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.

Further Readings

Egerton, Ray F. *Physical Principles of Electron Microscopy: An Introduction to TEM, SEM, and AEM*. New York: Springer, 2008.

Rasmussen, Nicolas. *Picture Control: The Electron Microscope and the Transformation of Biology in America*. Palo Alto, CA: Stanford University Press, 1997.

Wells, Oliver C. and David C. Joy. "The Early History and Future of the SEM." *Surface and Interface Analysis*. v.38/12–13 (2006).

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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, electron microscopy by requiring that samples be kept in vacuum and coated in gold.

At the same time that the SEM and TEM were developed, a third electron microscope emerged which did not use electron optical elements to focus an electron beam onto a sample. Instead, the field emission microscope (FEM) used the sample as the source of an electron beam. Invented by Erwin Müller in 1936, the FEM requires a metal sample that is carved into a very sharp point, placed in high vacuum, and kept at a high voltage. Under these conditions, electrons will be "emitted" from near the sample tip (i.e., they will quantum-mechanically "tunnel" out of the sample and then move ballistically through the vacuum). The voltage near the tip will vary slightly depending on features of the sample surface such as grain boundaries. Thus, if a fluorescent screen is placed in the path of the emitted electrons, they will form an image of those surface features. In this way, FEM gives fine-grained information about the sample, but without any focusing element.

After Müller moved to Penn State in 1952, he developed a variant called the field ion microscope (FIM). FIM works much like FEM, except that a small quantity of gas molecules are introduced into the vacuum. These adsorb onto the sample and then are ionized by the high electric field, causing them to fly into the fluorescent screen. In late 1955, Müller's graduate student, Kanwar Bahadur, surreptitiously cooled the sample with liquid nitrogen and was able to observe single atoms of the tungsten tip arrayed in their crystalline lattice.

Thus, FIM was the first microscope to achieve the ultimate in resolution—single atoms. Yet very few people adopted it, partly because of Müller's tight gatekeeping but also because there were very few samples that could survive the harsh conditions FIM imposed—basically only tungsten and a few other hard metals.

Variation and Selection

The grip of optical and electron microscopy loosened a little further in the 1970s, as new alternative microscopes emerged. These included the near-field scanning microwave microscopy and scanning acoustic microcopy—instruments that worked somewhat like a physician moving a stethoscope over a patient's chest to build up a "picture" of their lungs and heart. Acoustic microscopy is notable partly because it required advanced microfabrication techniques to make good sonic lenses. It is often claimed that new microscopes enabled the transition from microtechnology to nanotechnology, but in fact this was a process of feedback—those new microscopes could only be built with tools from microtechnology.

The other enabling technology of exotic microscopy was the computer. Small, cheap, fast computers became ubiquitous in laboratories in the 1980s, allowing instruments to be developed that depended on real-time data processing to generate an image. The golden age of exotic microscopies partly began with the invention of the scanning tunneling microscope in 1981, but really only came to fruition with the marketing of the IBM personal computer (PC) in 1982. With the PC, images from new microscopes could be generated much more quickly, understood much more easily, and fed back into the process of microscope development much more tightly. One result was the proliferation of scanning probe microscopes, which operate a little like a blind person reading Braille with their finger—except that the microscope probe (the finger) can be tuned to gather many different kinds of information: temperature, chemical reactivity, resistance, capacitance, etc. Cheap computing also breathed new life into exotic microscopies that had seemed to have run their course. This is perhaps most apparent with the latest generation of field-ion microscopy, known as local-electrode atom-probe (LEAP) tomography or just atom probe tomography (APT). In LEAP, the atoms of the sample themselves are ionized, usually by a laser pulse.

They then go into a time-of-flight spectrometer, which can identify their chemical species. A computer then reassembles each of the spectrometer readings into a three-dimensional atomic-resolution reconstruction of the original sample. Thus, advances in computing and microfabrication provide the means for today's exotic microscopies, while the desire for new kinds of information about the fine structure of materials provides the motive. Nanotechnology operates largely, though not exclusively, at that intersection of means and motive, as the field draws on the ever-growing array of instrumentation to understand and manipulate nanoscale structures.

See Also: Microscopy, Atomic Force; Microscopy, Electron (Including TEM and SEM); Microscopy, Optical; Microscopy, Scanning Probe; Microscopy, Scanning Tunneling.

Further Readings

Melmed, Alan J. "Recollections of Erwin Müller's Laboratory: The Development of FIM (1951–1956)." *Applied Surface Science*, v.94/5, (1996).

Tsong, Tien T. *Atom-Probe Field Ion Microscopy: Field Ion Emission, and Surfaces and Interfaces at Atomic Resolution.* New York: Cambridge University Press, 2005.

Zheludev, Nikolay I. "What Diffraction Limit?" *Nature Materials,* v.7/6 (2008).

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Microscopy, Optical

The discovery of how to grind glass lenses to magnify tiny objects was one of the critical first steps in the Scientific Revolution. Seventeenth-century natural philosophers hoped that the microscope might reveal the "corpuscles" thought to be the elementary constituents of matter. When this proved not to be the case, interest in microscopy ebbed for almost two centuries. In the late 19th century, optical microscopy rebounded as mass-produced instruments with fewer distortions became available. In the 20th century, other techniques of magnification—such as electron microscopy—began to compete with optical microscopes. Because of its first-mover advantage and continuing improvements, however, optical microscopy has remained crucial to industry and research even in the era of nanotechnology.

Hooke and Leeuwenhoek

People have peered through quartz or glass to magnify objects since antiquity. Like alchemy, astronomy, algebra, and much of medicine, classical knowledge of lenses was preserved in the Arab and Muslim world. It was only in the 14th century that Western Europeans figured out how to grind lenses for spectacles. Two centuries later, Dutch lensmakers had learned to combine multiple lenses, thereby inventing the telescope and the microscope.

Italian natural philosophers, including Galileo, took up microscopy in the 1620s, but elsewhere it was not an important tool of the Scientific Revolution until the 1660s. At that point, alchemists and philosophers of matter such as Robert Boyle came to believe that the microscope could provide direct evidence for "corpuscles," the particulate constituents of matter that—perhaps through differences in shape—accounted for observed qualities such as the taste and hardness of materials. Boyle's assistant, Robert Hooke, published a beautifully illustrated compendium of microscope images, the *Micrographia* of 1665. Boyle also encouraged an extraordinarily gifted Dutch lensmaker, Antoni van Leeuwenhoek, whose keen eyesight and exquisite simple microscopes offered resolution of the microscale that was unsurpassed until the 19th century.

Abbe and Aberrations

By 1700, though, it was obvious that microscopes would be unable to resolve the elementary constituents of matter, and natural philosophers rapidly lost interest. Microscopes contributed little to science for the next century. However, technical improvements starting in the 1820s—particularly new lenses to correct for spherical and chromatic aberration, and new dyes to stain biological samples—reignited interest, particularly from botanists and zoologists.

In the 1870s, Ernst Abbe, a physicist working for the Zeiss workshop of instrument makers, developed a theoretical understanding of optical microscopy that has defined the technique ever since. At the time, Abbe's work was probably meant simply to advertise Zeiss' microscopes as having a scientific underpinning. Over the medium term, Abbe guided Zeiss to more powerful instruments. In the long run, though, Abbe's work established a limit to improvements in optical microscopy. No matter how many aberrations microscope designers overcame, the smallest object a light microscope could resolve would be directly proportional to the wavelength of the light shining on the object, and inversely proportional to the sine of the index of refraction of the material from which the microscope's lenses were made.

Abbe's limit implies that even the best optical microscope will be unable to distinguish features less than about 200 nanometers apart. This would seem to bar optical microscopy from use in nanoscience. It also implies a limit to the use of optical lithography (the inverse of microscopy) in microelectronics manufacturing. Yet ingenious design gradually overcame Abbe's limit in both microscopy and lithography.

Competition and Continuing Improvement

In the 20th century, once quantum mechanics demonstrated the wave-particle duality, some researchers saw that a way around the Abbe limit was to "shine" electrons on a sample rather than optical photons—since the electron's wavelength is more than three orders of magnitude smaller than that of visible light.