AFM manufacturers also adapted the microscope to the needs of industry. Adaptations included AFMs in which the cantilever (rather than the sample) is scanned back and forth, allowing for larger samples (including whole manufactured products) to be imaged. Also, AFMs were developed with automated systems for handling samples and replacing cantilevers, a prerequisite for selling the microscopes to the microelectronics industry. As that market has matured, the original start-up AFM manufacturers have lost share to more established firms such as KLA-Tencor, though the start-ups continue to be the primary suppliers of research microscopes.

See Also: IBM; International SPM Image Competition; Microscopy, Scanning Probe; Microscopy, Scanning Tunneling; Nanoscale Science and Engineering.

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Microscopy, Electron (Including TEM and SEM)

Electron microscopy emerged in the 1920s as the first practical alternative to optical microscopy. The upheavals of World War II caused the locus of electron microscopy development to shift to North America, where the technique rapidly gained a foothold in biology, metallurgy, and a few other fields. It was not until the 1960s, however, that electron microscopes had become cheap, powerful, and reliable enough for large numbers of nonexpert researchers to become users. By the end of that decade, scanning electron microscopes were being used both to image and create some of the smallest artificial structures in the world. This dual capability has made electron microscopy a crucial technique for the semiconductor industry and nanoscience.

Changing the Rules

By the 1920s, it was increasingly apparent that electron beams acted somewhat like beams of light—they cast shadows, they could be reflected, and (in 1927) researchers at Bell Laboratories showed they could be diffracted. That same year, Hans Busch showed that a magnetic coil could focus an electron beam in the same way that a glass lens focuses light. This was the first indication that a new kind of microscope could be built with electrons as the imaging radiation. Since the resolution of a microscope is directly proportional to the wavelength of radiation shining on the sample, and electron wavelengths are more than three orders of magnitude smaller than the wavelength of visible light, such a microscope would have a much higher resolution than traditional light microscopy.

Such a microscope was developed in the early 1930s by Ernst Ruska and Max Knoll at the Technical University of Berlin. The Berlin team soon realized that two broad types of electron optical microscope were possible. In one, the beam would simply pass through a thin sample onto a detector—the transmission electron microscope or (TEM). In the other, a beam of electrons would move back and forth over a sample. This beam would either be reflected off the sample, or would excite the sample and cause it to emit its own "secondary" electrons. The reflected and secondary electrons would enter a detector, be amplified, and turned into a new electron beam that would be scanned back and forth in the same fashion as the original beam.

Unlike the TEM, this scanning electron microscope, or (SEM), would produce images that resembled (though were higher resolution than) ordinary light microscope images. However, the SEM's complex circuitry, and the fact that its resolution would be lower than the TEM's, meant that TEM was developed first. By the end of the 1930s, TEM and SEM had formed long-lasting alliances with different groups of users. TEM's need for very thin samples made it more attractive to metallurgists and others interested in material properties. Life scientists found SEM more attractive because it did not require thin samples and because the images it produced were more comparable to light microscopy. Though there are many, and important, exceptions, the general outlook of

TEM toward materials science and SEM toward biology continues to inform use of these instruments in nanoscience. Since TEM has higher resolution, the biologists who use it rather than SEM tend to be those looking at the very smallest constituents of life (e.g., viruses or cell organelles) where the line between chemistry and biology is fuzziest.

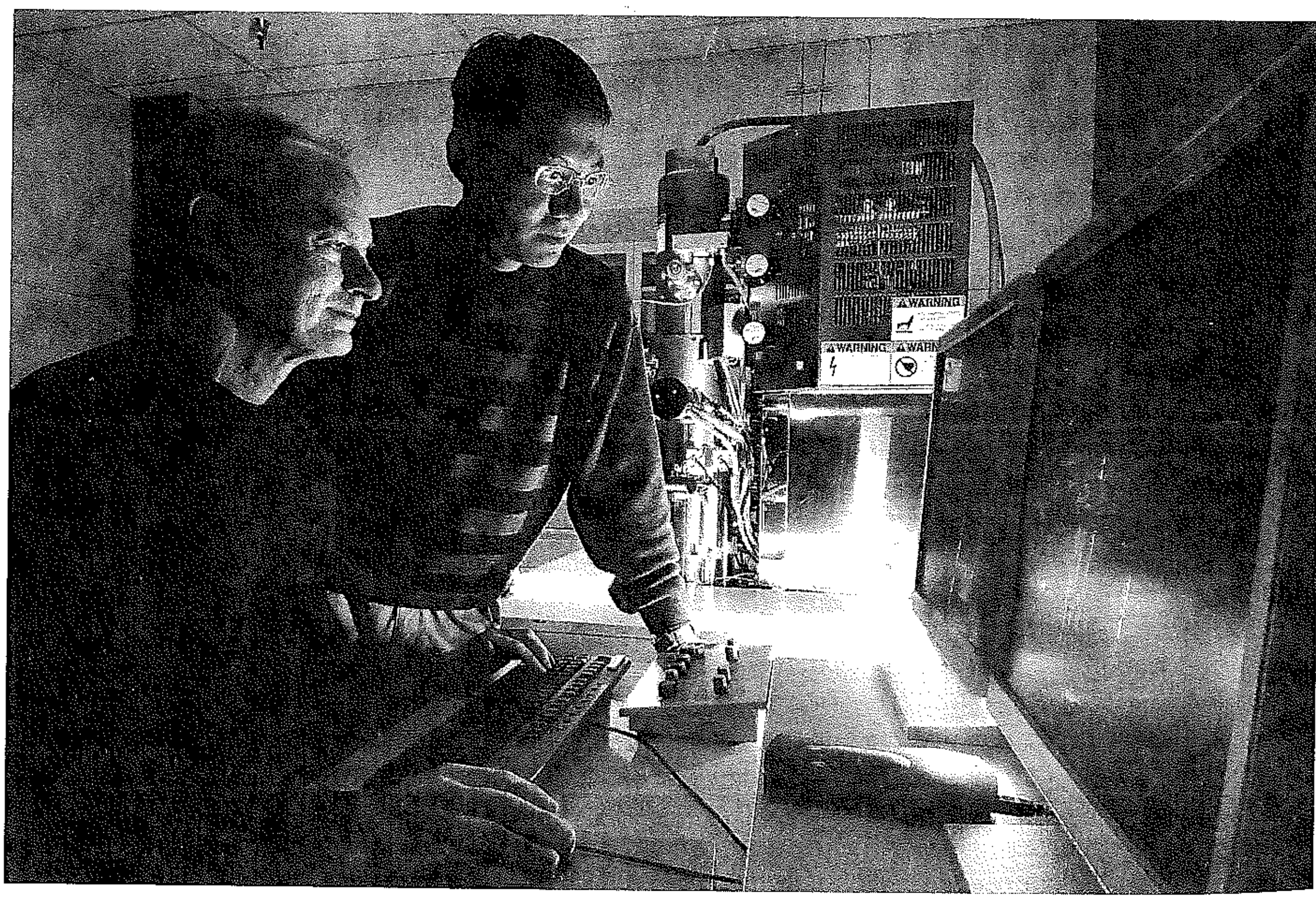
Imaging and Intervening

Although Siemens developed a commercial TEM in the 1930s, and RCA a commercial SEM in the 1940s, neither was particularly successful. Indeed, RCA's instrument was designed less as a viable product and more as a way for the company to advertise the biomedical benefits of its research when lobbying the Federal Communications Commission to adopt its standard for television broadcasting. It was not until the 1960s that reliable, user-friendly electron microscopes were marketed, especially by firms in Japan.

One consequence of commercialization was that it became easier for users to adapt electron microscopy for unforeseen applications. In particular, some researchers at microelectronics firms (especially IBM and Bell Laboratories) began using commercial microscopes to carve tiny circuits in silicon and other materials. Electron beam, or "e-beam," lithography advanced rapidly in the early 1970s, and IBM advocated that it replace the optical lithographic techniques then (and still) used to make integrated circuits. Silicon Valley firms, however, preferred more incremental innovation, adopting e-beam lithography only in very specialized applications such as making the "masks" used in optical lithography.

Continuing Improvement

Just like optical microscopy, electron microscopy has continued to improve along a number of axes throughout its history. Although the advent of nanotechnology is often traced to the invention of new types of microscopes



A Sandia National Laboratory researcher and a Ph.D. student observe platinum at the nanoscale on a scanning electron microscope (SEM) at the University of New Mexico's Center for Micro Engineered Materials.

such as the scanning tunneling microscopes, this is inaccurate—continual improvements to SEM and TEM have made these instruments indispensable to nanoscience.

In the 1970s, for instance, Albert Crewe combined the two major electron microscopies to invent the scanning transmission electron microscope, or STEM, which is capable of resolving single atoms. Somewhat more common in nanoscience, particularly in microelectronics research and development, is high-resolution transmission electron microscopy (HRTEM), which relies on diffraction of the electron beam within the sample to "resolve" the sample's crystalline lattice (the meaning of "resolve" is not well understood for this technique). Other improvements include high-voltage SEMs that can operate in "wet" or "environmental" conditions rather than vacuum, and the use of digital processing to remove aberrations and even to gain chemical information about the sample. Electron microscopists continue to innovate, and thereby maintain the relevance of their technique to nanoscience.

See Also: Microscopy, Atomic Force; Microscopy, Exotic; Microscopy, Optical; Nanoscale Science and Engineering.

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Microscopy, Exotic

For a half century starting in 1931, optical and electron microscopy together dominated attempts to visualize the microworld. Exotic microscopies have, however, provided alternative visualization methods for nearly as long. Until the 1980s, none of these exotic alternatives were serious challengers to optical and electron microscopy. The advent of the scanning tunneling microscope (STM) and atomic force microscope (AFM) gave new impetus to the search for exotic alternatives to optical and electron microscopy. Yet the STM and AFM were themselves made possible by a rich, if largely unimpressive, history of exotic microscopies that preceded them. Today, the search for new microscopies is one of the most dynamic and competitive areas of nanoscience.

What Is a Microscope For?

A microscope is, essentially, a tool for creating a visual image of a sample that contains information that is finer grained than information available to the naked eye. Microscopes can do other things as well, of course—some microscopes generate aural "images," some manipulate the sample while imaging it, and so on. But the gathering and amplification of fine-grained information, and conversion of that information into something perceived by the microscopist's eye, are the fundamental traits of a microscope. This general definition helps explain why the development of new microscopes is such a thriving part of nanoscience. A naive understanding of microscopy would see the development of new types as purely a matter of increasing resolution—a drive to ever-more fine-grained images. However, by defining the purpose of microscopy as capturing information, we can see that microscopists will pursue new instrumentation so long as it yields new kinds of data about a sample, even if that data is not at a high resolution.

Field Emission

Until the 1930s, "microscope" meant exclusively an optical microscope, usually one in which light is focused on a sample using glass and flint lenses. In the 1930s, though, it became possible to focus electrons on a sample, leading to the scanning electron microscope (SEM) and transmission electron microscope (TEM). For the next 50 years, optical and electron microscopy would dominate microscope development. Electron microscopy delivered higher resolution, while optical microscopy offered greater convenience and a more secure theoretical understanding. Both technologies had drawbacks, though. For instance, both gave only rudimentary information about the chemical species present in a sample—a major hindrance to the adoption of microscopes by chemists. Both damaged and distorted samples, especially biological materials—optical microscopy by requiring chemical dyes ("stains") to increase contrast,