Origin of the Electron Microscope

The history of a great invention, and of a misconception concerning the inventors, is reviewed.

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In 1878, Ernst Abbé (*1*) proved that the resolution of the optical microscope is limited by the wavelength of light. This meant that even when immersion optics and ultraviolet light are used, the smallest detail that can ever be resolved optically is of the order of 100 millimicrons, or 10 angstroms.

No means were conceived of resolving finer detail until two discoveries were made: (i) the wave properties of the moving electron, postulated by de Broglie, on theoretical grounds, in 1924 (*2*) and verified by Davisson and Germer (*3*) and by Thomson and Reid (*4*) in 1927; and (ii) the discovery by Busch (*5*) in 1926-1927 of the analogy between the effect of a magnetic coil—the focusing coil used since 1899 (*6*)—on an electron beam and the effect of a convex lens on a light beam.

Since the wavelength of the moving electron is smaller by many orders of magnitude than the shortest wavelength of light, these discoveries made it conceivable that extremely small objects might be imaged with an electron beam and electron lenses.

Development of Electron Microscope by Knoll and Ruska

The first electron microscope was built and publicly demonstrated in 1931 by Max Knoll and Ernst Ruska, working at the High Tension Laboratory of the Technical University (Technische Hochschule), Berlin, under A. Matthias (*7*). The development of this microscope was an offshoot of their work on demountable cathode-ray oscillographs, which were used for the investigation of lighting and other surge phenomena. At that time, only continuously pumped, high-voltage (30 to 75 kv) cathode-ray tubes could be used for such investigations, since sealed-off tubes had still too low a writing speed. Pioneering work in the development of this type of demountable tube had been done by Dufour (*8*), Rogowski (*9*), and Norinder (*10*).

Matthias, the head of the High Tension Laboratory, held two positions. At the Technical University, Berlin, he taught electrical engineering. At the same time he was the director of the Studiengesellschaft für Höchstspannungsanlagen, a research organization of the German public utilities and of the industrial companies that supplied gear for these utilities. The High Tension Laboratory and the Studiengesellschaft complemented each other in the investigation of voltage surges, which frequently damaged the high-tension lines and the switchgear and transformers operating in conjunction with these lines. The High Tension Laboratory supplied the research tools and the laboratory testing facilities, while the Studiengesellschaft supplied the funds and made measurements both directly on the distribution lines and at special lightning research stations. One of these stations was located near Berlin, and another was located on Monte Generoso, a high Alpine peak reported to have the highest incidence of lightning in Europe.

For this lightning and surge research and the extensive testing of components, high-speed oscillographs were indispensable. The first of these oscillographs was built by Gabor (*11*) between 1924 and 1927, in fulfillment of the requirements for his doctoral thesis. In 1927 Max Knoll joined the Studiengesellschaft; in 1928 he transferred to the Technical University, where he became lecturer and head of the Electronics Laboratory established for him by Matthias. Here he directed basic research on electron beams and on cathode-ray oscillographs, working in close cooperation with a small group of selected students.

Knoll divided the research into various fields of investigation, each field forming the subject of a student's research work, which would culminate in his doctoral thesis. The researchers and their fields of investigations were as follows: H. Knoblauch, the cold cathode electron source (*12*); B. von Borries, photographic recording methods (*13*); H. G. Lubszynski, electromagnetic shielding (*14*); M. M. Freundlich, hot-cathode electron sources and trigger and time-base circuits (*15*); and E. Ruska, beam focusing (*16–18*).

Ruska started his research in 1928 by investigating the focusing coil used in most high-voltage oscillographs and first proposed by Wiechert (*6*). Ruska tested Busch's theory in painstaking experiments. Instead of imaging the cathode electron-emitting spot, as Busch had done, he imaged a small anode aperture. By using a uranium glass plate instead of a phosphor screen, he obtained a sharper image, avoiding loss of resolution due to phosphor graininess. In numerous measurements he varied the anode-to-screen distance, the ratio of object distance to image distance, and the cathode potential. The measured focusing currents agreed quite well with Busch's theory.

Knoll and Ruska took a significant step forward when they extended the iron encapsulation of the focusing coil first used by Gabor (*11*). Gabor limited the length of the magnetic field of the coil by surrounding it with an iron cylinder and top and bottom end plates. Knoll and Ruska added to this an inner cylinder, leaving only a short unshielded gap of approximately 10 millimeters. They thereby shortened the magnetic field and reduced the number of ampere-turns required for a given focal length. The results of Ruska's measurements are reported in his graduate thesis, submitted in 1929, and in a paper by Ruska and Knoll (*19*) submitted for publication on 28 April 1931.

After making the early measurements, Knoll and Ruska changed to objects that could be defined better than a round aperture. They used T-shaped apertures, multiple apertures, and metal meshes. These experiments proved that the aberrations of magnetic lenses could be made very much smaller

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than Busch and practically everyone else had expected, and that good resolution was indeed obtainable (*20*). Having obtained images of very high optical quality with single magnetic lenses, they proceeded to build an "electron microscope" consisting of two magnetic lenses with an intermediate image. Using two standard focusing coils and other available components, they assembled the microscope shown in Fig. 1.

Though the magnification thus obtained was modest, the setup proved the principle. Between February and May 1931 the microscope was shown to many interested scientists from the Technical University as well as from industrial laboratories. On 4 June 1931, Knoll delivered a lecture at the Crantz Colloquium, where he showed on slides the experimental setup and some of the pictures obtained. These colloquia were held at regular intervals by Crantz, who taught physics at the Technical University.

Knoll and Ruska followed up their demonstration with a paper, "Beitrag zur geometrischen Elektronenoptik" (*21*), which was submitted for publication 10 September 1931. This paper, one of the most comprehensive in electron optics, describes the setup and the various experiments, showing both single and double magnifications of T-apertures, meshes, and multiple apertures, besides going deeply into the theory of electron optics.

In a follow-up paper, entitled "Das Elektronenmikroskop" (*22*), submitted for publication 16 June 1932, Knoll and Ruska showed magnifications of molybdenum meshes of 150 and reported magnifications of 400. They used a condenser lens between the anode and the object. They realized that high magnifications can be achieved only with short object distances, since the available height of the microscope is limited. Only with lenses that have not only short gaps but also small diameters can this be accomplished. They proposed, therefore, to build the magnetic lens into the wall of the vacuum chamber and to use pole pieces to form lenses with a diameter no greater than the diameter of the electron beam (*22, 23*).

A magnetic lens with interchangeable, very narrow pole pieces is described in Ruska's doctoral thesis (*18*), submitted 31 May 1933. This design is still in general use; most commercial electron microscopes use magnetic lenses of a design practically identical with it.

When Knoll left the High Tension Laboratory in 1932, Ruska continued to work on the electron microscope and built the first "supermicroscope" (Fig. 2). In his paper (*24*), which he submitted for publication 12 December 1933, he showed pictures in which he had achieved magnifications of 8000 and 12,000. Knoll and Ruska had thus developed single-handed the electron microscope to the point where it surpassed the resolution of the optical microscope.

Rüdenberg's Part in Development of the Electron Microscope

In two publications (*25*), the late Reinhold Rüdenberg is called the inventor of the electron microscope. Gabor (*26*) and Mulvey (*27*), each of whom wrote an excellent history of the development of the electron microscope, say, "At least in patent law Rüdenberg is the inventor of the electron microscope." Actually, Rüdenberg, though the first to apply for patent rights, did not contribute directly or indirectly to the early development of the electron microscope.

Knoll and Ruska had studied thoroughly the lens effect of the magnetic

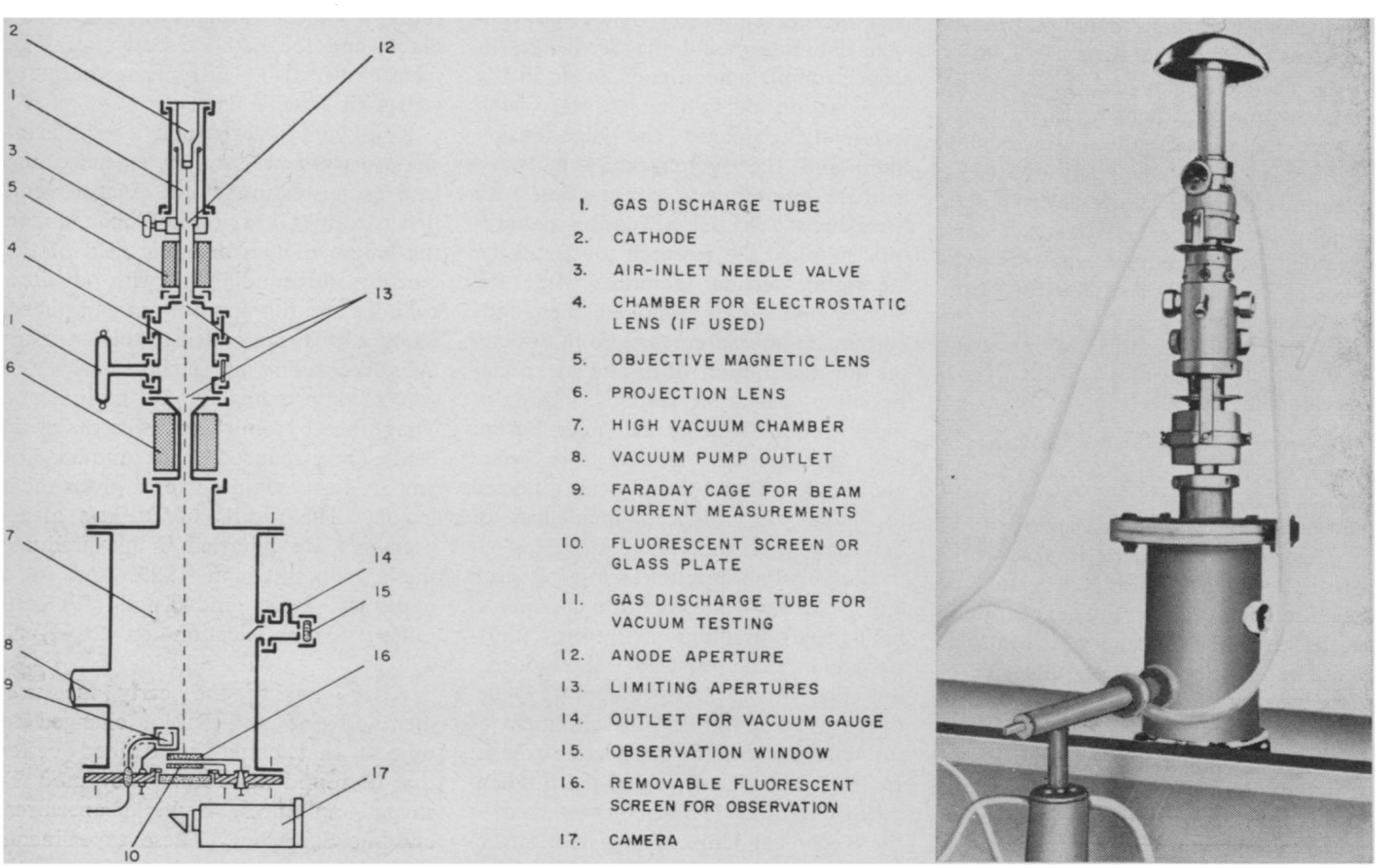

Fig. 1. The first electron microscope, developed by M. Knoll and E. Ruska in 1931. (Left) Functional diagram; (right) photograph.

coil, had built a microscope in which two lenses were used in series, had shown it to many interested scientists, and were putting the finishing touches to the paper in which their findings were to be presented, at a public lecture long scheduled for 4 June 1931, when Rüdenberg, director of the research department of Siemens Schuckert Werke, filed patent applications with the German Patent Office on 31 May 1931. These applications led to the granting of three German patents (*28*) and three non-German patents based on the German priority (*29*). Rüdenberg filed four additional applications with the German Patent Office between June 1931 and March 1932 (*30*). These, together with the original applications, led to the granting of four additional non-German patents (*31*). One more patent application was filed after the priority of the three original German patents had expired (*32*).

The original Rüdenberg patent applications, filed on 31 May 1931, expound the principle of combining several electron lenses, either electrostatic or electromagnetic, to obtain magnifications surpassing those obtainable with optical microscopes. The essential ideas contained in these three patents are expressed in the following excerpt taken from patent DBP 895,635 (the translation is mine).

> The invention relates to an arrangement whereby objects are imaged on a magnified scale by means of electron beams and by means of electrostatic or electromagnetic fields (electron lenses) that influence the flow of the electrons. In accordance with the invention several electron lenses influence the electron beam and together effect a higher magnification in the manner of a microscope or telescope. The electromagnetic electron lens and the negatively charged electrostatic electron lens are, as described before, the equivalent of the convergent lens in optics, while the positively charged electrostatic electron lens is the equivalent of the divergent lens. By combining such lenses it is, therefore, possible to imitate for electron beams any of the devices well known in optics that make use of convergent or divergent beams. It is, furthermore, possible to build in this way a microscope or a telescope that uses electron beams directly or after a reflection. By combining several lenses in the manner of a microscope or a telescope, it is possible to obtain an especially high image magnification. The use of electron beams presents an especially great advantage, since such microscopes or telescopes permit a magnification greater, by several orders of magnitude, than optical instruments, whose resolution is limited by the wavelength of light. This limitation does not exist for lenses working with electron beams.

Since these patents were not published prior to the granting of the French patents, the information they contain did not become available before December 1932—that is, after Knoll's lecture and after the publication of several papers on the electron microscope by Knoll and Ruska. Though Rüdenberg attended Knoll's lecture on 4 June 1931, he did not take part in the discussion.

Rüdenberg published a short letter in *Die Naturwissenschaften* in 1932 (*33*), in which he said: "Work has been proceeding for several years within the Siemens Group on the use of magnetic or electrostatic fields in microscopes or telescopes using electron or ion beams. . . . Though basic patents were filed in May 1931, publications are not intended before the practical realization has been advanced further."

Again, no technical information is

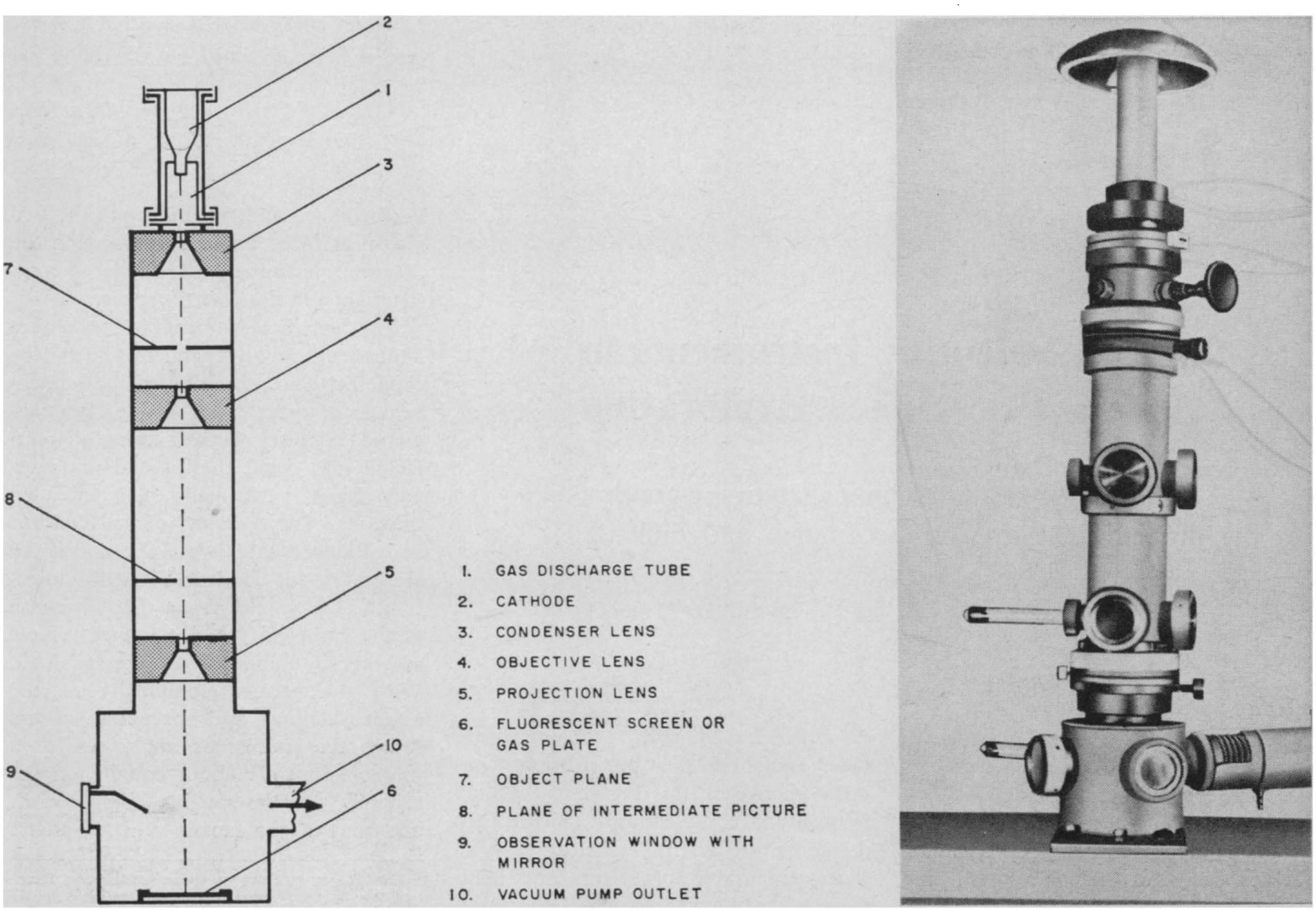

Fig. 2. The first supermicroscope, developed by E. Ruska in 1933. (Left) Functional diagram; (right) photograph.

given. Results of the research mentioned have not been published, either by Rüdenberg or by any of his collaborators. The well-known development of the commercial Siemens electron microscope was undertaken by Ruska and von Borries (after they had left the High Tension Laboratory) in a then newly established department of Siemens and Halske, a company concerned with electrical measurement equipment and quite independent of Siemens Schuckert, whose field is electrical power equipment. Their work was completely independent of Rüdenberg's work. In 1943 Rüdenberg wrote a letter to the editor of the *Journal of Applied Physics* (*34*), in which he describes extensively the contents of U.S. patents 2,058,914 and 2,070,319. He claims a priority of 31 May 1931, though the more sophisticated patent applications were filed later.

Summary

Knoll and Ruska developed the first electron microscope during their research to improve the demountable high-voltage cathode-ray oscillograph. Starting with the investigation of the well-known focusing coil, they progressed step by step until, in 1933, Ruska could show the first pictures with resolutions beyond those obtainable with an optical microscope. Reinhold Rüdenberg is sometimes called the inventor of the electron microscope because he was the first to apply for patents on it. Actually, he did not contribute to the development of the first microscope. When he filed his first patent applications, Knoll and Ruska had already built the first model and had shown it to many interested people (*35*).

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15. M. Freundlich, theses (1928, 1929, 1933, respectively).
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Scientific Instruments in Space Exploration

As our mission capability increases, the problems become more complex and difficult.

Raymond L. Heacock

Our rapidly expanding space technology is making possible achievements that men could only dream about a few years ago. The future offers still more promising opportunities for expanding our knowledge of the solar system and the universe. The achievements to date were not easily accomplished. Many complex and difficult problems were faced and solved. As our mission capability increases, the problems become even more complex and difficult. In designing the scientific instruments we face comparable problems, and solutions must be forthcoming if the progress made to date is to be sustained. Performance and reliability are the two measures to be applied in assessing the potential usefulness of a scientific instrument for missions in space.

The early achievements in space were almost entirely dependent upon the capability and reliability of the launch-vehicle system. Had the early Vanguard satellites been successfully injected into orbit, they would undoubtedly have performed their intended missions. The successes of the Explorer and Pioneer satellites were correlated almost one-for-one with successful injection. This relationship existed because of the complexity of the launch-vehicle system as compared to the payload. With the greater complexity of the larger satellites and spacecraft in use today, the success or nonsuccess of a mission depends about equally on the reliability of the satellite or spacecraft and that of the launch-vehicle system.

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