Scanning electron microscope

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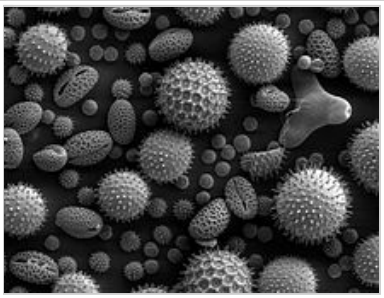
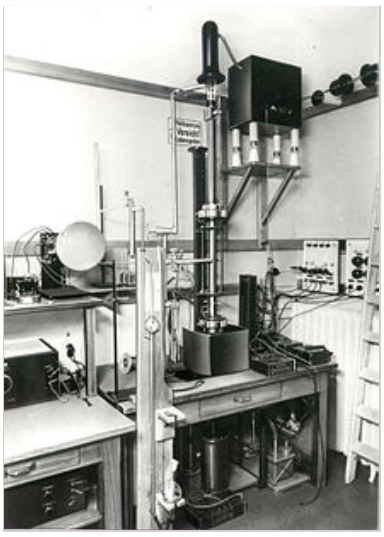
Not to be confused with Scanning tunneling microscope.

A **scanning electron microscope** (**SEM**) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that can be detected and that contain information about the sample's surface topography and composition. The electron beam is generally scanned in a raster scan pattern, and the beam's position is combined with the detected signal to produce an image. SEM can achieve resolution better than 1 nanometer. Specimens can be observed in high vacuum, in low vacuum, in wet conditions (in environmental SEM), and at a wide range of cryogenic or elevated temperatures.



These pollen grains taken on an SEM show the characteristic depth of field of SEM micrographs.

The most common SEM mode is detection of secondary electrons emitted by atoms excited by the electron beam. The number of secondary electrons depends on the angle at which beam meets surface of specimen, i.e. on specimen topography. By scanning the sample and collecting the secondary electrons with a special detector, an image displaying the topography of the surface is created.



M. von Ardenne's first SEM

SEM opened sample chamber

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Analog type SEM

History

An account of the early history of SEM has been presented by McMullan.[1][2] Although Max Knoll produced a photo with a 50 mm object-field-width showing channeling contrast by the use of an electron beam scanner,[3] it was Manfred von Ardenne who in 1937 invented[4] a true microscope with high magnification by scanning a very small raster with a demagnified and finely focused electron beam. Ardenne applied the scanning principle not only to achieve magnification but also to purposefully eliminate the chromatic aberration otherwise inherent in the electron microscope. He further discussed the various detection modes, possibilities and theory of SEM, [5] together with the construction of the first high magnification SEM.[6] Further work was reported by Zworykin's group,[7] followed by the Cambridge groups in the 1950s and early 1960s[8][9][10][11] headed by Charles Oatley, all of which finally led to the marketing of the first commercial instrument by Cambridge Scientific Instrument Company as the "Stereoscan" in 1965 (delivered to DuPont).

Principles and capacities

The types of signals produced by a SEM include secondary electrons (SE), back-scattered electrons (BSE), characteristic X-rays, light (cathodoluminescence) (CL), specimen current and transmitted electrons. Secondary electron detectors are standard equipment in all SEMs, but it is rare that a single machine would have detectors for all possible signals. The signals result from interactions of the electron beam with atoms at or near the surface of the sample. In the most common or standard detection mode, secondary electron imaging or SEI, the SEM can produce very high-resolution images of a sample surface, revealing details less than 1 nm in size. Due to the very narrow electron beam, SEM micrographs have a large depth of field yielding a characteristic three-dimensional appearance useful for understanding the surface structure of a sample. This is exemplified by the micrograph of pollen shown above. A wide range of magnifications is possible, from about 10 times (about equivalent to that of a powerful hand-lens) to more than 500,000 times, about 250 times the magnification limit of the best light microscopes.

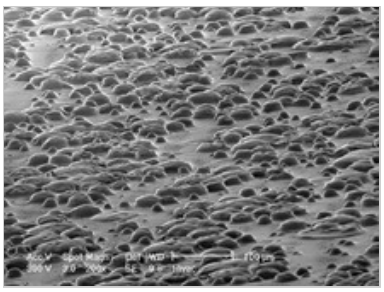
Back-scattered electrons (BSE) are beam electrons that are reflected from the sample by elastic scattering. BSE are often used in analytical SEM along with the spectra made from the characteristic X-rays, because the intensity of the BSE signal is strongly related to the atomic number (Z) of the specimen. BSE images can provide information about the distribution of different elements in the sample. For the same reason, BSE imaging can image colloidal gold immuno-labels of 5 or 10 nm diameter, which would otherwise be difficult or impossible to detect in secondary electron images in biological specimens. Characteristic X-rays are emitted when the electron beam removes an inner shell electron from the sample, causing a higher-energy electron to fill the shell and release energy. These characteristic X-rays are used to identify the composition and measure the abundance of elements in the sample.

Sample preparation

All samples must be of an appropriate size to fit in the specimen chamber and are generally mounted rigidly on a specimen holder called a specimen stub. Several models of SEM can examine any part of a 6-inch (15 cm) semiconductor wafer, and some can tilt an object of that size to 45°.

A spider sputter-coated in gold, having been prepared for viewing with an SEM.

For conventional imaging in the SEM, specimens must be electrically conductive, at least at the surface, and electrically grounded to prevent the accumulation of electrostatic charge at the surface. Metal objects require little special preparation for SEM except for cleaning and mounting on a specimen stub. Nonconductive specimens tend to charge when scanned by the electron beam, and especially in secondary electron imaging mode, this causes scanning faults and other image artifacts. They are therefore usually coated with an ultrathin coating of electrically conducting material, deposited on the sample either by low-vacuum sputter coating or by high-vacuum evaporation. Conductive materials in current use for specimen coating include gold, gold/palladium alloy, platinum, osmium,[12] iridium, tungsten, chromium, and graphite. Additionally, coating with heavy metals may increase signal/noise ratio for samples of low atomic number (Z). The improvement arises because secondary electron emission for high-Z materials is enhanced.



Low-voltage micrograph (300 V) of distribution of adhesive droplets on a Post-it note. No conductive coating was applied: such a coating would alter this fragile specimen.

An alternative to coating for some biological samples is to increase the bulk conductivity of the material by impregnation with osmium using variants of the OTO staining method (O-osmium, T-thiocarbohydrazide, O-osmium).[13][14]

Nonconducting specimens may be imaged uncoated using environmental SEM (ESEM) or low-voltage mode of SEM operation.[15] Environmental SEM instruments place the specimen in a relatively high-pressure chamber where the working distance is short and the electron optical column is differentially pumped to keep vacuum adequately low at the electron gun. The high-pressure region around the sample in the ESEM neutralizes charge and provides an amplification of the secondary electron signal. Low-voltage SEM is typically conducted in an FEG-SEM because the field emission guns (FEG) is capable of producing high primary electron brightness and small spot size even at low accelerating potentials. Operating conditions to prevent charging of non-conductive specimens must be adjusted such that the incoming beam current was equal to sum of outcoming secondary and backscattered electrons currents. It usually occurs at accelerating voltages of 0.3–4 kV.

Embedding in a resin with further polishing to a mirror-like finish can be used for both biological and materials specimens when imaging in backscattered electrons or when doing quantitative X-ray microanalysis.

The main preparation techniques are not required in the environmental SEM outlined below, but some biological specimens can benefit from fixation.

Biological samples

For SEM, a specimen is normally required to be completely dry, since the specimen chamber is at high vacuum. Hard, dry materials such as wood, bone, feathers, dried insects, or shells can be examined with little further treatment, but living cells and tissues and whole, soft-bodied organisms usually require chemical fixation to preserve and stabilize their structure. Fixation is usually performed by incubation in a solution of a buffered chemical fixative, such as glutaraldehyde, sometimes in combination with formaldehyde[16][17][18] and other fixatives,[19] and optionally followed by postfixation with osmium tetroxide.[16] The fixed tissue is then dehydrated. Because air-drying causes collapse and shrinkage, this is commonly achieved by replacement of water in the cells with organic solvents such as ethanol or acetone, and replacement of these solvents in turn with a transitional fluid such as liquid carbon dioxide by critical point drying. The carbon dioxide is finally removed while in a supercritical state, so that no gas–liquid interface is present within the sample during drying. The dry specimen is usually mounted on a specimen stub using an adhesive such as epoxy resin or electrically conductive double-sided adhesive tape, and sputter-coated with gold or gold/palladium alloy before examination in the microscope.

If the SEM is equipped with a cold stage for cryo microscopy, cryofixation may be used and low-temperature scanning electron microscopy performed on the cryogenically fixed specimens.[16] Cryo-fixed specimens may be cryo-fractured under vacuum in a special apparatus to reveal internal structure, sputter-coated, and transferred onto the SEM cryo-stage while still frozen.[20] Low-temperature scanning electron microscopy is also applicable to the imaging of temperature-sensitive materials such as ice[21][22] (see e.g. illustration at left) and fats.[23]

Freeze-fracturing, freeze-etch or freeze-and-break is a preparation method particularly useful for examining lipid membranes and their incorporated proteins in "face on" view. The preparation method reveals the proteins embedded in the lipid bilayer.

Materials

Back scattered electron imaging, quantitative X-ray analysis, and X-ray mapping of specimens often requires that the surfaces be ground and polished to an ultra smooth surface. Specimens that undergo WDS or EDS analysis are often carbon coated. In general, metals are not coated prior to imaging in the SEM because they are conductive and provide their own pathway to ground.

Fractography is the study of fractured surfaces that can be done on a light microscope or commonly, on an SEM. The fractured surface is cut to a suitable size, cleaned of any organic residues, and mounted on a specimen holder for viewing in the SEM.

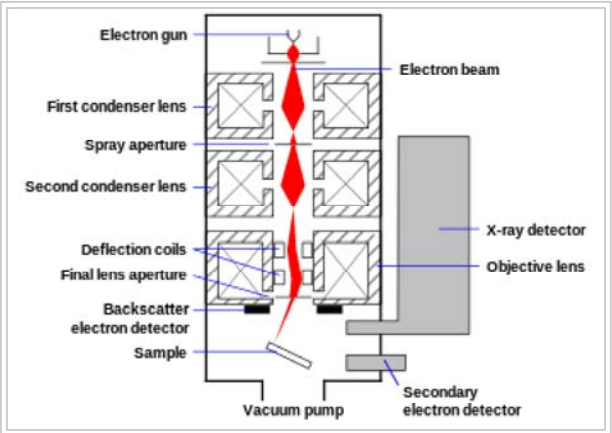
Integrated circuits may be cut with a focused ion beam (FIB) or other ion beam milling instrument for viewing in the SEM. The SEM in the first case may be incorporated into the FIB.

Metals, geological specimens, and integrated circuits all may also be chemically polished for viewing in the SEM.

Special high-resolution coating techniques are required for high-magnification imaging of inorganic thin films.

Scanning process and image formation

In a typical SEM, an electron beam is thermionically emitted from an electron gun fitted with a tungsten filament cathode. Tungsten is normally used in thermionic electron guns because it has the highest melting point and lowest vapour pressure of all metals, thereby allowing it to be heated for electron emission, and because of its low cost. Other types of electron emitters include lanthanum hexaboride (LaB_6) cathodes, which can be used in a standard tungsten filament SEM if the vacuum system is upgraded and FEG, which may be of the cold-cathode type using tungsten single crystal emitters or the thermally assisted Schottky type, using emitters of zirconium oxide.



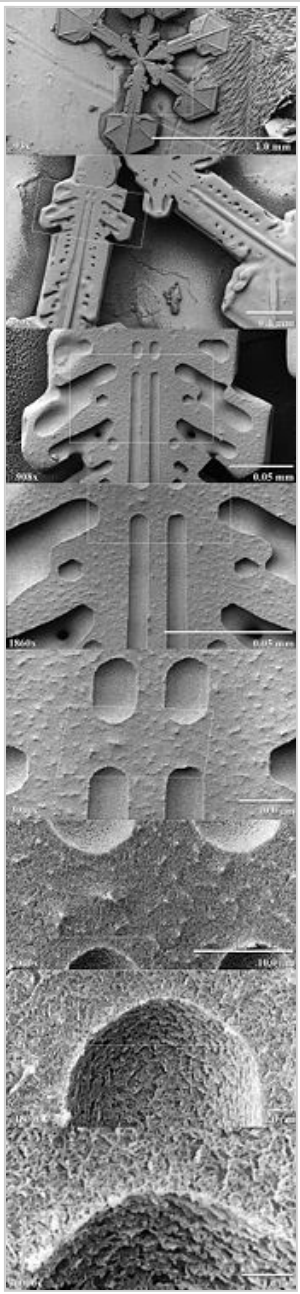
Schematic of an SEM.

The electron beam, which typically has an energy ranging from 0.2 keV to 40 keV, is focused by one or two condenser lenses to a spot about 0.4 nm to 5 nm in diameter. The beam passes through pairs of scanning coils or pairs of deflector plates in the electron column, typically in the final lens, which deflect the beam in the *x* and *y* axes so that it scans in a raster fashion over a rectangular area of the sample surface.

When the primary electron beam interacts with the sample, the electrons lose energy by repeated random scattering and absorption within a teardrop-shaped volume of the specimen known as the interaction volume, which extends from less than 100 nm to approximately 5 µm into the surface. The size of the interaction volume depends on the electron's landing energy, the atomic number of the specimen and the specimen's density. The energy exchange between the electron beam and the sample results in the reflection of high-energy electrons by elastic scattering, emission of secondary electrons by inelastic scattering and the emission of electromagnetic radiation, each of which can be detected by specialized detectors. The beam current absorbed by the specimen can also be detected and used to create images of the distribution of specimen current. Electronic amplifiers of various types are used to amplify the signals, which are displayed as variations in brightness on a computer monitor (or, for vintage models, on a cathode ray tube). Each pixel of computer videomemory is synchronized with the position of the beam on the specimen in the microscope, and the resulting image is therefore a distribution map of the intensity of the signal being emitted from the scanned area of the specimen. In older microscopes image may be captured by photography from a high-resolution cathode ray tube, but in modern machines image is saved to a computer data storage.

Magnification

Magnification in a SEM can be controlled over a range of up to 6 orders of magnitude from about 10 to 500,000 times. Unlike optical and transmission electron microscopes, image magnification in the SEM is not a function of the power of the objective lens. SEMs may have condenser and objective lenses, but their function is to focus the beam to a spot, and not to image the specimen. Provided the electron gun can generate a beam with sufficiently small diameter, a SEM could in principle work entirely without condenser or objective lenses, although it might not be very versatile or achieve very high resolution. In



Low-temperature SEM magnification series for a snow crystal. The crystals are captured, stored, and sputter-coated with platinum at cryogenic temperatures for imaging.

an SEM, as in scanning probe microscopy, magnification results from the ratio of the dimensions of the raster on the specimen and the raster on the display device. Assuming that the display screen has a fixed size, higher magnification results from reducing the size of the raster on the specimen, and vice versa. Magnification is therefore controlled by the current supplied to the x, y scanning coils, or the voltage supplied to the x, y deflector plates, and not by objective lens power.

Colour

The most common configuration for an SEM produces a single value per pixel, with the results usually rendered as black-and-white images.[24] However, often these images are then colourised, in either true colour or false color, by using a colour look-up table, through the use of feature-detection software, or simply by hand-editing using a graphics editor. This is usually for aesthetic effect, for clarifying structure, or for adding a realistic appearance to the sample[25] and generally does not add information about the specimen.[26]

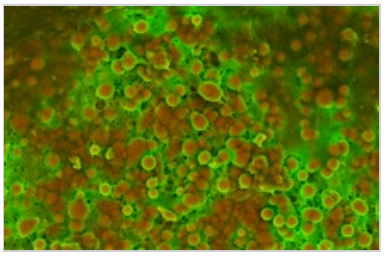
SEM images are often colorized to clarify structure or to add an aesthetic effect. *Tradescantia* pollen and stamens.

In some configurations more information is gathered per pixel, often by the use of multiple detectors.[27] The attributes of topography and material contrast can be obtained by a pair of backscattered electron detectors and such attributes can be superimposed on a single colour image by assigning a different primary color to each attribute.[28] Similarly, a combination of backscattered and secondary electron signals can be assigned to different colors and superimposed on a single color micrograph displaying simultaneously the properties of the specimen.[29]

In a similar method, secondary electron and backscattered electron detectors are superimposed and a colour is assigned to each of the images captured by each detector, with an end result of a combined colour image where colours are related to the density of the components. This method is known as density-dependent colour SEM (DDC-SEM). Micrographs produced by DDC-SEM retain topographical information, which is better captured by the secondary electrons detector and combine it to the information about density, obtained by the backscattered electron detector.[30] [31]

Some types of detectors used in SEM have analytical capabilities, and can provide several items of data at each pixel. Examples are the Energy-dispersive X-ray spectroscopy (EDS) detectors used in elemental analysis and Cathodoluminescence microscope (CL) systems that analyse the intensity and spectrum of electron-induced luminescence in (for example) geological

specimens. In SEM systems using these detectors it is common to color code the signals and superimpose them in a single color image, so that differences in the distribution of the various components of the specimen can be seen clearly and compared. Optionally, the standard secondary electron image can be merged with the one or more compositional channels, so that the specimen's structure and composition can be compared. Such images can be made while maintaining the full integrity of the original signal, which is not modified in any way.



Density-dependent colour scanning electron micrograph SEM (DDC-SEM) of cardiovascular calcification, showing in orange calcium phosphate spherical particles (denser material) and, in green, the extracellular matrix (less dense material).[30]

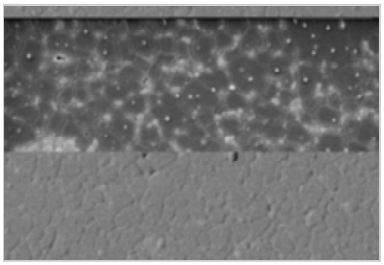
Detection of secondary electrons

The most common imaging mode collects low-energy (<50 eV) secondary electrons that are ejected from the k-shell of the specimen atoms by inelastic scattering interactions with beam electrons. Due to their low energy, these electrons originate within a few nanometers from the sample surface.[32] The electrons are detected by an Everhart-Thornley detector,[33] which is a type of scintillator-photomultiplier system. The secondary electrons are first collected by attracting them towards an electrically biased grid at about +400 V, and then further accelerated towards a phosphor or scintillator positively biased to about +2,000 V. The accelerated secondary electrons are now sufficiently energetic to cause the scintillator to emit flashes of light (cathodoluminescence), which are conducted to a photomultiplier outside the SEM column via a light pipe and a window in the wall of the specimen chamber. The amplified electrical signal output by the photomultiplier is displayed as a two-dimensional intensity distribution that can be viewed and photographed on an analogue video display, or subjected to analog-to-digital conversion and displayed and saved as a digital image. This process relies on a raster-scanned primary beam. The brightness of the signal depends on the number of secondary electrons reaching the detector. If the beam enters the sample perpendicular to the surface, then the activated region is uniform about the axis of the beam and a certain number of electrons "escape" from within the sample. As the angle of incidence increases, the "escape" distance of one side of the beam will decrease, and more secondary electrons will be emitted. Thus steep surfaces and edges tend to be brighter than flat surfaces, which results in images with a well-defined, three-dimensional appearance. Using the signal of secondary electrons image resolution less than 0.5 nm is possible.

Detection of backscattered electrons

Backscattered electrons (BSE) consist of high-energy electrons originating in the electron beam, that are reflected or back-scattered out of the specimen interaction volume by elastic scattering interactions with specimen atoms. Since heavy elements (high atomic number) backscatter electrons more strongly than light elements (low atomic number), and thus appear brighter in the image, BSE are used to detect contrast between areas with different chemical compositions.[32] The Everhart-Thornley detector, which is normally positioned to one side of the specimen, is inefficient for the detection of backscattered electrons because few such electrons are emitted in the solid angle subtended by the detector, and because the positively biased detection grid has little ability to attract the higher energy BSE. Dedicated backscattered electron detectors are positioned above the sample in a "doughnut" type arrangement, concentric with the electron beam, maximizing the solid angle of collection. BSE detectors are usually

either of scintillator or of semiconductor types. When all parts of the detector are used to collect electrons symmetrically about the beam, atomic number contrast is produced. However, strong topographic contrast is produced by collecting back-scattered electrons from one side above the specimen using an asymmetrical, directional BSE detector; the resulting contrast appears as illumination of the topography from that side. Semiconductor detectors can be made in radial segments that can be switched in or out to control the type of contrast produced and its directionality.



Comparison of SEM techniques: Top: backscattered electron analysis – composition Bottom: secondary electron analysis – topography

Backscattered electrons can also be used to form an electron backscatter diffraction (EBSD) image that can be used to determine the crystallographic structure of the specimen.

Beam-injection analysis of semiconductors

The nature of the SEM's probe, energetic electrons, makes it uniquely suited to examining the optical and electronic properties of semiconductor materials. The high-energy electrons from the SEM beam will inject charge carriers into the semiconductor. Thus, beam electrons lose energy by promoting electrons from the valence band into the conduction band, leaving behind holes.

In a direct bandgap material, recombination of these electron-hole pairs will result in cathodoluminescence; if the sample contains an internal electric field, such as is present at a p-n junction, the SEM beam injection of carriers will cause electron beam induced current (EBIC) to flow.

Cathodoluminescence and EBIC are referred to as "beam-injection" techniques, and are very powerful probes of the optoelectronic behavior of semiconductors, in particular for studying nanoscale features and defects.

Cathodoluminescence

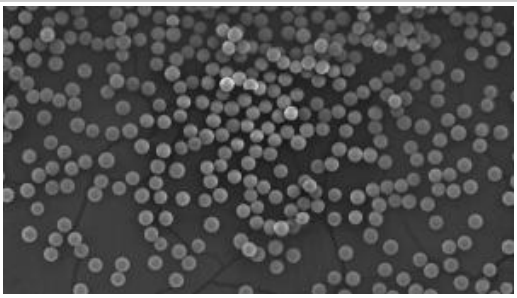
Cathodoluminescence, the emission of light when atoms excited by high-energy electrons return to their ground state, is analogous to UV-induced fluorescence, and some materials such as zinc sulfide and some fluorescent dyes, exhibit both phenomena. Over the last decades, cathodoluminescence was most commonly experienced as the light emission from the inner surface of the cathode ray tube in television sets and computer CRT monitors. In the SEM, CL detectors either collect all light emitted by the specimen or can analyse the wavelengths emitted by the specimen and display an emission spectrum or an image of the distribution of cathodoluminescence emitted by the specimen in real color.

X-ray microanalysis

X-rays, which are produced by the interaction of electrons with the sample, may also be detected in an SEM equipped for energy-dispersive X-ray spectroscopy or wavelength dispersive X-ray spectroscopy.

Resolution of the SEM

The spatial resolution of the SEM depends on the size of the electron spot, which in turn depends on both the wavelength of the electrons and the electron-optical system that produces the scanning beam. The resolution is also limited by the size of the interaction volume, the volume of specimen material that interacts with the electron beam. The spot size and the interaction volume are both large compared to the distances between atoms, so the resolution of the SEM is not high enough to image individual atoms, as is possible transmission electron microscope (TEM). The SEM has compensating advantages, though, including the ability to image a comparatively large area of the specimen; the ability to image bulk materials (not just thin films or foils); and the variety of analytical modes available for measuring the composition and properties of the specimen. Depending on the instrument, the resolution can fall somewhere between less than 1 nm and 20 nm. As of 2009, The world's highest resolution conventional (<30kV) SEM can reach a point resolution of 0.4nm using a secondary electron detector.[34]



A video illustrating a typical practical magnification range of a scanning electron microscope designed for biological specimens. The video starts at 25x, about 6 mm across the whole field of view, and zooms in to 12000x, about 12 μm across the whole field of view. The spherical objects are glass beads with a diameter of 10 μm, similar in diameter to a red blood cell.

Environmental SEM

Main article: Environmental scanning electron microscope

Conventional SEM requires samples to be imaged under vacuum, because a gas atmosphere rapidly spreads and attenuates electron beams. As a consequence, samples that produce a significant amount of vapour, e.g. wet biological samples or oil-bearing rock, must be either dried or cryogenically frozen. Processes involving phase transitions, such as the drying of adhesives or melting of alloys, liquid transport, chemical reactions, and solid-air-gas systems, in general cannot be observed. Some observations of living insects have been possible,[35] however.

The first commercial development of the ESEM in the late 1980s [36][37] allowed samples to be observed in low-pressure gaseous environments (e.g. 1–50 Torr or 0.1–6.7 kPa) and high relative humidity (up to 100%). This was made possible by the development of a secondary-electron detector [38][39] capable of operating in the presence of water vapour and by the use of pressure-limiting apertures with differential pumping in the path of the electron beam to separate the vacuum region (around the gun and lenses) from the sample chamber.

The first commercial ESEMs were produced by the ElectroScan Corporation in USA in 1988. ElectroScan was taken over by Philips (who later sold their electron-optics division to FEI Company) in 1996.[40]

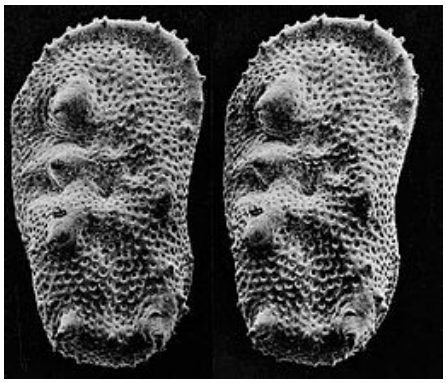
ESEM is especially useful for non-metallic and biological materials because coating with carbon or gold is unnecessary. Uncoated Plastics and Elastomers can be routinely examined, as can uncoated biological samples. Coating can be difficult to reverse, may conceal small features on the surface of the sample and

may reduce the value of the results obtained. X-ray analysis is difficult with a coating of a heavy metal, so carbon coatings are routinely used in conventional SEMs, but ESEM makes it possible to perform X-ray microanalysis on uncoated non-conductive specimens; however some specific for ESEM artifacts are introduced in X-ray analysis. ESEM may be the preferred for electron microscopy of unique samples from criminal or civil actions, where forensic analysis may need to be repeated by several different experts.

3D in SEM

SEMs do not naturally provide 3D images contrary to SPMs. However 3D data can be obtained using a SEM with different methods such as:

- photogrammetry (2 or 3 images from tilted specimen)



A SEM stereo pair of microfossils of less than 1 mm in size (Ostracoda) produced by tilting along the longitudinal axis.

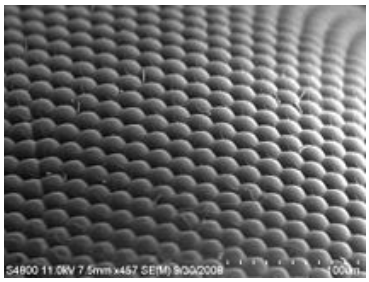
From this pair of SEM images, the third dimension has been reconstructed by photogrammetry (using MountainsMap software) ; then a series of 3D representations with different angles have been made and assembled into a GIF file to produce this animation.

- photometric stereo also called "shape from shading"

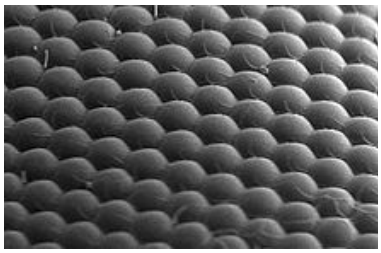
This method typically uses a four-quadrant BSE detector. The microscope produces four images of the same specimen at the same time, so no tilt is required. The method gives metrological 3D dimensions as far as the slope of the specimen remains reasonable. As it works by integration of the slope, vertical slopes and overhangs are ignored ; for instance, if an entire sphere lies on a flat, only the main part of the upper hemisphere is seen emerging above the flat, resulting in wrong altitude of the sphere apex.

- photometric single image topography reconstruction

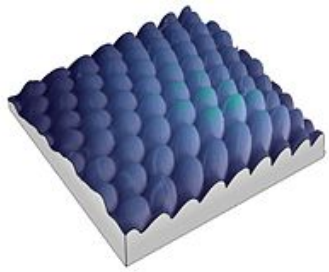
This method requires a SEM image obtained in oblique low angle lighting. The grey-level is then interpreted as the slope, and the slope integrated to restore the specimen topography. This method is interesting for visual enhancement and the detection of the shape and position of objects ; however the vertical heights cannot usually be calibrated, contrary to other methods such as photogrammetry.



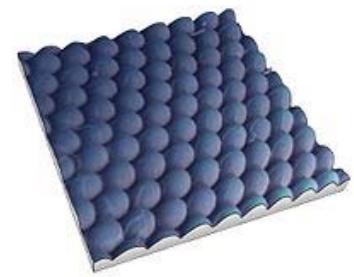
SEM image of a house fly compound eye surface at 450× magnification.



Detail of the previous image.



SEM 3D reconstruction from the previous using shape from shading algorithms.



Same as the previous, but with lighting homogenized before applying the shape from shading algorithms

- inverse reconstruction using electron-material interactive models[41][42]
- vertical stacks of SEM micrographs plus image-processing software[43]

Possible applications are roughness measurement, measurement of fractal dimension, corrosion measurement, and dimensional measurements at the nano scale (step height, volume, angle, flatness, bearing ratio, coplanarity, etc.).

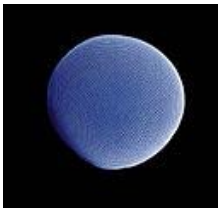
Transmission SEM

The SEM can also be used in transmission mode by simply incorporating an appropriate detector below a thin specimen section .[44] Both bright and dark field imaging has been reported in the generally low accelerating beam voltage range used in SEM, which increases the contrast of unstained biological specimens at high magnifications with a field emission electron gun. This mode of operation has been abbreviated by the acronym TSEM.

Gallery of SEM images

The following are examples of images taken using an SEM.

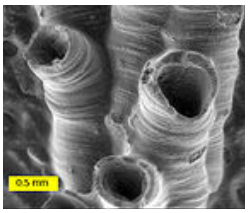
Colored SEM image of soybean cyst nematode and egg. The artificial coloring makes the image easier for non-specialists to view and understand the structures and surfaces revealed in micrographs.



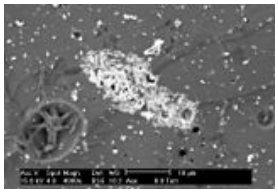
Compound eye of Antarctic krill *Euphausia superba*. Arthropod eyes are a common subject in SEM micrographs due to the depth of focus that an SEM image can capture. Colored picture.

Ommatidia of Antarctic krill eye, a higher magnification of the krill's eye. SEMs cover a range from light microscopy up to the magnifications available with a TEM. Colored picture.

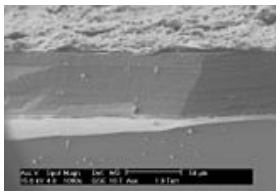
SEM image of normal circulating human blood. This is an older and noisy micrograph of a common subject for SEM micrographs: red blood cells.



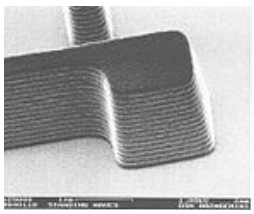
SEM image of a hederelloid from the Devonian of Michigan (largest tube diameter is 0.75 mm). The SEM is used extensively for capturing detailed images of micro and macro fossils.



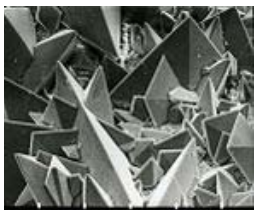
Backscattered electron (BSE) image of an antimony-rich region in a fragment of ancient glass. Museums use SEMs for studying valuable artifacts in a nondestructive manner.



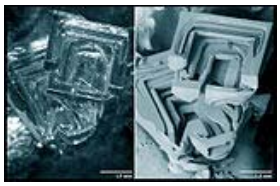
SEM image of the corrosion layer on the surface of an ancient glass fragment; note the laminar structure of the corrosion layer.



SEM image of a photoresist layer used in semiconductor manufacturing taken on a field emission SEM. These SEMs are important in the semiconductor industry for their high-resolution capabilities.



SEM image of the surface of a kidney stone showing tetragonal crystals of Weddellite (calcium oxalate dihydrate) emerging from the amorphous central part of the stone. Horizontal length of the picture represents 0.5 mm of the figured original.



Two images of the same depth hoar snow crystal, viewed through a light microscope (left) and as a SEM image (right). Note how the SEM image allows for clear perception of the fine structure details which are hard to fully make out in the light microscope image.

See also

- Forensic engineering
- Forensic science
- List of surface analysis methods
- Energy-dispersive X-ray spectroscopy
- Transmission electron microscopy (TEM)

- *Teeny Ted from Turnip Town* (World's smallest book requires a scanning electron microscope to read).
- Microscopy

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External links

General

Wikibooks has a book on the topic of: ***Nanotechnology***

Wikimedia Commons has media related to ***Scanning electron microscope***.

Wikimedia Commons has media related to ***Scanning electron microscopic images***.

- HowStuffWorks – How Scanning Electron Microscopes Work (http://www.howstuffworks.com/scanning-electron-microscope.htm)
- Notes on the SEM (http://www.uga.edu/caur/semindex.htm) Notes covering all aspects of the SEM
- Scanning Electron Microscopy basics (http://virtual.itg.uiuc.edu/training/EM_tutorial/) an animated tutorial on how SEM works
- Virtual SEM – sparkler. (http://www.ammrf.org.au/myscope/sem/practice/virtualsem/sparkler.php) Interactive simulation of a scanning electron microscope (SEM)
- Preparing a Sample for the SEM (http://virtual.itg.uiuc.edu/training/esem-prep.mov) preparing a non-conducting subject for the SEM (QuickTime-movie)
- multichannel color SEM imaging (http://www.danilatos.com/scancol/scancol09.html) and (http://www.danilatos.com/colorESEM/colrESEM317.html)
- DDC-SEM image examples (https://twitter.com/sbertazz)

- Video on the scanning electron microscope (http://www.youtube.com/watch?v=GY9lfO-tVfE), Karlsruhe University of Applied Sciences

History

- Microscopy History links (http://bama.ua.edu/~hsmithso/class/bsc_656/websites/history.html) from the University of Alabama Department of Biological Sciences
- Environmental Scanning Electron Microscope (ESEM) history (http://www.danilatos.com)

Images

- Rippel Electron Microscope Facility (http://remf.dartmouth.edu/imagesindex.html) Many dozens of (mostly biological) SEM images from Dartmouth College.

Categories: Electron microscopy | Scientific techniques
