To the DIFFRACTION LIMIT *...and* BEYOND

Anton van Leeuwenhoek produced the first light microscope in the mid-1600's using a new technique he developed to create high quality, if small, lenses. About 200 years later, Ernst Karl Abbe, working with German engineer and entrepreneur, Carl Zeiss, published (in 1873) the seminal observation that the resolution of a microscope could be defined as the wavelength of the light used, divided by twice the numerical aperture. Although there is some debate as to whether Abbe was the first to make this discovery, he has historically been credited. The resulting equation implies that there is a point, known as the Abbe diffraction limit, at which two objects viewed under a light microscope cannot be separately distinguished, and is roughly half the wavelength of the light used. As a consequence, the fine details of any objects smaller than that limit remained tantalizingly out of reach. For many years, this limit was seen as immutable, but this did not stop researchers from dreaming of one day pushing past it.

It took until 1931 for this dream to become a reality, when Ernst August Friedrich Ruska, while working at Siemens-Reiniger-Werke AG (precursor to present-day Siemens AG) built the first transmission electron microscope. Using electrons, which have a far shorter wavelength than light, it was possible to resolve individual objects at a far greater magnification, up to 12,000x. It was not an easy path to this milestone and Ruska undoubtedly stood on the shoulders of giants when developing his microscope, but it set the foundation for the development of electron microscopy technology. Four years later, Max Knoll discovered a means to sweep an electron beam over the surface of a sample, creating the first scanning electron microscope (SEM) images. Although both of these developments were a huge step forward, it was another 30 years, in 1965, before the first commercial SEM became available to scientists, revolutionizing high-magnification microscopy.

In the ensuing 50 years the field has experienced both gradual progress as well as quantum leaps. Many of these milestones are laid out in the illustrated historical timeline of SEM development, to be seen on the front of this poster. They accompany a primer on SEM, explaining the basics of the technology, the types of signals that can be detected, and how these are applied today in a research setting. Be sure also to visit our richly interactive website online (posters.sciencemag.org/sem) where you will find additional information and multimedia that we hope will help you better understand this extraordinary technology as it takes you to the light diffraction limit and beyond.

Sean Sanders, Ph.D.
Editor, Custom Publishing, *Science*

Background: SEM image of a tungsten-steel composite metal.

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THE SCANNING ELECTRON MICROSCOPE

A Small World *of* Huge Possibilities

It's been 50 years since the first commercial scanning electron microscope (SEM) was launched, and researchers' view of the nanoscale world is sharper than ever. SEMs create surface images of bulk material by scanning an electron beam over the sample, recording the resulting echoes and electrical interactions point by point. Resolution in the nanometer range is routine.

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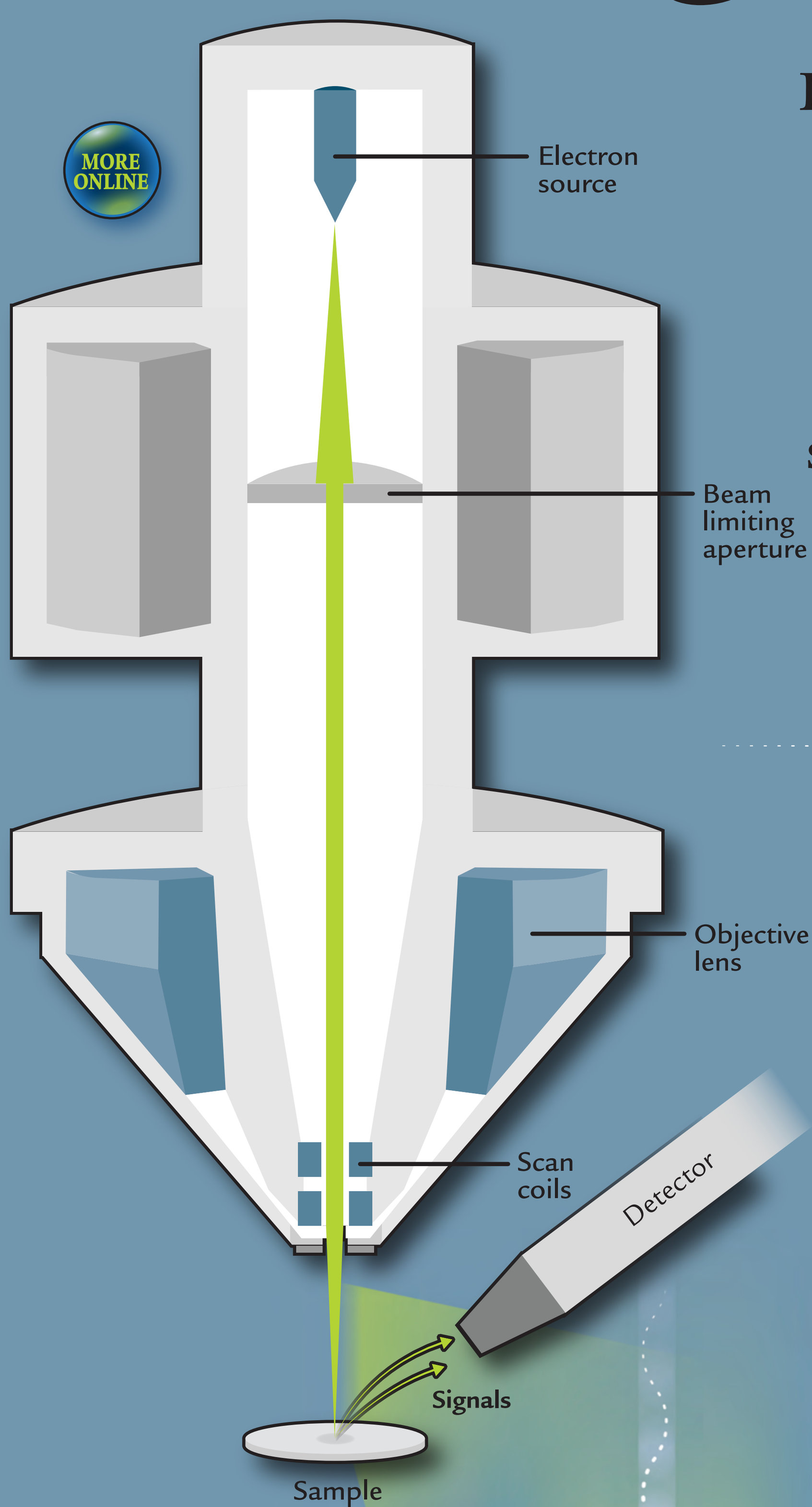
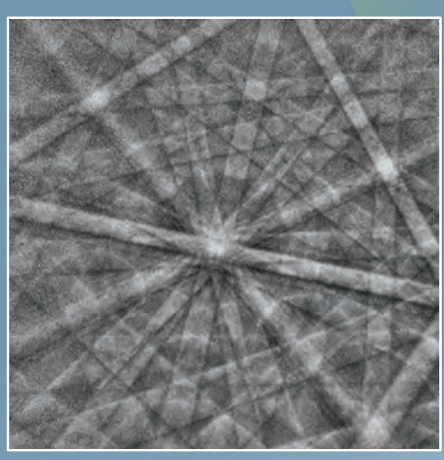


SEM TECHNOLOGY AND SIGNAL DETECTION

Analogous in design to laser-scanning confocal microscopes, SEMs use electromagnetic "lenses" to focus an electron beam to a sharp point and raster-scan across the sample. Instead of recording fluorescence, however, SEMs create images by recording the interactions of the electron beam with the sample surface, which could be a ceramic material, metal, or biological specimen. These interactions can take many forms, and SEM users can install a range of detectors around the sample chamber to interrogate them, as described below.

ELECTRON BEAM

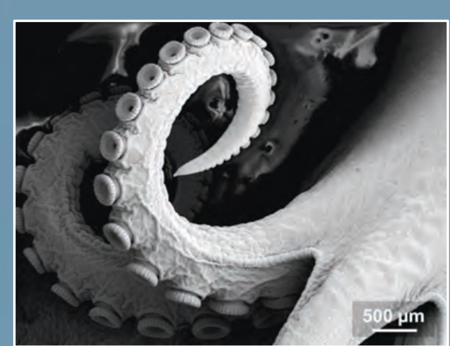
Sample surface



EBSD pattern of silicon.

Backscatter diffracted electrons (EBSD)

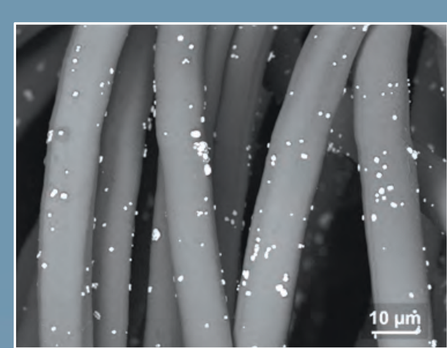
Bragg diffraction occurs when the SEM beam strikes crystalline matter. The resulting electron backscatter diffraction (EBSD) patterns (see image) reveal the underlying crystal structure. Among other applications, EBSD is used in solar cell development to ensure that the cells are fabricated correctly.



SE (Everhart-Thornley) image of the arms of octopus Eledone larva.

Secondary Electrons (SE)

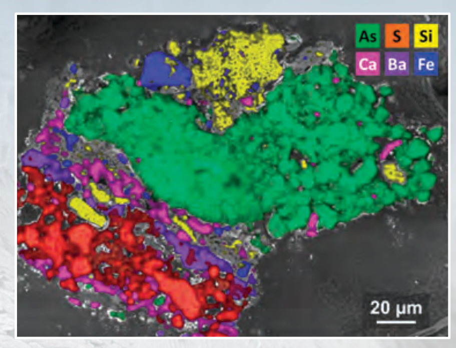
Low-energy (<50eV) secondary electrons (SE) result from "inelastic" interaction of the primary electron beam (and backscattered electrons) with the sample, revealing topography and (to some extent) electrical properties of the sample. The Everhart-Thornley SE detector is the most widely used SEM detector. Today's advanced SEMs complement it with "in-lens" or "in-column" detectors.



BSE image of Ag particles on antimicrobial dressing.

Backscattered Electrons (BSE)

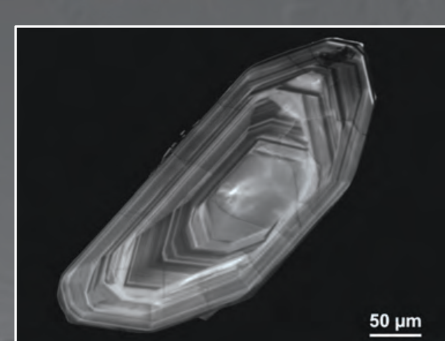
BSE reflect off the sample surface like light from a mirror. As backscattering efficiency depends on atomic number, BSE can discern differences in sample composition, such as the presence of a silver particle coating on the synthetic fiber of an antimicrobial dressing.



EDS map image of a paint sample from original artwork.

X-rays (EDS/WDS)

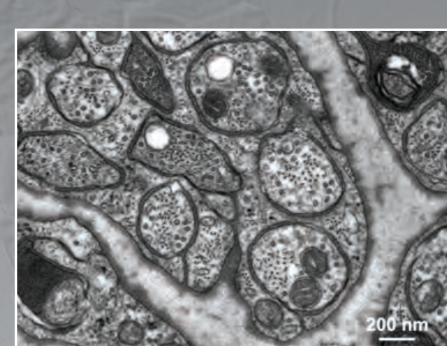
The SEM beam can excite emission of characteristic x-rays from the sample. Detection of these x-rays by energy-dispersive or wavelength-dispersive x-ray spectroscopy (EDS or WDS) reveals a sample's elemental composition. EDS and WDS are used, for example, in museum laboratories for chemical analysis of paintings and forgery detection.



CL image of Zircon.

Cathodoluminescence (CL)

When electrons hit luminescent materials they produce light. A CL detector picks up those photons, producing "live-color" images of minerals in geology applications—for instance, in oil and gas research and mining—or of luminescent proteins in biology.



STEM image of mouse brain.

Transmitted electrons (STEM)

When imaging very thin samples (<100 nm thick), electrons can pass through the sample. Detection of transmitted electrons yields scanning transmission electron microscopy (STEM) images of particularly high resolution. STEM has both materials and life sciences applications.

MORE ONLINE For more information, go online to: posters.sciencemag.org/sem

TIMELINE *of* SEM DEVELOPMENT

1920s

1926 – Hans Busch demonstrates that charged particles can be bent in a magnetic field as glass lenses bend visible light.

1931 – Ernst Ruska builds the first transmission electron microscope with resolution higher than a light microscope (~12,000x).

1930s

1933 – Ruska (right) and Knoll working on their transmission electron microscope (Berlin).

1938 – Manfred von Ardenne develops the first scanning transmission electron microscope, with an electron beam diameter on target of ~10 nm. His first image is of a zinc oxide crystal at 8000x magnification.

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1935 – Max Knoll (shown with Ruska, above) becomes the first researcher to scan a surface with an electron beam to obtain an image. Lacking lenses, his system has a resolution of ~100 µm.

1940s

1942 – Vladimir Zworykin (sitting), James Hillier (standing), and Richard Snyder (not pictured), working at RCA, implement a working SEM instrument with 50-nm resolving power.

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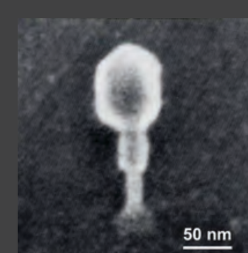
1948 – Charles Oatley begins SEM development at Cambridge University, UK, spending some two decades on the project.

1950s

1960 – Development of the Everhart-Thornley secondary electron detector.

1960s

1965 – Cambridge Scientific Instruments releases the first commercial SEM, the Stereoscan Mark I, here being demonstrated for Great Britain's Prince Philip (second from left).



1972 – Albert Crewe at the University of Chicago, US, and researchers at Hitachi develop the first practical field emission (FE)-SEM. Its brighter source allowed for higher resolution, as shown by this image of a T2 bacteriophage particle.

1970s

1985 – ZEISS launches the first fully digital SEM, the DSM 950.

1980s

1986 – Ernst Ruska wins the Nobel Prize in Physics, "for his fundamental work in electron optics, and for the design of the first electron microscope."

credit: Archiv der Max-Planck-Gesellschaft, Berlin-Dahlem

1988 – ElectroScan Corp. launches the first commercial environmental SEM, enabling "wet" life science applications. That same year, Pierre Sudraud and colleagues incorporate a focused ion beam (FIB) column, pioneered by Riccardo Levi-Setti (1975), into an SEM, enabling researchers to excavate the sample surface to probe its interior.

1990s

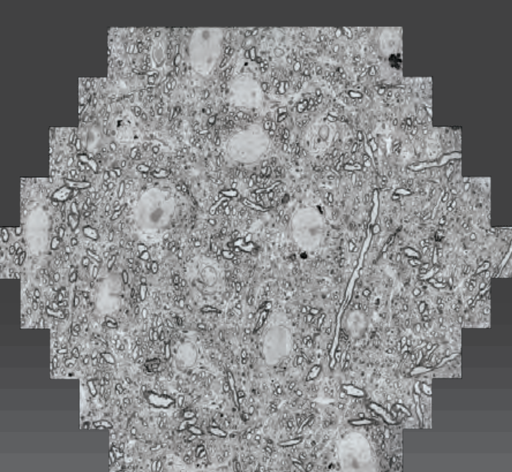
1990s – Thermal-assisted (Schottky) FE-SEMs launched, offering superior electron current stability relative to "cold-field" emitters.

2000s

2003 – JEOL launches the first commercial "aberration-corrected" SEM, the JSM-7700F.

2010s

2014 – ZEISS launches the MultiSEM 505, a 61-beam (multi-beam) SEM.



2014 – Image represents data from a 61-beam (multi-beam) SEM, arranged hexagonally. Field of view: 100 µm. Imaging time: 1.3 s

credit: Jeff Lichtman, Harvard University

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