Microscopy, Atomic Force

The scanning tunneling microscope (STM) was recognized as a revolutionary instrument almost immediately after its invention in 1981. Yet even the inventors of the STM quickly realized its inherent limits. In particular, the STM could not inspect insulating materials—a grave obstacle to its use in biology or industry.

Early STMsers, therefore, worked together to invent the atomic force microscope (AFM)—a very similar instrument that could image almost any surface. Today, the AFM is the most widely used scanning probe microscope: they are ubiquitous in academic research and industrial quality control labs; million-dollar AFMs are part of the production line in semiconductor fabs (fabrication plants); and one AFM has even made it to the surface of Mars.

Overcoming the STM’s Limits
The STM gained quick acclaim starting with the publication of the first atomic-resolution images of silicon in 1983. However, since the STM’s imaging mechanism relies on exchanging electrons between a sample and a small, solid probe, it is only capable of characterizing metal or semiconductor samples, where electrons can move from sample to probe without damaging the sample. Two important classes of samples were left out: microelectronic circuits (which, though partly semiconducting, also contain significant insulating regions) and biological materials. Two members of the IBM Zurich team that invented the STM began working with Stanford applied physicist Calvin Quate (co-inventor of the scanning acoustic microscope) to develop a version of the STM that would overcome this difficulty.

Their answer was the atomic force microscope, a more sophisticated version of the stylus profilometers used since the 1950s. In AFM, a very small (a few millimeter) cantilever (originally made from aluminum foil, today from silicon nitride or other crystalline materials) is brought to within a few nanometers of the sample. The cantilever is usually weighted at the end with a small tip that interacts with the surface via van der Waals and other attractive and repulsive forces. These forces bend the cantilever in toward the sample or push it away. The degree of cantilever bending is thus a proxy for the height of (and other information about) the sample surface.

Commercialization and Coming Into Its Own
In the first AFMs, cantilever bending was detected by mounting an STM on the back of the cantilever. This proved finicky and oversensitive, so other detection schemes came to the fore. The most widespread is optical lever detection, in which a laser is bounced off a mirror on the back of the cantilever into a photodiode. Optical lever detection, combined with mass production of cantilevers, made AFM a much more user-friendly technique. This made it feasible for AFMs to be commercialized and sold to disciplines and industries where researchers wished to use, rather than build, a microscope. Up to 2000, commercialization happened largely through start-up companies affiliated with leading universities in the AFM field—for example, Park Scientific Instruments, founded by veterans of Quate’s group, or Digital Instruments, which worked with Paul Hanusa’s group at the University of California, Santa Barbara.

A Routine and Powerful Technique
These start-up firms and academic groups continued developing variants on the AFM, such as magnetic force microscopy (used in the magnetic storage industry), tapping mode AFM (well suited to soft samples such as polymers and biological materials), and force spectroscopy (a way to pull molecules apart using an AFM cantilever). Although most AFMs have considerably lower resolution than the STM, academic researchers have built a few AFMs capable of even subatomic resolution.
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 Microscopy; Nanoscale Science and Engineering.

**Further Readings**


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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