Electron Microscope Inventors Share Nobel Physics Prize

Ernst Ruska built the first electron microscope in 1931; Gerd Binnig and Heinrich Rohrer developed the scanning tunneling microscope 50 years later

THE Royal Swedish Academy of Sciences has awarded half of this year's Nobel Prize in physics to Ernst Ruska of the Fritz Haber Institute in West Berlin for "his fundamental work in electron optics and for the design of the first electron microscope." The other half of this year's prize will be shared by Gerd Binnig and Heinrich Rohrer of the IBM Zürich Research Laboratory for "their design of the scanning tunneling microscope."

Except for their ability to make atomic-resolution images of matter, the transmission electron microscope and the scanning tunneling microscope have little in common. Moreover, the inventions for which this year's prize was awarded came almost exactly half a century apart. The Swedish academy did not explain this unusual combination but it noted that in one case it was honoring a promise fulfilled and in the other a promising future.

Said the academy's announcement, "[t]he significance of the electron microscope in different fields of science such as biology and medicine is now fully established: it is one of the most important inventions of this century," whereas "[t]he scanning tunneling microscope is completely new, and we have so far seen only the beginning of its development. It is, however, clear that entirely new fields are opening up for the study of the structure of matter."

Ruska began his work as a graduate student under Max Knoll at the Berlin Technical University in the late 1920's. In those days, the theoretical foundation for the idea of an electron microscope had already been laid. Almost a century earlier, Sir William Hamilton had shown that it was possible to describe the paths of light rays through optical media and the trajectories of material particles through mechanical fields of force by means of identical mathematical equations. In 1926 and 1927 in Germany, Hans Busch considered the case of axially symmetric electrostatic and magnetic fields and showed that the focusing effect of these fields on charged particles was identical to that of a lens on light rays.

Wide World

Ernst Ruska. *"His was the step that got everyone going."*

The operation of an electron microscope is explainable entirely in terms of classical mechanics. However, to account for its high spatial resolution, which is the motivation for building an instrument, one must turn to quantum mechanics. In 1924, Louis de Broglie in France proposed that material particles also had a wavelike character with a wavelength inversely proportional to the particle's momentum. The 1927 electron diffraction experiments of Clinton Davisson and Lester Germer in the United States and of George Thomson and A. Reid in the United Kingdom confirmed this idea.

In direct analogy with the light microscope, the fundamental limit on the resolution of a microscope based on charged particles is this quantum mechanical wavelength. For an electron with an energy of 100 kiloelectron volts (keV), for example, the wavelength is about 0.1 angstrom. In their second electron microscope publication in 1932, Knoll and Ruska called attention to this promised atomic resolution by calculating a resolution limit for a 75-keV instrument of 2.2 angstroms based on their initial experiments with magnetic lenses. But, they cautioned, "[w]hether this high resolving power can be used to make visible structures of this order of magnitude cannot be decided in the present state of knowledge." The promise has been borne out. While the first commercial electron microscopes had resolutions near 100 angstroms, the newest instruments have resolutions of 1.7 angstroms or better.

Under Knoll, Ruska began studying the electron-optical properties of magnetic coils and found that the use of suitably designed iron encapsulation improved them considerably. In particular, it became possible to build a lens with a short focal length, which is a prerequisite for high magnification. In the fall of 1931, Knoll and Ruska submitted for publication a lengthy paper part of which described the electron microscope (although they did not use the term until their second paper) that had been built in Berlin. It achieved a magnification of 15, but the resolution was not even as good as that of a light microscope.

Ruska received his Ph.D. in 1933, while work was in progress on a second-generation instrument, which he described in a 1934 paper. Unlike the first instrument, which had a horizontal electron column, the second was vertical and resembled in appearance today's commercial electron microscopes. Its estimated resolution was 500 angstroms. When Ruska left the university to take a job with Siemens, his successors refined the instrument to the point where it actually did surpass the light microscope in resolving power.

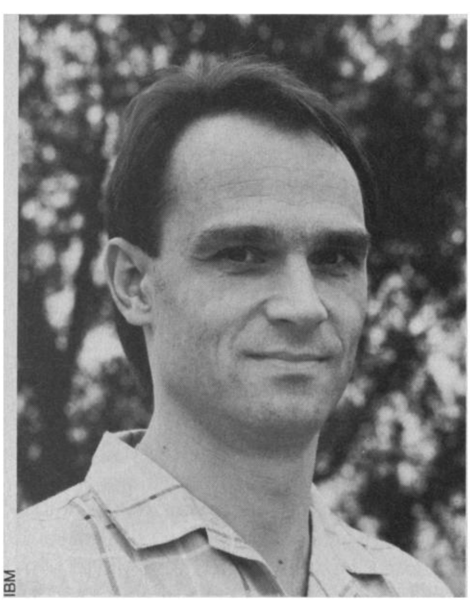
At Siemens, Ruska took part in the development of a commercial electron microscope, which nominally entered the market in 1939, although the advent of World War II surely did not help in assuring an immediate commercial success. In 1955, Ruska became director of the Institute for Electron Microscopy at the Fritz Haber Institute. He was made professor of electron optics and electron microscopy there in 1959. He continued to be a contributor to his field until his retirement from active research in 1972 at the age of 65.

An interesting aspect of the story is that Reinhold Rüdenberg, who was research director of the German company Siemens-Schuckert, actually applied for an electron microscope patent in Germany in 1931 before Knoll and Ruska's first paper on the subject. The German patent office did not grant a patent, but Rüdenberg did succeed in obtaining one in the United States, in the United Kingdom, and in France. Later, after an RCA group headed by James Hillier developed its own commercial electron microscope in 1942, Rüdenberg sued for patent infringement and won. With Ruska's receipt of the Nobel Prize, it would seem the U.S. patent office made a mistake.

The story of the electron microscope is actually much more complex than this capsule summary can indicate, and the contributions of many researchers were needed to turn the initial idea into a workable instrument. Nonetheless, as John Reisner of RCA recalls, "While electron-optics people knew of the idea after the work by Busch on electron trajectories, Ruska did it. It was tough technology, and his was the step that got everyone going."

Binnig and Rohrer began their work at the IBM Zürich Research Laboratory on the scanning tunneling microscope at the end of 1978, a half century after Ruska began his studies with Knoll. Binnig was fresh from a Ph.D. at the University of Frankfurt, where he studied superconductivity. Rohrer, who took his degree at the Swiss Federal Institute of Technology in 1960, had been with IBM since 1963. From the start, their aim was to find a way to solve some problems related to the electrical problems of thin oxide layers by means of local quantum mechanical tunneling of electrons.

By the late 1970's, solid-state physicists had a well-developed tunneling spectroscopy based on solid barriers only a few tens of angstroms thick rigidly sandwiched between the materials of interest. However, any information obtained was averaged over the area of the interface between the materials.



Gerd Binnig. *"The good lateral resolution was a surprise at the time."*

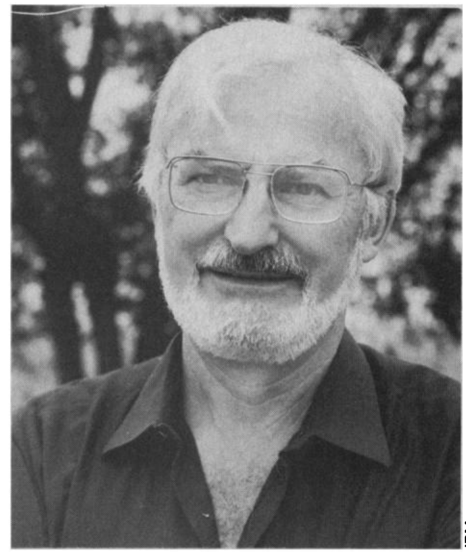
To obtain tunneling information that could be related to specific points on the interface, Binnig and Rohrer were led to the idea of tunneling through a vacuum. The idea was that a vacuum barrier would allow them to scan a fine metal tip over the surface, so that electrons tunneled across the narrow gap between the tip and the region of the surface near the tip.

Rohrer told *Science*, "We were quite confident. Even at the beginning, we knew it would be a significant development. The surprising thing is that it went so fast." The first successful experiment came in the spring of 1981, when the IBM group, which also included Christoph Gerber and Edmund Weibel, was able to resolve steps on the surface of calcium-iridium-tin ($CaIrSn_4$) crystals only one atom high. Ironically, the first attempt to publish the result failed, when a referee found the paper "not interesting enough."

The major issue that had to be overcome to make the scanning tunneling microscope work was the elimination of vibrational noise. Because of the exponential dependence of the tunneling current on the distance between the surface and the tip of the scanning probe, the vertical position of the tip had to be controllable to a fraction of an angstrom. As noted by the Royal Swedish Academy, the best known earlier attempt to build a scanning instrument was that of Russell Young and his co-workers at the National Bureau of Standards in the early 1970's.

The NBS investigators obtained a vertical resolution of 30 angstroms and a lateral resolution of 4000 angstroms with high voltages and the tip far enough away from the surface so that the dominant process was field emission of electrons from the tip rather than tunneling. They were unable to solve the vibrational problems that would allow them to operate at low voltages of less than 1 volt and a gap of only a few angstroms before the project was cancelled.

Binnig and Rohrer, who did not learn of the NBS effort until they filed a patent application for their instrument, initially attacked the problem with a cumbersome appearing two-stage isolation strategy. The vacuum chamber containing their apparatus sat on a stone table isolated from the laboratory building by inflated rubber tires. Within the vacuum chamber, the apparatus was levitated above a bowl of superconducting lead by permanent magnets. The scanning tunneling microscope generated a topographic image of the surface from the vertical position of the tip as it scanned across the surface in a raster pattern at a fixed tunneling current. Precise movement of the tip in all directions was accomplished by means of piezoelectric ceramics, which contract or expand when voltages are applied.



Heinrich Rohrer. *"The surprising thing is that it went so fast."*

Since the initial effort, the instrument has undergone several stages of refinement. A contemporary scanning tunneling microscope (except for the vacuum chamber) fits in the palm of one's hand and is capable of a vertical resolution of 0.1 angstrom. The best lateral resolution of about 2 angstroms is made possible by the natural formation of "mini tips" only a few atoms wide on the otherwise rather blunt metal tip. Recently, researchers at IBM and at AT&T Bell Laboratories have shown with the field ion microscope that it is possible to prepare tips only one atom wide.

In the short time since the invention of this instrument, at least 50 scanning tunneling microscopes have made their appearance in laboratories around the world and two companies have begun making commercial versions. The instrument works in a variety of environments, including ultrahigh vacuum, air, water, and cryogenic fluids. While it has been used on biological materials, its major use so far has been to make atomic-resolution images of the surface structure of semiconductors and metals, and in so doing it has contributed to the resolution of long-standing controversies in surface science.

A new version of the instrument developed by Binnig, Gerber, and Calvin Quate of Stanford University, called the atomic force microscope, permits imaging the surfaces of insulating materials. There has also been substantial progress toward the initial goal of obtaining localized spectroscopic information. Finally, some groups are pursuing the possibility of using the instrument to fabricate ultraminiature structures. ■

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