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PVD Processes: Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is a method of visualizing the morphology of a surface at a high magnification and with a high depth-of-field. It can also be used for elemental analysis (microchemical analysis) and crystalline structure (grain size) analysis of the surface. In the scanning electron microscope, a focused beam of electrons with energies from 5 kV to 30 kV is rastered over the surface of an electrically conductive material, causing the ejection of secondary electrons (~5 eV) from the first 10–20 atomic layers of the surface. These electrons are then collected in an electron detector. The collected electron intensity is a function of position of the beam on the surface (positions 1–5 in Fig. 1), and depends on the surface morphology as shown in Fig. 1a. The electron intensities can be displayed on a cathode ray tube (CRT) or a PC monitor as a visual picture, and can be preserved as a photography or as a digital image. The use of digital imaging has many advantages, including storage and transmission of a high-resolution picture by electron means.

Backscattered electrons (BSE) from the primary electron beam, which have a higher energy than the secondary electrons, can be collected from a region that extends to a region of several thousand Ångstroms below the surface. The intensity of the BSE depends on the crystallographic orientation and elemental composition of the near-surface region, as shown in Fig. 1b. BSE analysis allows determination of grain boundaries on smooth surfaces, region of second-phase materials, and ferromagnetic domains in ferromagnetic materials.

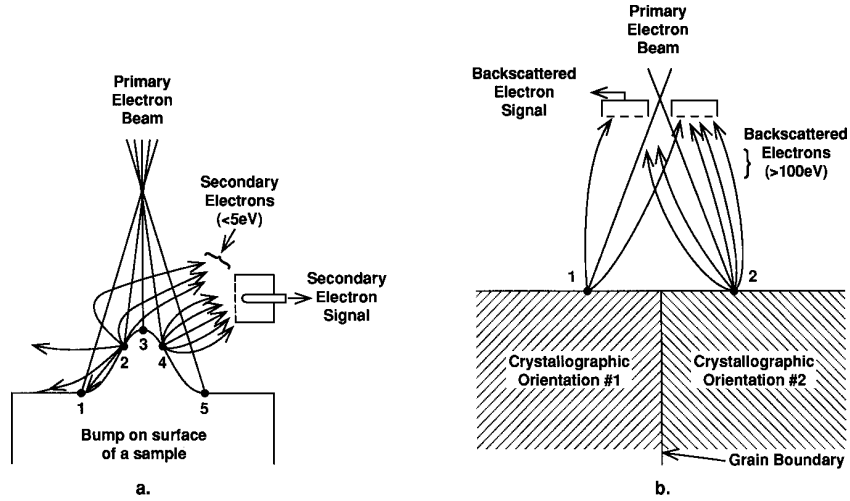

Fig. 1—Collection of electrons in an SEM: a—Collection of secondary electrons from a bump on a surface; b—collection of backscattered electrons from two regions on a surface that have different crystallographic orientations. Numbers show beam position on the surface.

Regions with specific crystallographic orientations of about 2 microns in size can be differentiated.

X-rays, which are characteristic of the atoms involved in electron-atom collisions, originate from a region up to a micron below the surface, and allow elemental chemical analysis to be performed. This chemical microanalysis is done by energy-dispersive spectrometry (EDS) or wavelength-dispersive spectrometry (WDS) X-ray analysis. When the SEM is used in this mode, it is essentially an electron probe microanalyzer (EPMA) One special application of the SEM/EPMA is the observation and then the elemental analysis of particles, features and inclusions whose sizes are as small as one micron.

Using secondary electron imaging, a conventional SEM typically provides magnifications to 50,000X (50,000 diameters). Using special configurations, such as the "in-lens" sample position, the magnification can reach 150,000X or even higher. For comparison, an optical microscope is capable of a maximum magnification of about 1500X using visual optics, and 5000–7000X using video display. At the same magnification, the depth-of-field of the SEM is about 300 times that of the common optical microscope and about the same as computer-generated "depth-of-field" of a scanning confocal laser optical microscope depending on the vertical scan range of the confocal microscope. Figure 2 shows an SEM picture of a 96 percent (4% glassy phase) "fired" slip-cast alumina surface that is commonly used in microelectronics fabrication. It is easy to see why a one-micron-thick deposited film does not form a continuous film over the surface. The SEM is not very useful at magnifications less than ~300X, and an optical microscope is a better choice for viewing surfaces at such low magnifi-

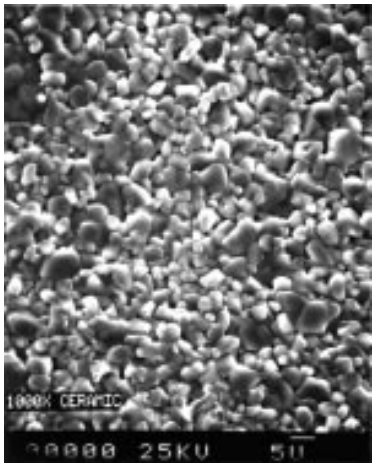

Fig. 2—Surface topography of a fused, slip-cast 96-percent alumina ceramic surface, as determined using an SEM.

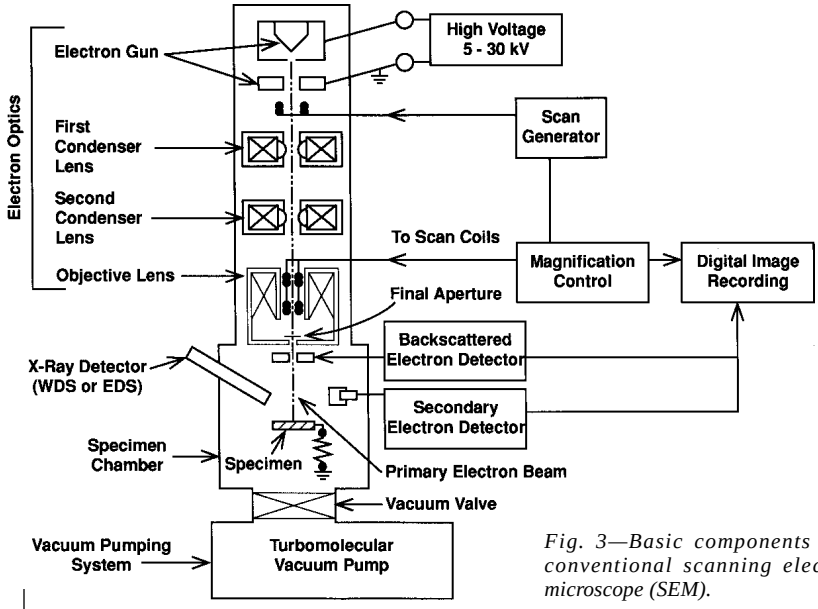

Fig. 3—Basic components of a conventional scanning electron microscope (SEM).

cations. In many applications, a scanning confocal laser optical microscope with a resolution of 0.25 microns is a better choice to magnifications of 7000X.

The electron optics of the SEM consists of an electron source, electromagnetic condenser lenses, electromagnetic objectives lenses, scanning coils, and an exit aperture, all in a vacuum, as shown in Fig. 3. Operating parameters include: Accelerating voltage, condenser settings (spot size), aperture size and the "working distance" between the exit aperture and the surface being viewed. In a conventional SEM configuration, the sample is between the exit aperture and the objective lens, and the secondary electron collector is above the objective lens. This reduces the working distance greatly.

For a given magnification, the SEM can be optimized for maximum spatial resolution or depth-of-field, but not both at the same time. The maximum resolution involves using a well-collimated (small beam dispersion) electron beam with a small electron spot size on the surface, a small size exit aperture and a close working distance (*e.g.*, the "in-lens" position). For maximum depth-of-field, the working distance should be long, in addition to having a small exit aperture. A conventional SEM, therefore, is good for intermediate magnifications and high depth-of-field, but doesn't give the maximum resolution or magnification that is attainable with the "in-lens" configuration.

Most SEMs use a thermoelectron-emitting tungsten or thoriated-tungsten filament (W-source) as the electron source. Hot LaB_6 emitting surfaces can be used for very high electron intensities. Some SEMs use field emission (FE-source) electron sources that have a small area of emission, thereby giving the least dispersion in the electron beam. The best spatial resolution for a W-source SEM is about 35Å at 25 kV accelerating voltage, while the FE-source SEM has a best resolution of about 15Å at 15 kV. This can be compared to the ~2000Å resolution available with an optical microscope. The FE-SEM must be operated at a lower pressure than the W-SEM. The FE-SEM can be used at a lower accelerating voltage than the W-SEM, which is important in some semiconductor applications where damage by high-energy electrons can be a problem.

Stereo pairs of SEM images can be formed by angular rotation (10–15° typically) of the specimen about an axis through the image plane that is perpendicular to the incident electron beam. These stereo pairs can be viewed in a stereoscope to give a three-dimensional view of the surface topography. By knowing the angle of rotation and the magnification, the vertical height of surface features can be determined in the same way as is done for aerial mapping of the topography of the earth. The vertical resolution by this stereo technique is generally about $^1/_{10}$ that of the lateral resolution.

Typically, an electrically conductive surface that is to be viewed by the SEM is in its natural state. If the surface is an electrical insulator, it will build up an electrical charge and prevent high-resolution viewing. An insulating surface can be made conductive by the deposition of a thin film of gold on the surface. In some cases, ionization of gaseous species in the SEM can be used to mitigate charge buildup without coating the surface. When the internal morphology of the material is of interest, a surface can be produced by fracturing and then looking at the fracture cross section. Chemical or sputter etching can be used to generate definable features on surfaces. In some very special cases, the SEM can be used to view an active process, such as fracture propagation, or tribological effects, such as sliding wear in the sample chamber. Sample size can be a problem in that the SEM sample chamber is limited in size, so samples often must be cut or broken in order to have one small enough to fit into the chamber.

There are a number of special applications of the SEM. The voltage contrast mode is used to look for open circuits in metallization stripes on semiconductor devices. The secondary electrons emitted by a grounded surface under electron bombardment leave the surface with about 5 eV of energy. If a retarding grid at 5 volts negative potential is placed above the surface, no electrons will reach the detector. If there is a break in the conductor stripe, part of the conductor will be under a negative potential and part will not, and the break will be readily detected by the SEM. **P&SF**