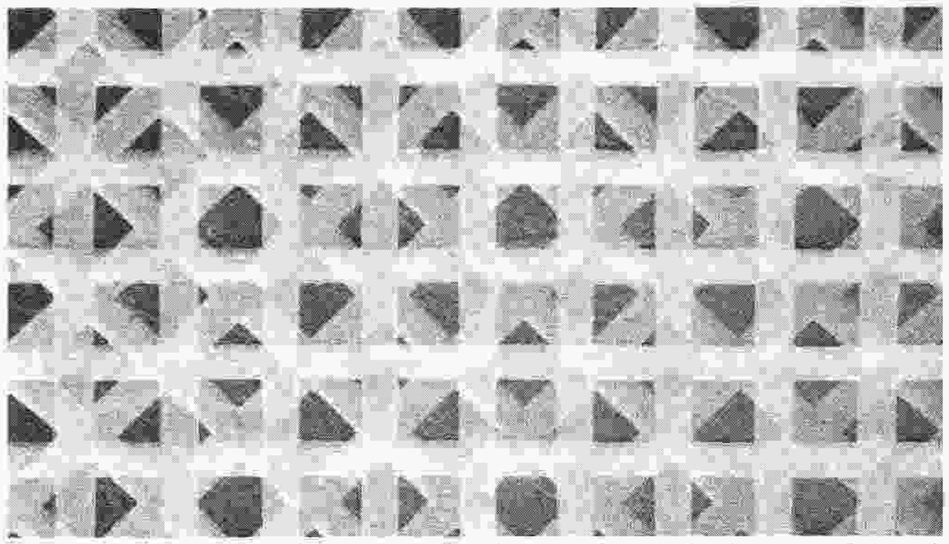
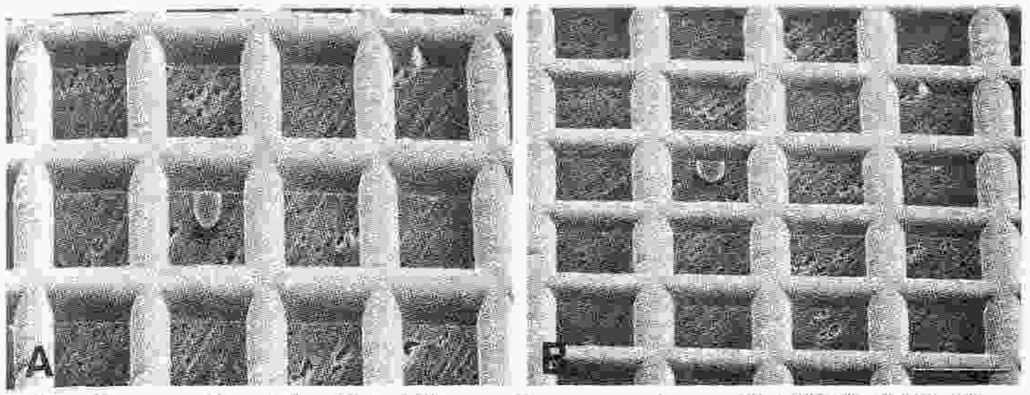


2-41. Effect of raster rotation. A scanning electron micrograph of a transmission electron microscope grid. The micrograph was double exposed with the beam rotated between exposures (Courtesy of International Scientific Instruments).

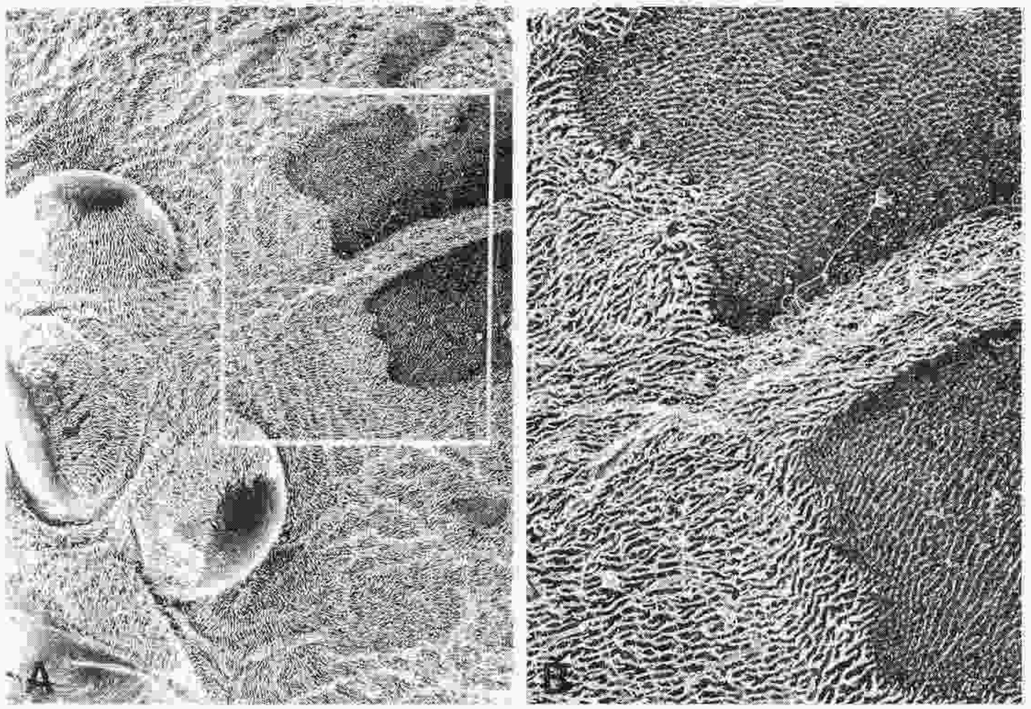
Dual magnification. Microscopes equipped with two visual cathode ray tubes, or microscopes whose cathode ray tubes are designed for split screen imaging, can be equipped with a dual magnification function. Dual magnification provides for simultaneous image display at different magnifications. In this way, the operator may view on CRT "I" a selected field at a relatively low magnification while simultaneously CRT "II" displays a higher magnification image, usually 2×, 5×, or 10× that of CRT "I" magnification. This function enables more efficient low magnification searching as the enlarged area "window," as seen on Figure 2-43, is moveable within the X and Y directions of the CRT "I" field of view. Therefore, the operator can electronically deflect the beam over the low magnification image and search more effectively at a higher magnification.

The dual magnification function requires that the primary electron beam alternately scan the specimen at different magnifications. In order to accomplish this, as illustrated in Figure 2-44, the beam first scans the long distance from A to A′; then the shorter distance from B to B′, then the large distance from C to C′ and so forth. Consequently, the beam scans two different raster patterns and the signal is divided into the two CRT images at different magnifications (26).

Independent video channels. A scanning electron miscroscope equipped with two (or more) independent video input channels may simultaneously display these independent signals. Since a number of phenomena take place as the primary electron beam impinges upon the sample, a properly equipped microscope could display a secondary electron image on CRT "I" and its corresponding x-ray element distribution map simultaneously on CRT "II". Depending upon the equipment available, the combinations could be quite numerous. Many of these signal images are illustrated in Chapter 3.



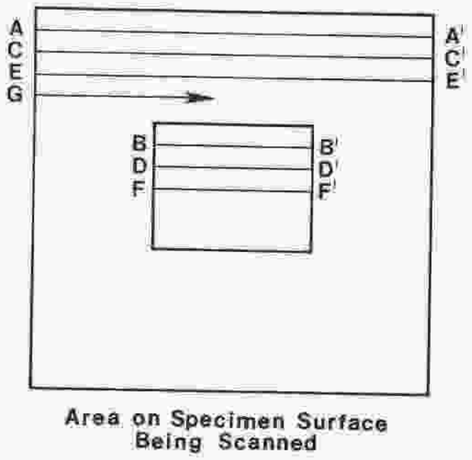
2-42. Demonstration of the effect of tilt correction on a specimen grid at 50° tilt. (A) No tilt correction. (B) Tilt correction applied. Line scale is equal to 100 μm (Courtesy of AMRAY).



2-43. Dual magnification as demonstrated on an insect head. (A) Low magnification image 50×. (B) Dual magnification image of area delimited by box in the low magnification micrograph 150 × (Courtesy of Cambridge Instruments).

Automatic Data Display. Alphanumeric generators, in conjunction with the scanning electron microscope electronics, can permanently display a wealth of information on each individual micrograph as it is being recorded. Such important data as micrometer marker, magnification, negative number and other information can be placed upon the negative to provide permanent records on the micrograph at the time of exposure.

Automatic Exposure. The two factors generally adjusted to take a micrograph are brightness and contrast. These two factors vary with a number



2-44. Raster pattern traversed by the electron beam in the dual magnification mode.

of parameters and are, therefore, manually adjusted for every micrograph. Addition of an automatic exposure module enables the calibration of a standard exposure within the "memory" of the module. Whenever an exposure is made the module automatically adjusts the contrast and brightness to this predetermined setting, thus, automatically providing consistently exposed micrographs.

Polarity Inversion. The cathode ray tube in the recording mode generally produces a negative image upon photographic film. Inversion of this signal, that is making whites black, and blacks white (along with the corresponding gray scale), will result in the recording of a positive image. This is advantageous since immediate projection slides may be produced without the standard intermediate steps or, photographic paper may be exposed directly with an inverted signal to produce a positive print.

Literature Cited

1. Ahmed, H. and A. N. Broers. 1972. Lanthanum hexaboride electron emitter. J. Appl. Phys. 43: 2185-2192.
2. Ahmed, H. and W. C. Nixon. 1973. 100kV boride emitter electron gun system for conventional and scanning transmission microscopy. *in* 31st Ann. Proc. Electron Microsc. Soc. Amer., C. J. Arceneaux (ed.), 300-301.
3. Becker, H. C. 1975. Scanning electron microscopy. Lubrication. Texaco, Inc., 61: 37-56.
4. Black, J. T. 1974. The scanning electron microscope: Operating principles. *in* Principles and Techniques of Scanning Electron Microscopy. Vol 1. M. A. Hayat (ed.), Van Nostrand Reinhold Co., New York and London, 1-43.
5. Broers, A. N. 1967. Electron gun using long life lanthanum hexaboride cathode. J. Appl. Phys. 4: 1991-1992.
6. Broers, A. N. 1974. Recent advances in scanning electron microscopy with lanthanum hexaboride cathodes. SEM/1974, IIT Research Institute, Chicago, IL, 60616, 9-18.

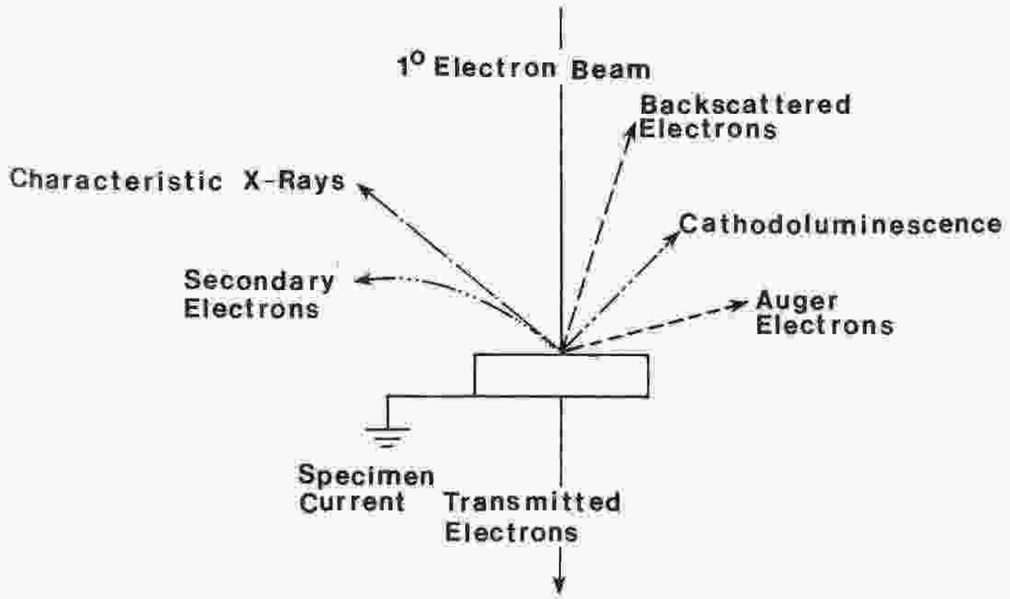
7. Broers, A. N. 1975. Electron sources for SEM. SEM/1975, IIT Research Institute, Chicago, IL, 60616, 661-670.
8. Crewe, A. V. 1966. Scanning electron microscopes: Is high resolution possible? Science 154: 729-738.
9. Crewe, A. V., D. N. Eggenberger, J. Wall and L. M. Welter. 1968. Electron gun using a field emission source. Rev. Sci. Instr. 39: 576-583.
10. Crewe, A. V., M. Isaacson and D. Johnson. 1969. A simple scanning electron microscope. Rev. Sci. Instr. 40: 241-246.
11. Crewe, A. V., J. Wall and L. M. Welter. 1968. A high-resolution scanning transmission electron microscope. J. Appl. Phys. 39: 5861-5868.
12. Derksen, W. 1977. Signal processing devices for the SEM. Amer. Lab. 9: 43-47.
13. Everhart, T. E. and T. L. Hayes. 1972. The scanning electron microscope. Scient. Amer. 226: 54-68.
14. Everhart, T. E. and R. F. M. Thornley. 1960. Wide-band detector for micro-microampere low-energy electron currents. J. Sci. Inst. 37: 246-248.
15. Ferris, S. D., D. C. Joy, H. J. Leamy and C. K. Crawford. 1975. A directly heated LaB_6 electron source. SEM/1975, IIT Research Institute, Chicago, IL, 60616, 11-26.
16. Geiss, R. H. and H. Arnal. 1976. Resolution high-higher-highest. Applications for the high resolution SEM in the computer industry. Ind. Res. 35: 82-84.
17. Goldstein, J. I. and H. Yakowitz. 1975. Practical Scanning Electron Microscopy. Electron and Ion Microprobe Analysis. Plenum Press, New York, 582p.
18. Hainfield, J. F. 1977. Understanding and using field emission sources. SEM/1977/I, IIT Research Institute, Chicago, IL, 60616, 591-604.
19. Hoffman, V. E. 1964. Ion pumping. Ind. Res. 23: 46-51.
20. Holland, L. 1970. Review of some recent vacuum studies. Vacuum 20: 175-192.
21. Joy, D. C. and C. M. Maruszewski. 1978. The physics of the SEM for biologists. SEM/1978/II, SEM, Inc., AMF O'Hare, IL, 60666, 379-387.
22. Komoda, T. and S. Saito. 1972. Experimental resolution limit in the secondary electron mode for a field emission source scanning electron microscope. SEM/1972, IIT Research Institute, Chicago, IL, 60616, 128-136.
23. Lafferty, J. M. 1951. Boride cathodes. J. Appl. Phys. 22: 299-309.
24. Miller, D. W. 1978. SEM vacuum techniques and contamination management. SEM/1978/I, SEM, Inc., AMF O'Hare, IL, 60666, 513-528.
25. Muir, M. D. 1974. Fundamentals of the scanning electron microscope for biologists. SEM/1974, IIT Research Institute, Chicago, IL, 60616, 1011-1018.
26. Nagatani, T., M. Okamura and H. Ito. 1972. Simultaneous display system of different magnification images in scanning electron microscopy. SEM/1972, IIT Research Institute, Chicago, IL, 60616, 265-272.
27. Nakagawa, S. and T. Yanaka. 1975. A highly stable electron probe obtained with LaB_6 cathode electron gun. SEM/1975, IIT Research Institute, Chicago, IL, 60616, 19-26.
28. Nakagawa, S. and T. Yanaka. 1975. 35-LBG LaB_6 cathode gun for JSM-35 SEM. JEOL News. 13e: 23-24.
29. Nixon, W. C. 1969. Introduction to scanning electron microscopy. SEM/1969, IIT Research Institute, Chicago, IL, 60616, 1-9.
30. Norton, J. T. and G. T. Cameron. 1976. Autofocus control for improvement of depth of focus in the SEM. AMR Tech. Bull. 1: 4.
31. Norton, J. T. and G. T. Cameron. 1976. Optimizing depth of focus in the SEM. AMR Tech. Bull. 1: 5-6.
32. Norton, J. T. and G. T. Cameron. 1976. Specimen charging and the effect of acceleration potention in the SEM. AMR Tech. Bull. 1: 8-10.

33. Norton, J. T. and G. T. Cameron. 1976. The combined use of raster rotation and autofocus in the SEM. AMR Tech. Bull. 1: 26-28.
34. Norton, J. T. and G. T. Cameron. 1976. Optimizing surface structure with acceleration potential in the SEM. AMR Tech. Bull. 1: 3.
35. Oatley, C. W. 1972. The Scanning Electron Microscope. Cambridge Univ. Press, Cambridge, UK, 194 p.
36. Pawley, J. B. 1974. Performance of SEM scintillation materials. SEM/1974, IIT Research Institute, Chicago, IL, 60616, 27-34.
37. Pease, R. F. W., and W. C. Nixon. 1965. High resolution scanning electron microscopy. J. Sci. Instr. 42: 81-85.
38. Veneklasen, L. H. and B. M. Seigel. 1972. A field-emission illumination system using a new optical configuration. J. Appl. Phys. 43: 4989-4996.
39. Verhoeven, J. D. and E. D. Gibson. 1977. On the design of the Broers type LaB_6 gun. SEM/1977/1, IIT Research Institute, Chicago, IL, 60616, 9-16.
40. Wells, O. C. 1974. Scanning Electron Microscopy. McGraw-Hill Book Co., New York, 421p.
41. Welter, L. M. 1975. Application of a field emission source to SEM. *in* Principles and Techniques of Scanning Electron Microscopy, Vol. 3. M. A. Hayat (ed.), 195-220.
42. Welter, L. M. and V. J. Coates. 1971. A compact field emission scanning electron microscope. *in* 29th Ann. Proc. Electron Microsc. Soc. Amer., C. J. Arceneaux (ed.), 32-33.
43. Wiesner, J. C. 1973. Characteristics and application of pointed cathodes in scanning electron microscopes. SEM/1973, IIT Research Institute, Chicago, IL, 60616, 33-40.
44. Wischnitzer, S. 1962. Introduction to Electron Microscopy. Pergamon Press, New York, N.Y., 132p.
45. Yew, N. C. 1971. Dynamic focusing technique for tilted samples in scanning electron microscopy. SEM/1971, IIT Research Institute, Chicago, IL, 60616, 33-40.

CHAPTER THREE

ELECTRON BEAM–SPECIMEN INTERACTION AND SEM SIGNALS

Solid specimens subjected to electron beam excitation in a scanning electron microscope exhibit complex interactions with primary beam electrons. These interactions result in a variety of signals that may be detected in the scanning electron microscope. To analyze a specimen visually, one might choose to see a "picture" of the specimen by collecting and displaying secondary electrons, backscattered electrons, transmitted electrons or specimen current. To determine information about specimen composition, one might choose to record x-ray or Auger electron spectra or, in selected cases, to measure cathodoluminescence. These seven modes of operation are among the most popular in scanning electron microscopy (Fig. 3-1). A general discussion

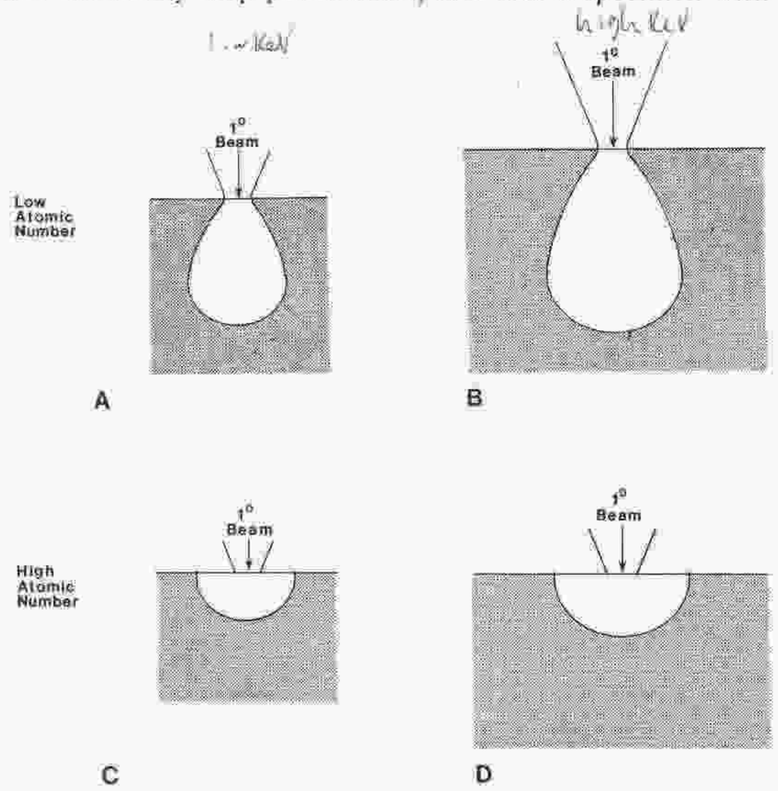


3-1. Illustration of seven of the possible signals generated by the primary electron beam–specimen interaction in the scanning electron microscope (adapted from Becker, 1975).

of the electron beam-specimen interaction and a brief explanation of the generation and detection of each of those signals are provided in this chapter to point out the importance of proper signal selection for successful employment of scanning electron microscope capabilities.

RANGE AND VOLUME OF PRIMARY EXCITATION

SIGNAL GENERATION. When the primary electron beam strikes a specimen, the beam electrons penetrate to a depth that is directly dependent upon the magnitude of their own energies and inversely dependent upon the atomic number of the specimen atoms. Figure 3-2 is an idealized diagrammatic representation of the variation in electron scattering resulting from differences in accelerating voltage and atomic number. The diagram shows that the volume and depth of excitation multiplies with increasing beam energy and decreases with increasing atomic number. It also points out that the shape of the excited volume varies with atomic number due to the decreased beam penetration into specimens of higher atomic number (15). It is apparent that with increasing beam energy, the primary electrons are able to penetrate deeper into the specimen. Likewise, it is logical that continued collisions within the specimen ultimately stop penetration, and that a specimen with atoms of



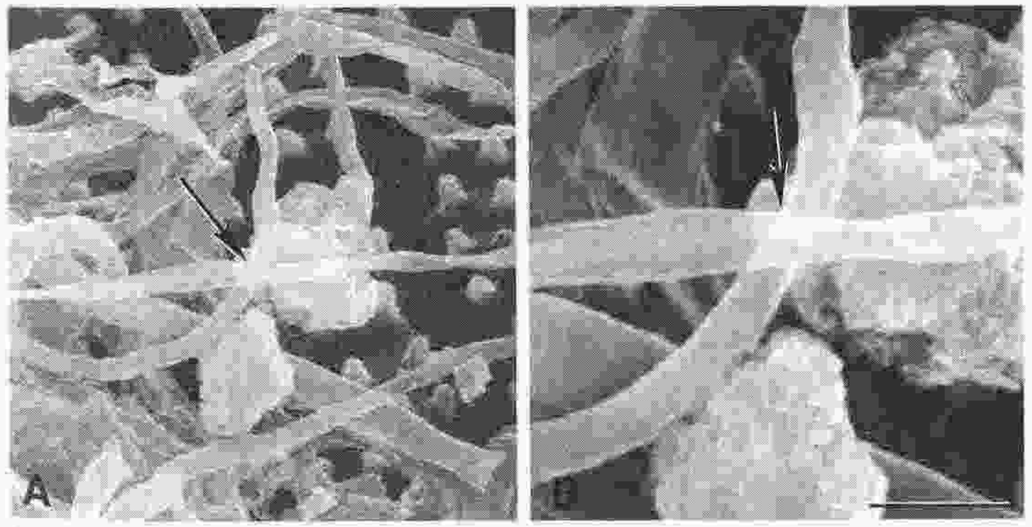
3-2. Diagrammatic representation of the variation of electron scattering in the specimen with voltage and atomic number. (A) Low accelerating voltage and low atomic number. (B) High accelerating voltage and low atomic number. (C) Low accelerating voltage and high atomic number. (D) High accelerating voltage and high atomic number. Note that the shape of the zone of primary excitation changes with atomic number and depth of excitation changes with accelerating voltage and composition.

high atomic number will have more particles available to stop electron penetration than one composed of low atomic weight elements.

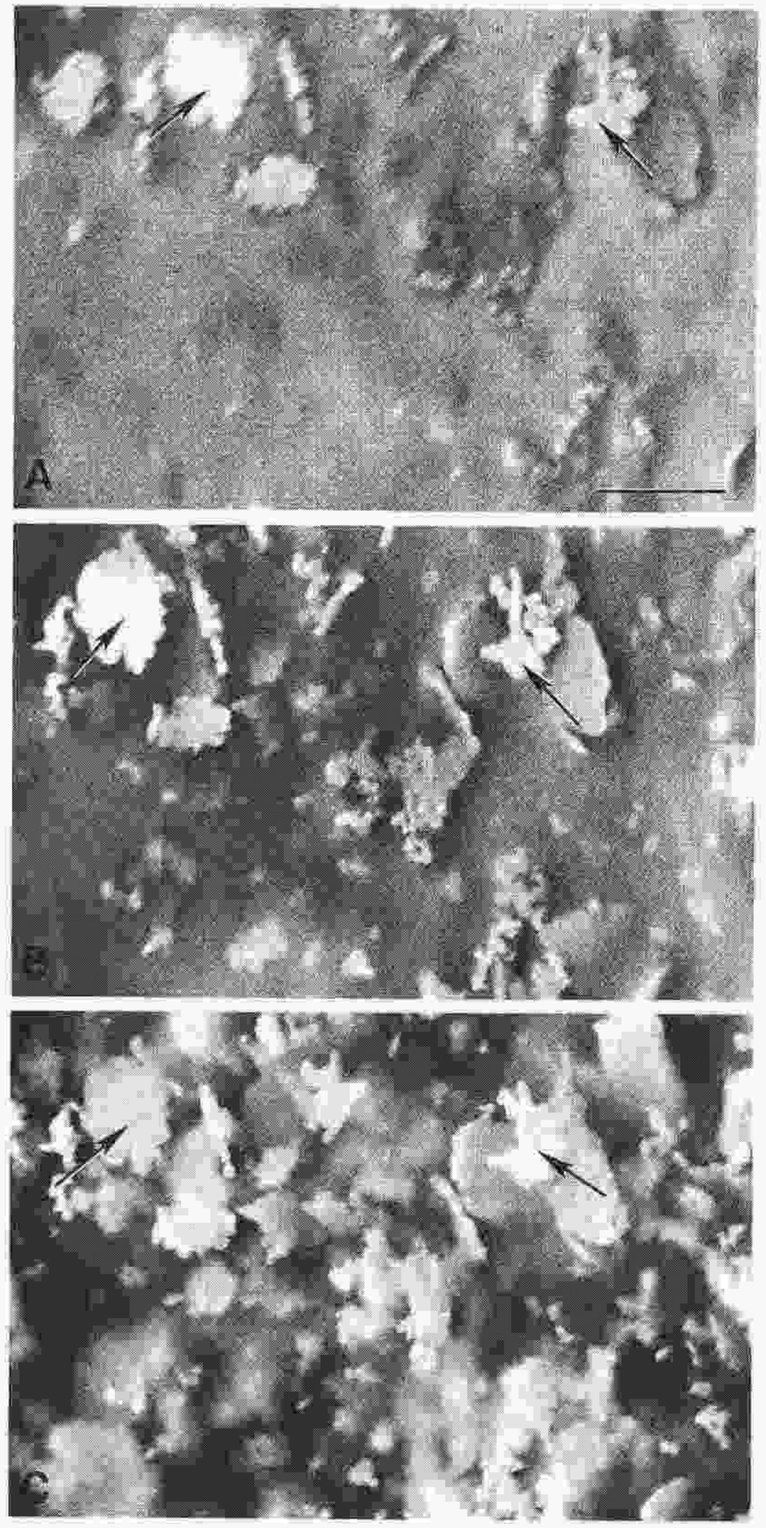
The application of relatively high accelerating voltages upon specimens composed of low atomic weight elements results in very deep penetration by the electron beam (2). If the initial surface is sufficiently thin or lacking in electron density, it may appear transparent as the electron beam travels completely through it. The resulting secondary electron image is then formed of a composite of the initial image (foreground) and any other detectable signals in the background (Fig. 3-3).

The application of high accelerating voltages has a second consequence upon a specimen in that as the beam penetrates deeper below the surface, the zone of primary excitation increases in depth and diameter. This results in a loss of detailed surface structure in the image due to the increased generation of additional signals (noise) (Fig. 3-4). Thus, accelerating voltage is one of the limits affecting ultimate specimen resolution in the scanning electron microscope. For many specimens, it is necessary to experiment with several accelerating voltages until an optimum is attained.

THE NATURE OF THE INTERACTION. Within the volume of primary excitation, several scattering events occur with the segregating factor being the relative amount of energy lost by primary beam electrons in their interactions with specimen atoms. These interactions may be placed into two groups. In the first group, a primary beam electron comes into close proximity with a specimen atom nucleus or outer shell electron and rebounds with negligible effect or energy loss. Such an interaction is termed "elastic," and the electrons so scattered are referred to as "backscattered electrons." A backscattered electron is subjected to wide-angle directional change due to a single scattering



3-3. Scanning electron micrographs of the fungal pathogen *Helminthosporium oryzae* on a rice leaf (A and B). The area indicated by the arrows demonstrates beam penetration through the fungal hyphae. Line scale is equal to 5 μm (Specimen preparation courtesy of Simon Hau).



3-4. The effect of accelerating voltage on electron beam penetration. Scanning electron micrographs of silver paint viewed at: (A) 5 KeV, (B) 10 KeV and (C) 30 KeV. Arrows indicate some of the particles common to each micrograph. Line scale equals 5 μm.

event or to multiple small-angle deviations (27,36). The second group of scattering events are the "inelastic collisions." This type of collision occurs whenever a primary beam electron collides with an electron from the specimen atom and loses substantial energy to that atom. When a beam electron collides inelastically, the energy imparted to the specimen atom will cause it to ionize. Electrons may be emitted as part of this ionization and are referred to as "secondary electrons." They are generally characterized by possessing energies of less than 50 eV (12,27).

Due to the primary beam-specimen interaction, both elastic and inelastic events produce signals as described above. In addition, other interactions may occur as a result of these events. For example, a backscattered electron possesses enough energy to subsequently ionize one or more specimen atoms before it escapes from the surface. Each subsequent ionization produces more secondary electrons. Holes left by the emission of secondaries must be filled with electrons from outer energy shells, thereby establishing a need for further energy release by the atom. When an electron from the specimen atom falls from an outer shell to an inner shell hole, the excess energy may be dissipated by the emission of another electron or by the emission of some form of electromagnetic radiation. A low energy electron emitted very near the surface in such a stabilization process is called an Auger electron after the man who first observed this emission process (1). A competing stabilization mechanism is the emission of characteristic x-rays.

The Auger and x-ray signals, as well as the backscattered and secondary electron signals, are constantly being generated during the electron beam-specimen interaction in the scanning electron microscope. One other mechanism for energy stabilization following electron transition is cathodoluminescence. Cathodoluminescence is the emission of photons of infrared, visible, or ultraviolet wavelengths to dissipate the excess energy occurring within a few classes of materials. A signal, such as any described above, will not be useful, however, unless the following criteria are met: The proper detection system must be present and a significant portion of the signal must escape from the specimen surface to be observed by that system.

For a given thick specimen, there will be a finite depth below which no beam electrons will have sufficient energy to penetrate. The shape of the volume excited by these beam electrons varies with the accelerating voltage and specimen atomic number. Within this volume, signals will be generated which can be observed. Detection depends on their strength and the orientation of the specimen surface with respect to the detector. The zones of signal emission are generalized in cross section in Figure 3-5.

If a specimen is prepared with a thickness of less than one micron, and a detector is mounted facing the underside of the specimen (perpendicular to the optical axis of the microscope), those electrons having enough energy to pass through the specimen will be collected. These transmitted electrons vary in energy. Included in this group will be beam electrons and those subjected to multiple interactions, as well as secondary electrons generated near the under-surface.

In addition to the interactions resulting in the generation of the above signals, one event occurs that does not result in a useful SEM signal. When the