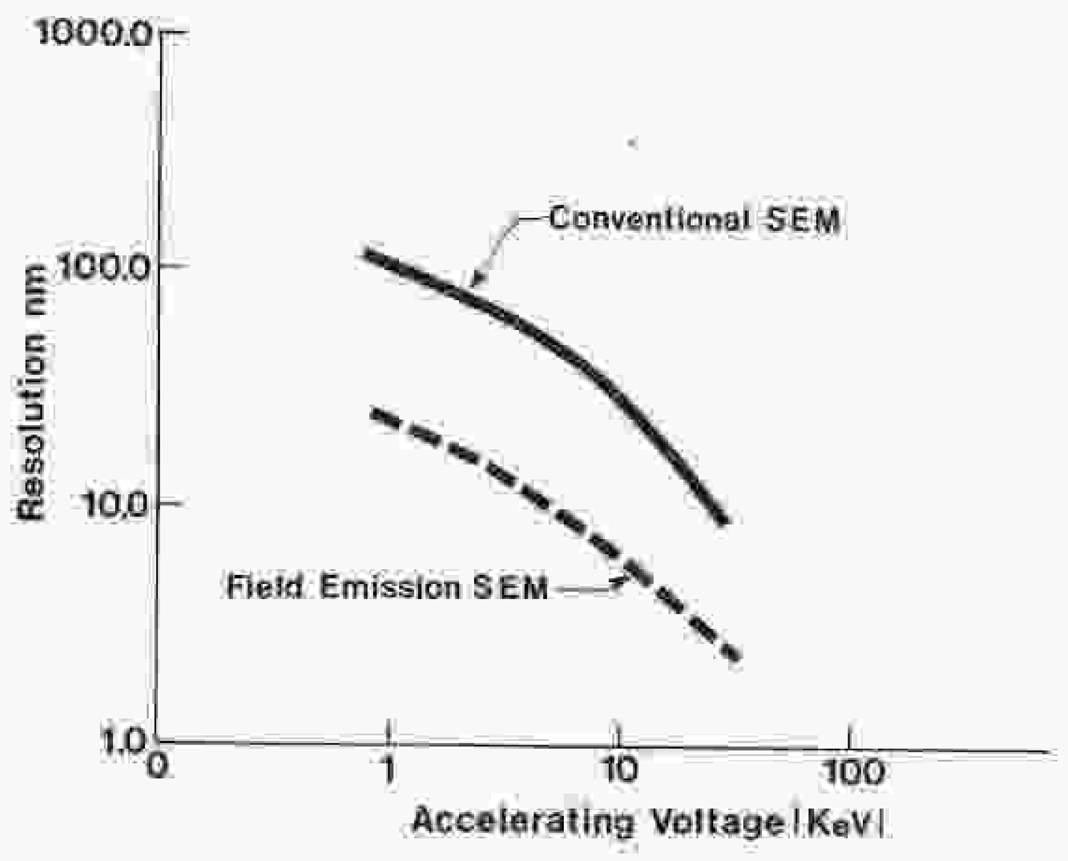
(chromacity) of approximately 0.3 eV (Table 2-3). Consequently, chromatic aberration is greatly reduced permitting higher currents to be concentrated into smaller spot diameters. This will yield higher resolution and a far more favorable signal-to-noise ratio.

The depth of field obtainable in a field emission scanning electron microscope is far greater than that of thermionic emission systems. The improved depth of field is a direct result of the combination of a very small effective source size with the specific accelerating and focusing systems. This combination allows the manipulation of the angle aperture to increase depth of field. From the design of the field emission column shown on Figure 2-31, it can be seen that long focal lengths are possible, further providing favorable angle apertures. In some designs, manipulation of the focal length can be accomplished by "de-energization" of the electromagnetic lens (a procedure not possible on thermionic emission type microscopes). In these systems, this will result in a substantial increase in focal length—up to 20 cm—with an equally sizeable increase in depth of field which is reported to be 15 times that of thermionic emission systems.

A field emission electron gun must operate at ultra-high vacuum (better than 10^{-9} torr) to stabilize electron emission and to prevent contamination of the filament tip. Such ultra-high vacuum is not compatable with many specimens. As a result, differentially pumped columns are utilized that maintain about 10^{-6} torr pressure at the specimen and 10^{-10} torr in the gun chamber.

SIGNAL PROCESSING. Electronic manipulation of the detected signals generated in the scanning electron microscope has enabled far more information to be obtained from the signal and, hence, the specimen. On early





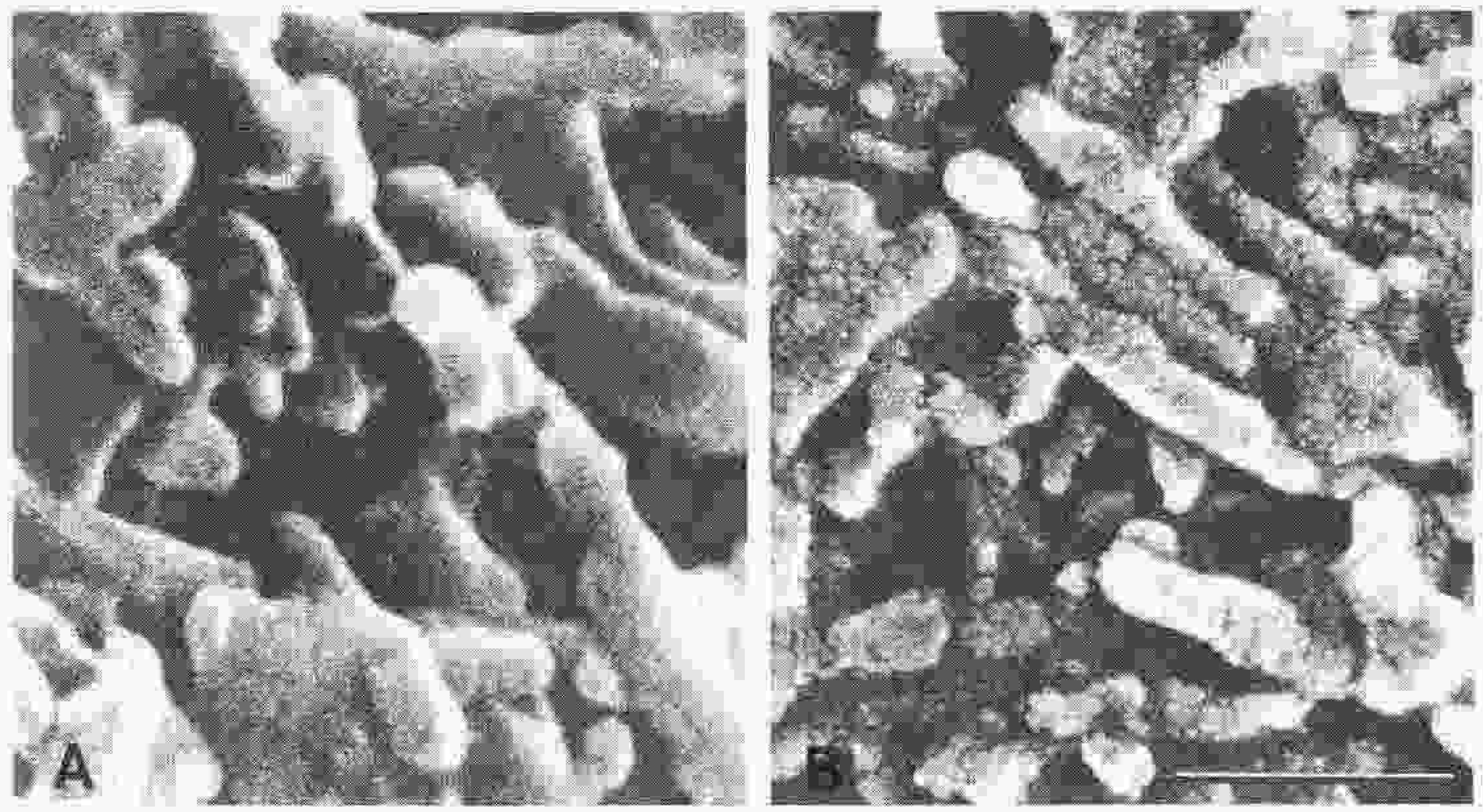
2-34. Graphic comparison of spot sizes (probe diameters) of a conventional tungsten hairpin filament, LaB_6 filament and field emission probe.

2-35. Comparison of the resolution obtainable between a field emission scanning electron microscope and a conventional scanning electron microscope.

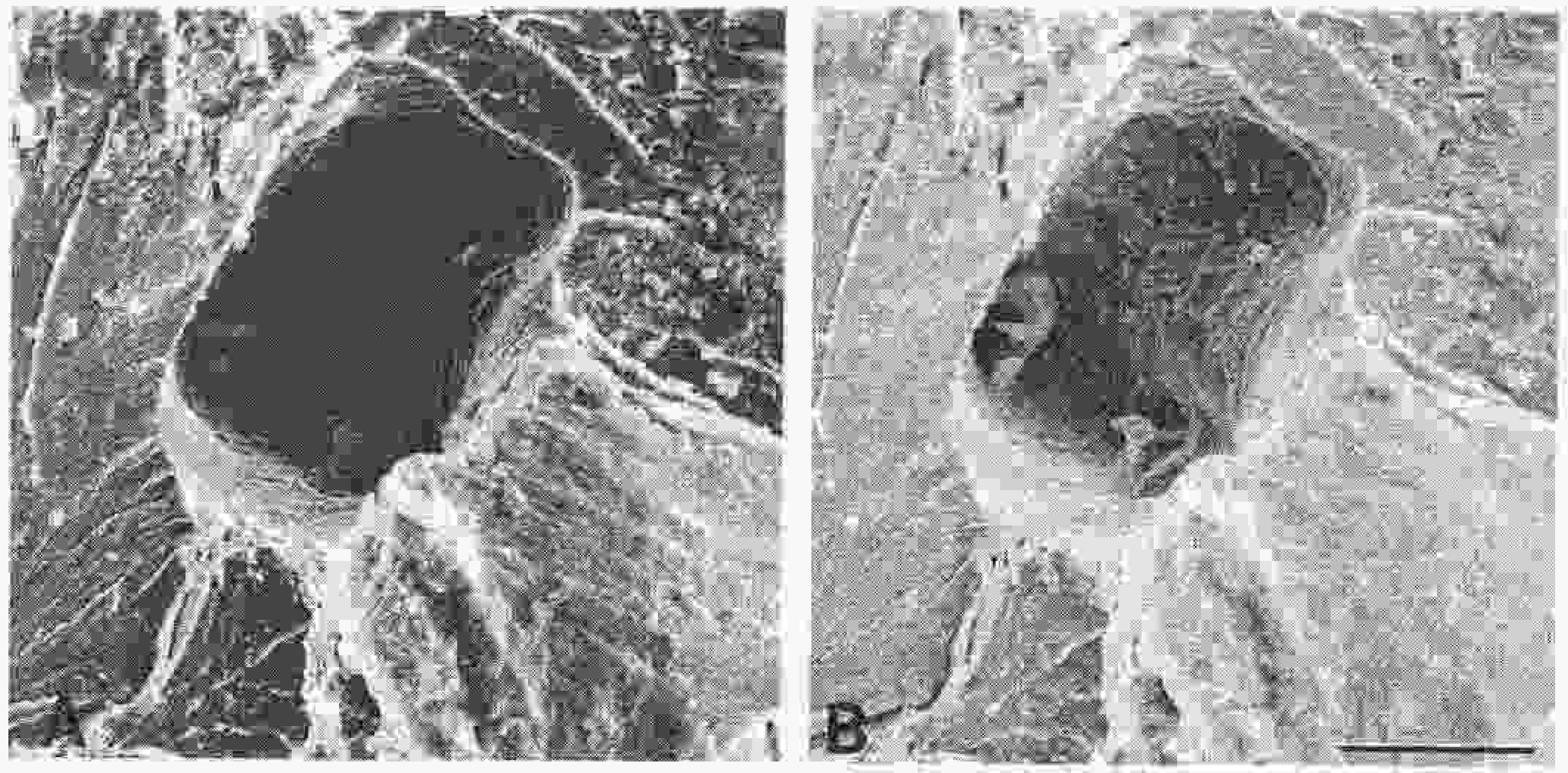
microscopes, many of the signal processing modules were optional or unavailable, but with their development and continued use, these modules have become standard equipment on many modern microscopes.

Gamma control. The video signal derived and, hence, recorded is a function of the signal strengths within a particular specimen. Not all the signals emanating from a sample fall within a useful recording range as there are usually very bright regions and very dark regions. Generally speaking, information from either of these two extremes is lost (or masked) to the investigator. In an effort to retrieve this lost detail, a module known as gamma control may be used. Gamma translates the linear input signal coming to the cathode ray tube into a logarithmic function (12). In this way, the overall signal level is compressed, resulting in the retention of fine detail in the two areas of extreme. Therefore, the resulting micrograph contains useful information that would otherwise have been lost (Fig. 2-37).

Dynamic focusing. Dynamic focusing, also known as "autofocus" (12,30,33,45), is an electronic device that actively changes the focus of the final lens of the scanning electron microscope to compensate for tilt angle of the specimen. This is a desirable accessory since most of the commercially available microscopes are designed with the secondary electron detector located to one side of the specimen chamber. For this detector position, the collection of the low energy secondary electrons is enhanced by tilting the specimen toward the detector. This being the case, at reasonable degrees of tilt, an extremely large depth of field is required to maintain the image in focus along the tilt plane. If an extremely small final lens aperture or long working distance is not used to enhance the depth of field, the "top" and the



2-36. Comparison micrographs of gold coated magnetic tape. (A) Conventional SEM. (B) Field emission SEM. These micrographs demonstrate the resolution difference between the two systems. Line scale is equal to 0.25 μm (Courtesy of Hitachi, Ltd.).



2-37. Micrographs of cleavage fractures in steel demonstrating the effect of gamma control. (A) No gamma control. (B) Gamma on. Line scale is equal to 20 μm (Micrographs courtesy of Cambridge Instruments).

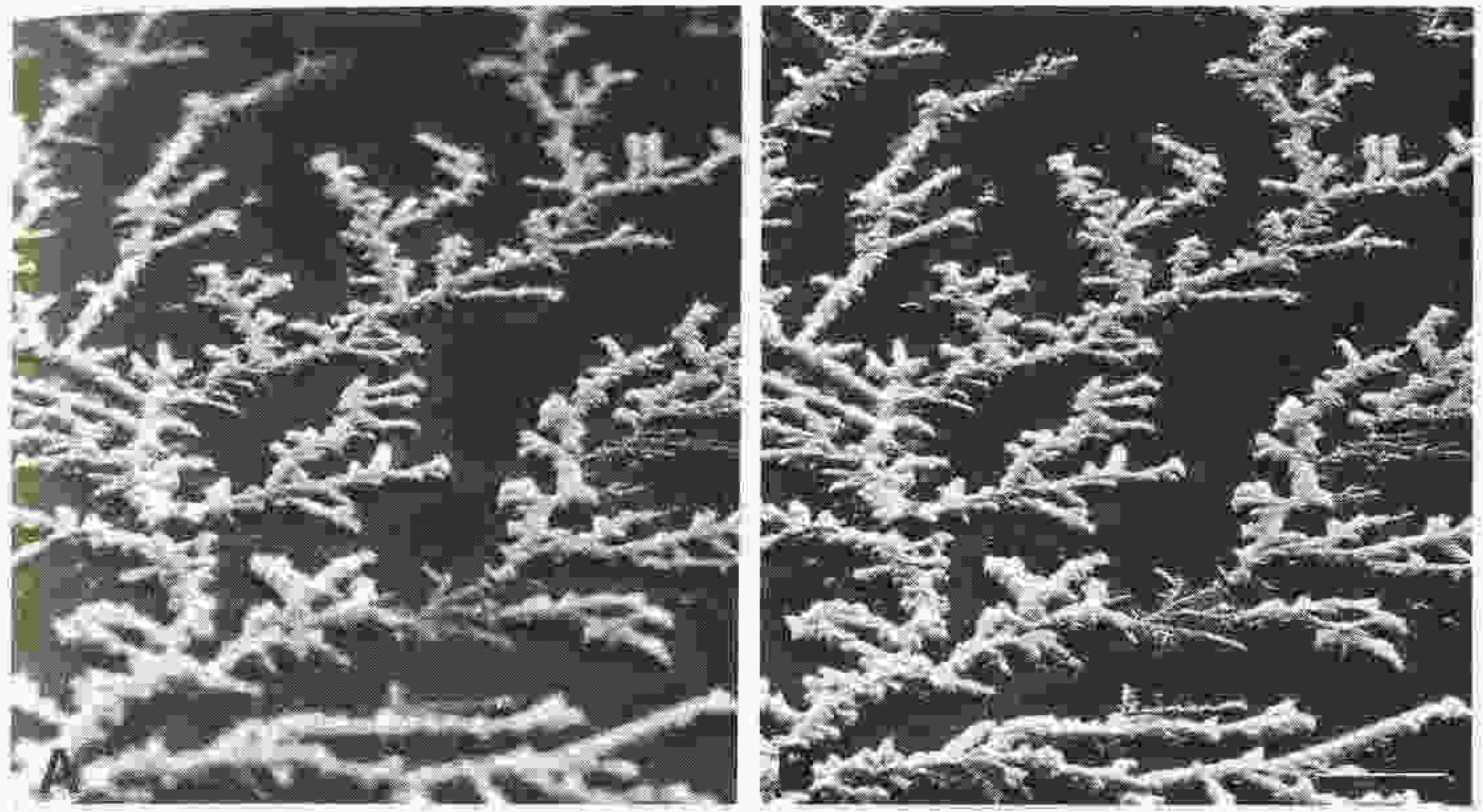
"bottom" of the micrograph in the direction of tilt will appear out of focus. Use of such an autofocus device enables these out of focus regions to be compensated for by the electronic alteration of the final lens, resulting in a sharp micrograph over the total field as shown in Figure 2-38.

Y-modulation. The "three-dimensionality" of the scanning electron micrograph is due to the varying signal strengths caused by specimen topography as the beam traverses a specimen. This is accomplished by the scanning of the beam in the Z direction (Figure 2-39). If, however, a sample having little or no surface topography is viewed, the resulting micrograph is difficult to interpret since the gray scale range in the image is so narrow that the features become indistinguishable (12).

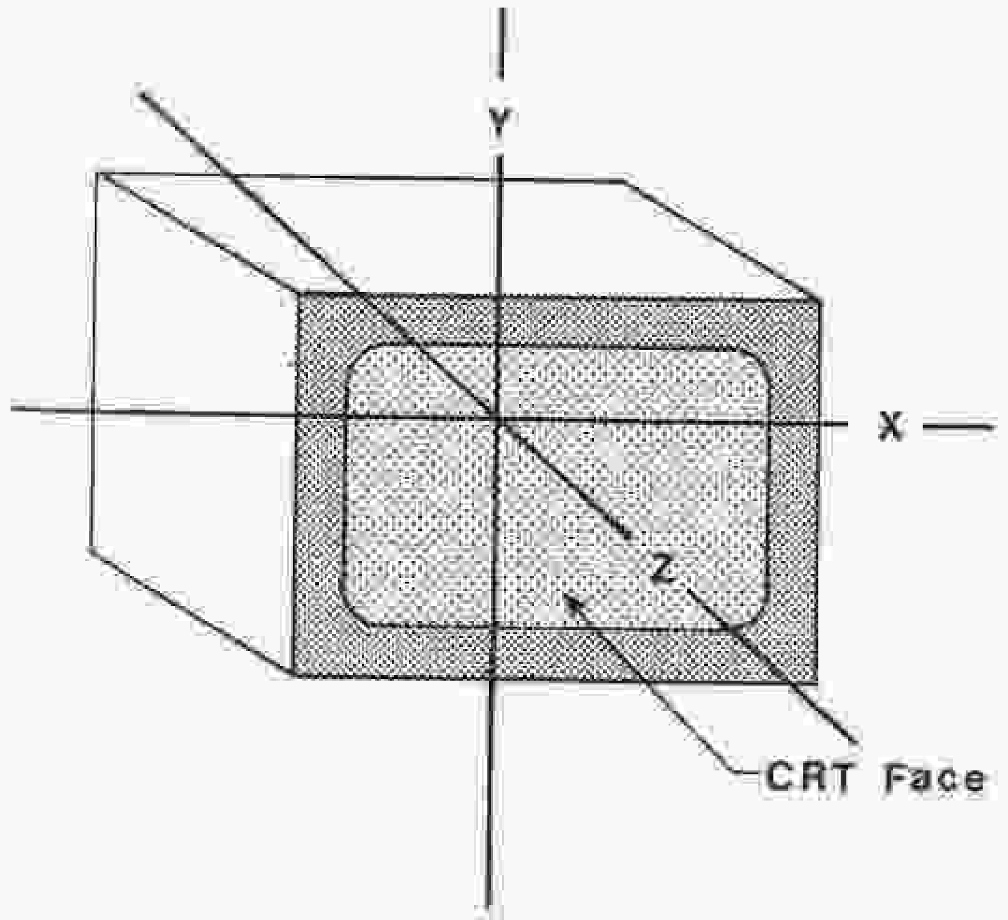
Inability to interpret a specimen having minimal topographic features may be overcome if a *Y*-modulation mode is employed to present these images. Y-modulation is a representation of the specimen in the Y direction on the CRT instead of the standard Z direction. The resulting micrograph describes the small topographical changes as changes in the height of lines, providing images which are easier to interpret (Fig. 2-40).

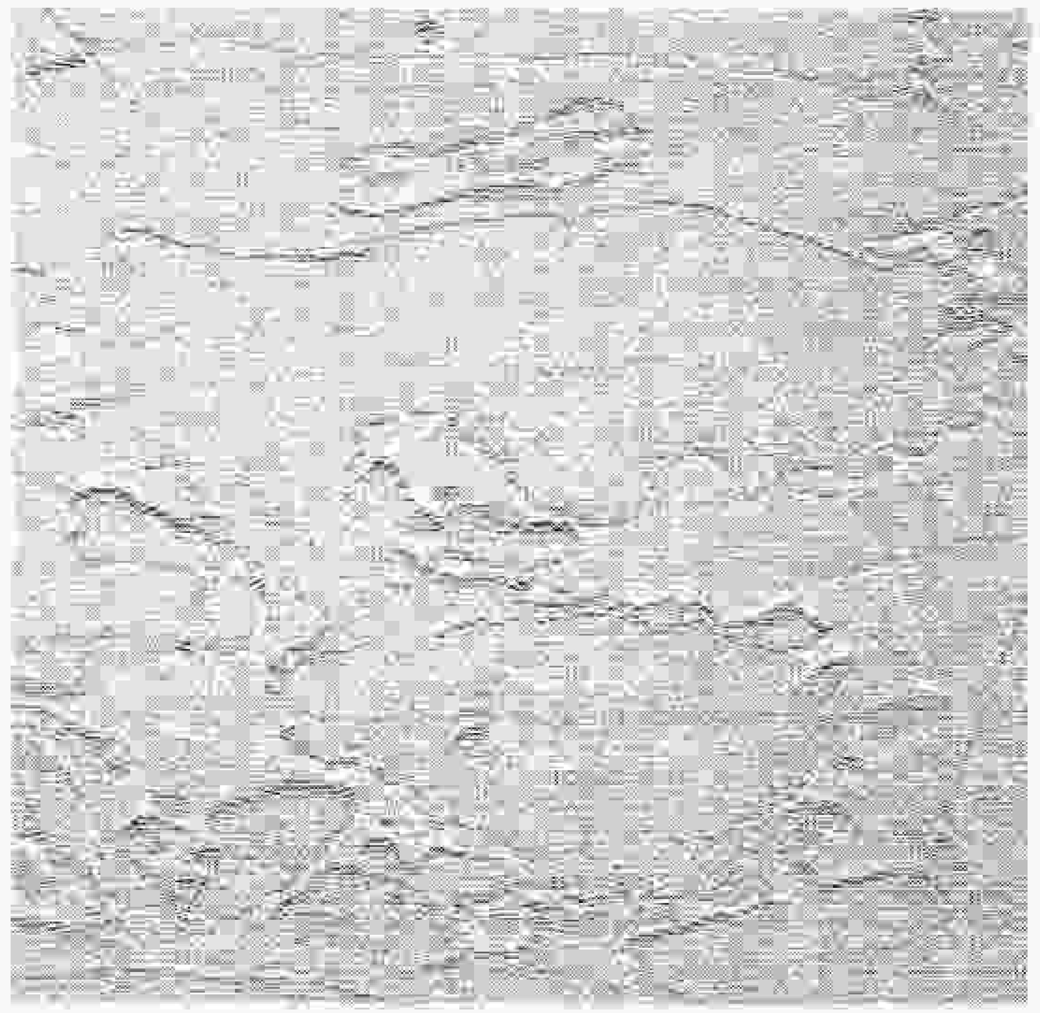
Raster rotation. Electrons travel in a spiral path down the electron microscope column. Due to this fact, changes in working distance from a higher setting to a lower setting will result in an image shift along that electron spiral. This results in a radial shift of the image that can be troublesome if alignment of two micrographs is necessary (12,33). A raster rotation module can electronically compensate for this shift and allow the image to be rotated into the same position for all micrographs (Fig. 2-41).

Tilt correction. The tilting of the specimen toward the detector in order to enhance the collection of secondary electrons results in a foreshortening effect on the specimen. This is a consequence of the fact that as a beam traverses a



2-38. Micrograph of silver dendrites at high tilt angle to demonstrate the effect of dynamic focus. (A) Without dynamic focus. (B) With dynamic focus. Line scale is equal to 20 μm (Courtesy of Philips Electronics).





2-39. Y-Modulation. Illustration of Y-modulation in relation to the cathode ray tube face.

2-40. A scanning electron micrograph of a specimen viewed with Y-modulation. Line scale is equal to 20 μm (Courtesy of Cambridge Instruments).

tilted specimen the magnification at the upper portion is slightly higher than the magnification of the lower portion. This means that a trapezoid is being scanned on the specimen surface and is being portrayed as a rectangle on the CRT. Tilt correction is an electronic module which compensates for this foreshortening and effectively makes both scan axes of equal length at any tilt angle for which the specimen stage is set (Fig. 2-42).