THE ELECTRON MICROSCOPE—ITS PAST AND PRESENT

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The limit of vision of the unaided human eye is about 0·1 mm. This limit was pushed downwards by a factor of 1,000 (to about 1000 Angstroms or ·0001 mm.) by 300 years' work on the optical microscope. However, within the incredibly short time of the last 35 years, the electron microscope has been able to further extend this limit of human vision by another 1,000 times, i.e. down to about 1 Angstrom or atomic dimensions. Starting as an unexpected child of high voltage cathode ray oscilloscope, development of the apparatus has been very rapid. The basic principle of the instrument is to use electrons as the image-forming beam and symmetrical electrostatic or electromagnetic fields as lenses. For several years after the discovery, both electrostatic and electromagnetic instruments were built side by side; however, almost all modern instruments today are fitted with electromagnetic lenses, as these have been found to give better performance. Although basically the operation of the instrument is simple, a large amount of highly complicated instrumentation had to be incorporated in the microscope, before the present state of performance could be attained. This monumental achievement of the present century has been possible due to the work of a large number of academic scientists, technologists and engineering concerns in Europe, U.S.A. and Japan. This article contains a historical account of the important steps and the advances made in different countries in the development of this basic scientific instrument.

INTRODUCTION

It is doubtful, if any instrument invented by man has done more for the benefit of human beings than the common microscope. Diagnosis of diseases, advances in biology, chemistry, pathology, metallurgy and many other sciences would have been impossible without this instrument. During the 300 years since the first microscope was invented, physical research has brought this instrument almost to perfection. Starting with the crude apparatus of Leeuwenhoek,[1] a variety of instruments have been produced, e.g. the polarizing, the fluorescent, the ultra-violet, the phase and the interference microscopes, each built for a special purpose. However, the ultimate limit of vision attained with all these instruments is limited by the length of waves with which they operate. The shorter the wavelength, the smaller

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is the object that can be seen. The smallest dimensions, resolved by a microscope, approximately equal one-half of the wavelength of light in the medium in which the object is embedded. With visible light as the source of radiation and an oil immersion lens, the best optical microscope can resolve dimensions of the order of 2000 Angstroms (two ten-thousandth parts of a millimetre). Using still shorter but invisible ultra-violet rays, one can go down to specimen details as small as 1000 Angstroms. No amount of magnification by the microscope can reveal objects smaller than this, because the limitation here is not due to any imperfection in the instrument, but due to the coarseness of visible light, compared to the objects to be seen.

This limitation of an optical instrument that depended on light waves was recognized by Abbe,[2] in whose hands the microscope reached its perfection. He wrote in 1878 that henceforth the ultimate resolving power of a microscope would be decided, not by the perfection of the instrument but by the size of the light waves, and that further improvements in extending the frontiers of human vision could only come by the use of waves of still shorter length. This discovery made him sad rather than elated. He said that it was poor comfort to hope that human ingenuity might, one day, develop such instruments, although they would have little in common with the existing microscope except the name. More than 50 years (1878–1931) were to pass, before human ingenuity could actually develop such an instrument and overcome the limitation imposed by the finite size of the visible light rays.

During these years, although we could not see them, many different lines of investigations brought home to us evidence about the existence in Nature of different living objects, particles and molecules which were smaller in size than the limit of 1000 A.U. reached by the ultra-violet microscope. X-rays were discovered by Rontgen in 1896.[3] The work of Bragg,[4] Laue and others,[5] on the diffraction of X-rays by the crystals, established the wave nature of these rays and the extreme shortness of their length (0·1 to 1·0 A.U.). The X-ray diffraction analysis revealed arrangements of atoms within the crystal and thus enabled us to reach indirectly the dimensions of the order of 1 A.U. but there was no means of visualizing anything smaller than 1000 A.U. in size. With the discovery of the electron microscope, this gap has now been bridged and one can see directly objects in the size range of 1000 A.U. (reached by ultra-violet microscopy) to 1 A.U. (reached indirectly from X-ray diffraction). This article traces the important steps in the discovery and development of the electron microscope.

EARLY WORK ON ELECTRON LENSES AND MICROSCOPES

The History of Science is seldom logical. The natural development of the electron microscope would have been: (*a*) the discovery of the wave nature of the electrons, (*b*) the discovery of the lens properties of magnetic and electrostatic fields, followed by (c) the gradual development of the electron microscope based on these sound ideas. However, in actual practice, the discovery of the electron microscope and its development for many years had little to do with the wave nature of the electron. It was more concerned with the corpuscular aspect of the electron.

The history of electron optics starts with the discovery of the cathode rays. Hittorf,[6] Goldstein,[7] Crookes,[8] Hertz,[9] Lenard,[10] Perrin,[11] Thomson[12] and Wiechert,[13] during the last quarter of the nineteenth century, established the corpuscular nature of these rays and showed further that these could be concentrated by the use of long solenoids, producing axial magnetic fields. During these investigations, the corpuscular nature of the electron was firmly ingrained in the minds of scientists and engineers. The cathode-ray tubes based on these rays were in great use in many laboratories in Europe towards the beginning of this century. These early tubes used gaseous discharge with cold cathodes; the hot filament in the cathode-ray tube was introduced later by Wehnelt.[14] Some of these cathode-ray tubes were operated at high voltage for better intensity. The electron microscope was a direct descendant of the high voltage cathode-ray oscilloscope.

Gabor, then a young engineer working with Prof. Matthias in the Technische Hochschule, Berlin, developed a 50 kV cathode-ray oscilloscope.[15] He used an internal four-plate camera and iron-shrouded concentration coils to restrict the cathode rays from spreading and to form a focused spot on the screen. Although this instrument had all the ingredients of the future electron microscope, it never occurred to these investigators that such an instrument could form electron images. In fact the concentration coil had been in the hands of many brilliant experimental physicists for over 25 years (1899–1925), but no one realized the true significance of the concentration coil, that it was really an electron lens.

On the other hand, Hamilton[16] enunciated his famous theory of the equivalence of optics and dynamics in 1828. For nearly a hundred years theoretical workers had been using this relation, without enquiring, if wave optics and particle dynamics were identical, then what was the equivalent of a lens in the case of particles ?

It was left for Busch,[17, 18] to show theoretically how a divergent beam of electrons can be 'bundled' together by making it pass through a current-carrying coil. He was the first to develop basic theories about the lens action of symmetrical magnetic fields and may, therefore, be said to be the real founder of geometrical electron optics.

The theoretical work of Busch was a great inspiration to the workers on cathode rays. Ruska, then a young engineer, working for the doctorate degree in the Technische Hochschule, Berlin, set about the experimental verification of the theory of Busch, on the focal length of magnetic lenses.

The apparatus used by Knoll and Ruska consisted merely of a cold cathode discharge (operating at 75 kV), the usual concentration coil whose focal length was to be measured, and a glass plate to act as a fluorescent screen, on which the image appeared and which could be photographed from outside. It was soon apparent that it was inconvenient to use the ill-defined gas discharge as the object. An anode with a small bore irradiated by the electron beam was much more convenient, so that the spot on the fluorescent screen remained smaller than the image of the cathode. Only in this way it was possible to be sure about the image formation; one could then estimate the focal length of the concentration coil by measuring the object and the image distances and thereby verify Busch formula. These investigations on the focal length of the magnetic concentration coils formed the basis of the thesis submitted by Ruska[19] and were also published by Ruska and Knoll in 1931.[20] The paper contained two electronic images of an aperture formed at a magnification of about unity.

In their first paper Ruska and Knoll did not emphasize the aspect of image formation by the concentration coil and of its implications. In their next papers Knoll and Ruska,[21, 22] described the construction of the first two-stage compound microscope. It consisted of the cold discharge as the source of radiation, two magnetic lenses (not yet iron-enclosed), an electrostatic grid lens and three apertures. The image could be observed on the usual fluorescent screen as well as photographed by an external camera. The paper contained images of apertures and of the emitting cathode, at magnifications varying from 10–17 times, so that the apparatus was no better than an electronic reading lens. Some improvements were soon effected in this instrument by enclosing the coils of the magnetic lenses in an iron-casing. By this method, the magnetic fields were confined to a narrow region along the axis, and the focal lengths of the lenses were therefore shorter. This device led to a better focusing action of the lenses, so that the condenser lens could irradiate the object more intensely, and the other two lenses gave a total magnification of 400 times. Soon afterwards Knoll, Houtermanns and Schulze[23] also constructed an apparatus with magnetic lenses for forming images of cathode surfaces.

Although the wave aspect of the electron was established a few years earlier by de Broglie,[24] it did not play any significant part in the development of the microscope so far. Only after the microscope was built, the help of de Broglie's conception was invoked to estimate the theoretically attainable resolution limit of the electron microscope. Based on the Broglie wavelength for 75 kV electrons and an imaging aperture of 0·02 radians, the theoretically attainable resolution limit of the electron microscope was estimated to be 2·2 A.U. This indicated a possible improvement by a factor of 1,000 over the light microscope limit.

In 1933, Ruska built a new supermicroscope.[25] A cold cathode gas discharge tube was still used as the source of electrons and the final image formed on a fluorescent screen was photographed through a window by means of an external camera. The microscope had a condenser lens for irradiating the aperture used as the object. This was followed by two magnifying lenses which were now provided with pole-pieces placed within the high vacuum. The pole-piece lenses which now form the heart of all magnetic microscopes were patented by Borries and Ruska in the previous year.[26] The use of pole-pieces immediately brought down the focal length from a few centimetres to a few millimetres and magnifications of the order of 8,000–12,000 could be achieved. This instrument was called supermicroscope because for the first time the resolution of the light microscope was exceeded.

But, although in theory the resolution expected was excellent, grave doubts arose as to the practical utility of such an instrument. Most of the organic specimens introduced into the microscope were found to be severely damaged by the vacuum and the electron irradiation. A rotary specimen stage with several specimens was provided by Ruska in his microscope so that as soon as one specimen was destroyed another could be brought into the beam. No solution of the problem of specimen damage was yet in sight.

Marton in the University of Brussels got interested in the electron microscopy since the early work of Knoll and Ruska. In 1934, he had already constructed a magnetic transmission electron microscope operating at 35 kV.[27] This microscope was mounted horizontally in contrast with Ruska's vertically mounted apparatus of 75 kV. This instrument had several improved features. Marton was the first to obtain an electron micrograph of a biological specimen and to record directly micrographs on photographic plates introduced into the microscope column.[28] With these improvements it was now possible to examine specimens more conveniently and the exposures needed were much reduced with internal photography. Marton's improved apparatus had the maximum operating voltage of 90 kV and showed resolution better than that of the light microscope, in spite of relatively low electronic magnification of 500 to 700 times. In order to prevent damage to the specimen during electron irradiation, Marton impregnated the sample by osmium salt. This also helped to provide better image contrast. Osmium impregnation of biological samples has now become an almost universal practice in electron microscope techniques.

Meanwhile Ruska having left the High Voltage Institute in 1933, his supermicroscope was operated first by Driest and Müller[29] and then by Krause,[30] who successfully got with it a resolution of about 500 A.U. Beischer and Krause[31] also showed with the supermicroscope a lattice spacing of less than 450 A.U. in an etched silver foil.

Simultaneously, with these practical developments, attention was also paid to the theoretical aspects of electron optics, viz. lens errors, limits of resolution attainable with the electron lenses (Glaser,[32, 33] Scherzer[34] and Marton[35]).

Towards the end of 1936, the original misgiving about the practical utility of the new instrument was somewhat weakened and von Borries and Ruska could persuade Siemens and Halske (Berlin) to undertake commercial development of the electron microscope. Finally von Borries and Ruska came together in the guest laboratory of electron microscopy set up by Siemens and Halske and continued further development of the instrument. In 1938, they finished the construction of a complete laboratory model[36] and this was followed a year later by the production of the first commercial electron microscope of the magnetic type by the Siemens Co. This microscope had a resolution of about 100 A.U. In this microscope, the magnetic lens coils and the filament used currents from storage batteries and the coils were water-cooled. The high-voltage unit, consisting of conventional transformer rectifier system, was in a separate assembly so as to protect the microscope from the 50-cycle radiation. The filament battery was mounted on an insulator within the high-voltage shield above the microscope. Control of the filament and the grid voltage was by the use of insulated knobs projecting through this shield. The evacuation was taken care of by means of a gas heated mercury diffusion pump, connected to the microscope, through a freezing trap. The total length of the microscope from the filament tip to the photographic plate was about a metre and the objective and the projector magnified 100 and 200 times respectively.[37] With the construction of the first commercial electron microscope, the most serious crisis in the life of the electron microscope was over. Within the next 10 years electron microscopy spread in most of the technically advanced countries and many other industrial concerns besides Siemens took up commercial production of this instrument.

Two other developments in the German laboratories during this early period deserve special mention. Boersch,[38, 39] in the A.E.G. laboratories in Berlin, showed that the Abbe principle of image formation was also applicable in the imaging by the electrons. This opened up the possibility of using the electron microscope as a micro-diffraction camera, by selecting only a part of the secondary image. This idea was later utilized by Le Poole in his selected area diffraction. Von Ardenne[40] pointed out the importance of the alignment correction in electron microscopy. He built a microscope in 1940 in which he incorporated nearly all constructional features conceivable at that time. It was called 'the Universal Microscope'; it was suitable for bright field, dark field and stereo microscopy. The maximum magnification of it was 50,000 and with this complicated instrument he demonstrated a resolution of 30 A.U., which was a record at that time. Von Ardenne proposed the scanning microscope developed further by Zworykin, Hillier and Snyder

(1942) and also suggested the X-ray shadow microscope which was realized by Cosslett and Nixon in England in 1951.

The general design of the microscope as adopted in the instruments constructed about this time is typified by the schematic diagram (Fig. 1). It had a self-biased electron gun consisting of a hot filament surrounded by a grid shield (G) and followed by the apertured anode (A). The filament was maintained at a high negative potential and the anode and the rest of the instrument were at the earth potential. The grid cylinder was maintained at a few hundred volts negative with respect to the filament. The electrons

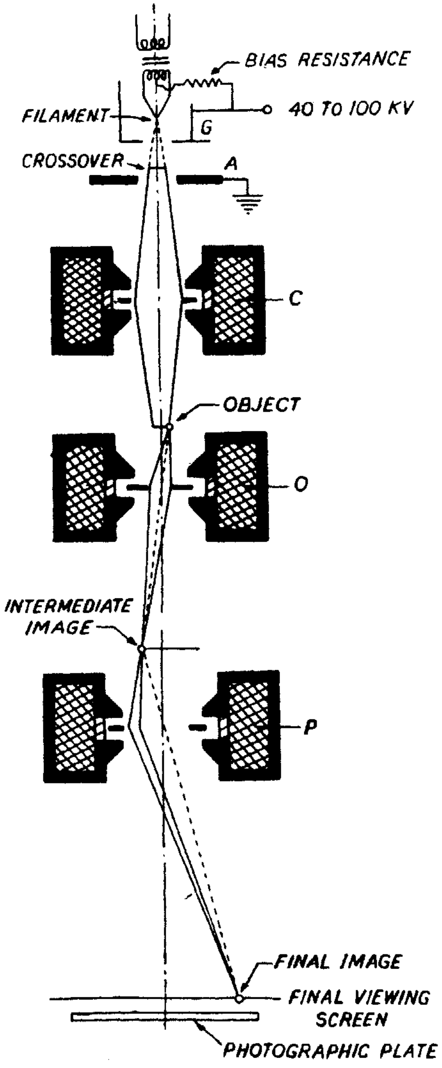


FIG. 1. Ray-diagram of the electron microscope.

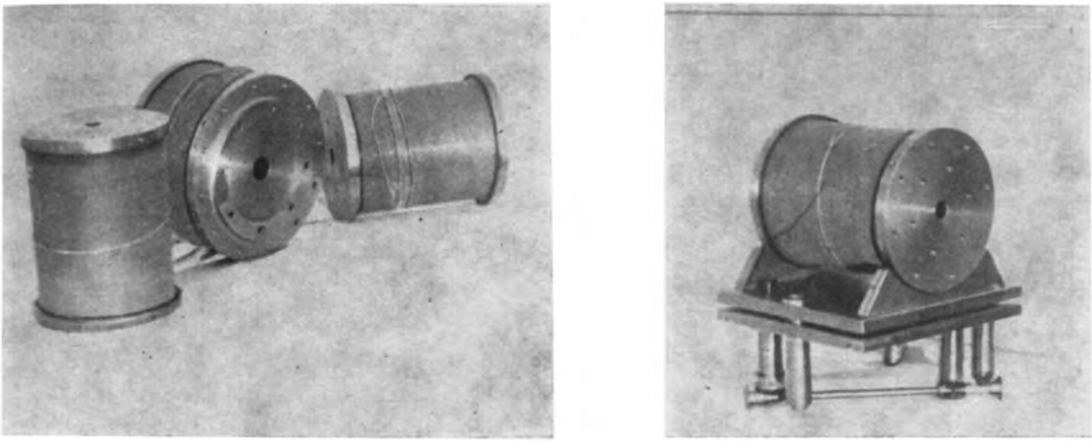
from the gun were concentrated by the condenser lens (C) on to the specimen. The objective (O) produced a highly magnified electron image, which was further enlarged by the projector (P). The image formed on the fluorescent screen could either be visualized directly or recorded on a photographic plate.

ELECTRON MICROSCOPY IN OTHER COUNTRIES

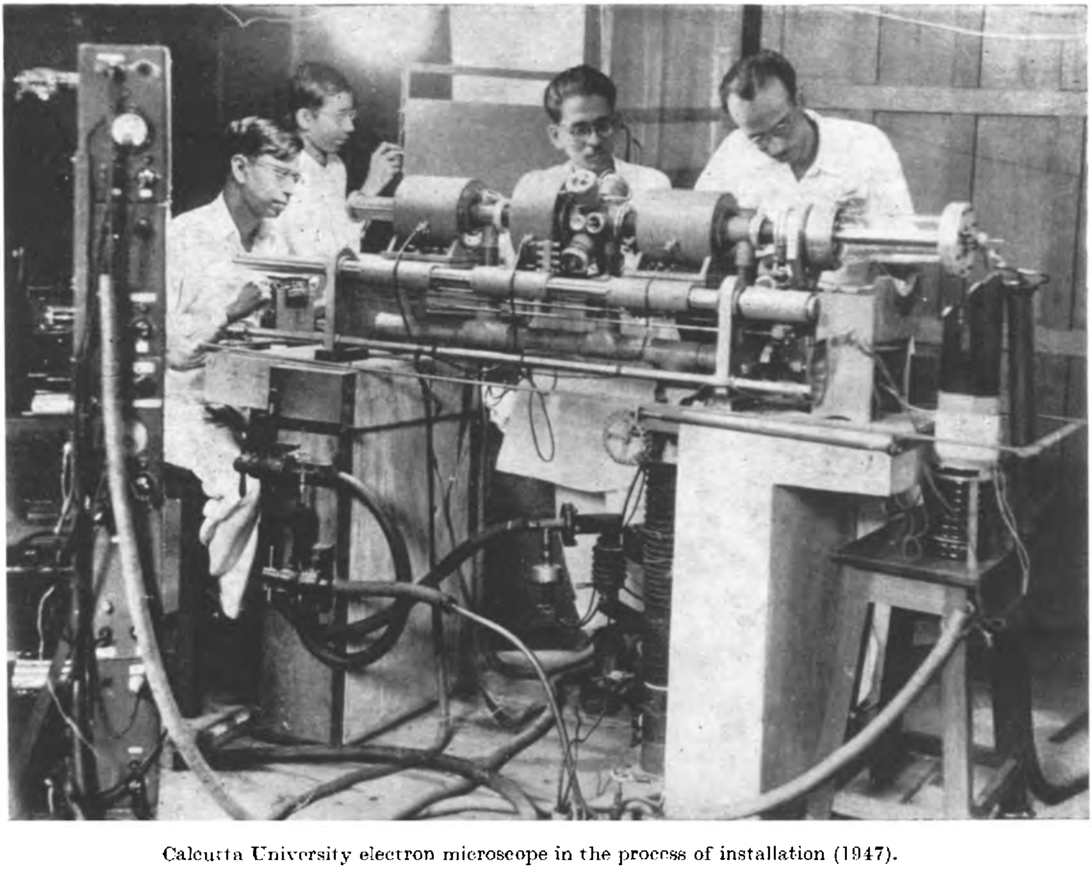
The production of commercial electron microscopes has been discussed in the next two sections. Here we consider only the developments in different universities or technological institutions of different countries.

The electron microscopy in America owes much to the initiative of Prof. Burton of the University of Toronto, Canada. He paid a visit to Berlin at the time when Borries and Ruska had developed their electron microscope. On return to Canada, he started experiments in electron optics in his own laboratory. Two of his students, Albert Prebus and James Hillier, built the first electron microscope in the continent of America (45 kV, 200 A.U.).[41] An improved version of this instrument was built later in the same university in 1944. Burton's student, Prebus, joined Ohio State University, where he built another instrument of this design.[42] Dr. Hillier joined the R.C.A. company and helped in the development of the R.C.A. instruments described later. An electron microscope of the same general design was also constructed in the laboratories of Eastman Kodak Co. at Rochester by C. E. Hall in 1942. Another instrument which was not a commercial one was built by Prof. Marton at Stanford University (100 kV, 50 A.U.). This instrument had double condensers and three-stage magnification.[43]

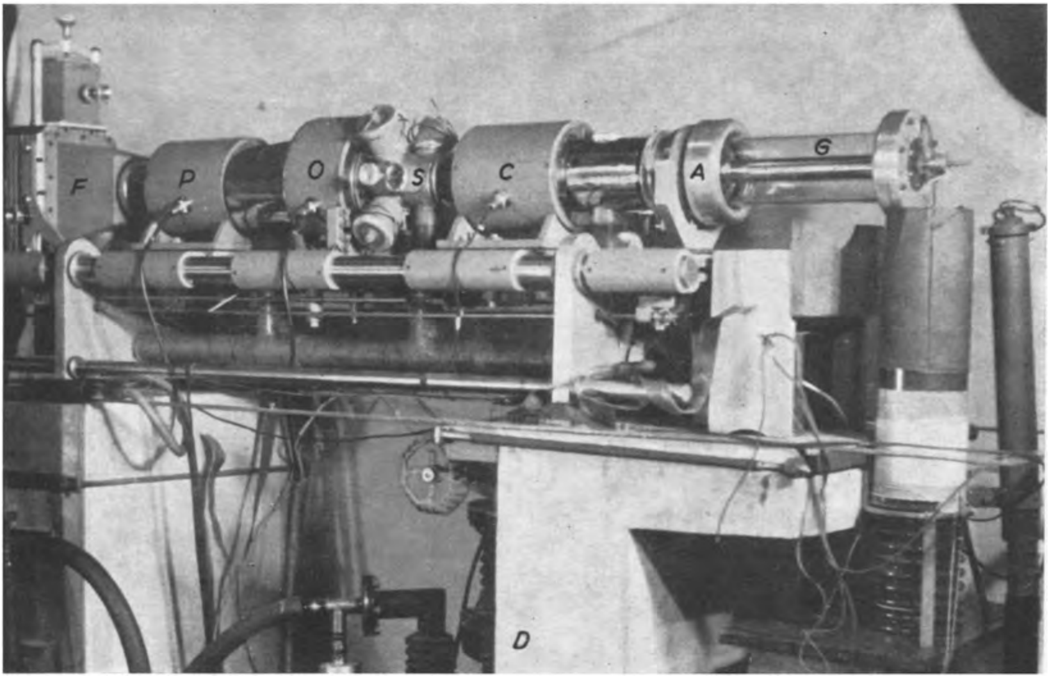
A very successful instrument (150 kV, 25-30 A.U.) was built in 1944 by Dr. Le Poole at the Institute for Electron Microscopy, Delft, Holland.[44] The instrument was in operation for a month, when it had to be taken apart and hidden in order to prevent its being carried away by the enemy. After liberation, the instrument was reassembled and put back to operation. An important improvement over the previous instruments was the introduction of a new lens—called the intermediate lens—between the objective and the projector lenses. The objective and the projector were now operated at fixed magnifications and the total magnification could be varied continuously from 6,000 to 80,000 times, by varying the current in the intermediate lens. There was no necessity of the change of pole-pieces. A fourth lens of large bore—called diffraction lens—introduced between the objective and the intermediate, could cover the magnification range 1,000 to 6,000 thus overlapping the optical domain. With the help of this extra lens, it was also possible to switch over very easily from electron microscopy to electron diffraction and to make an electron diffraction pattern of a selected region of the sample (3 μ in diameter), whose image was first studied under the microscope. This



Electron lenses with carriage for Calcutta University electron microscope.

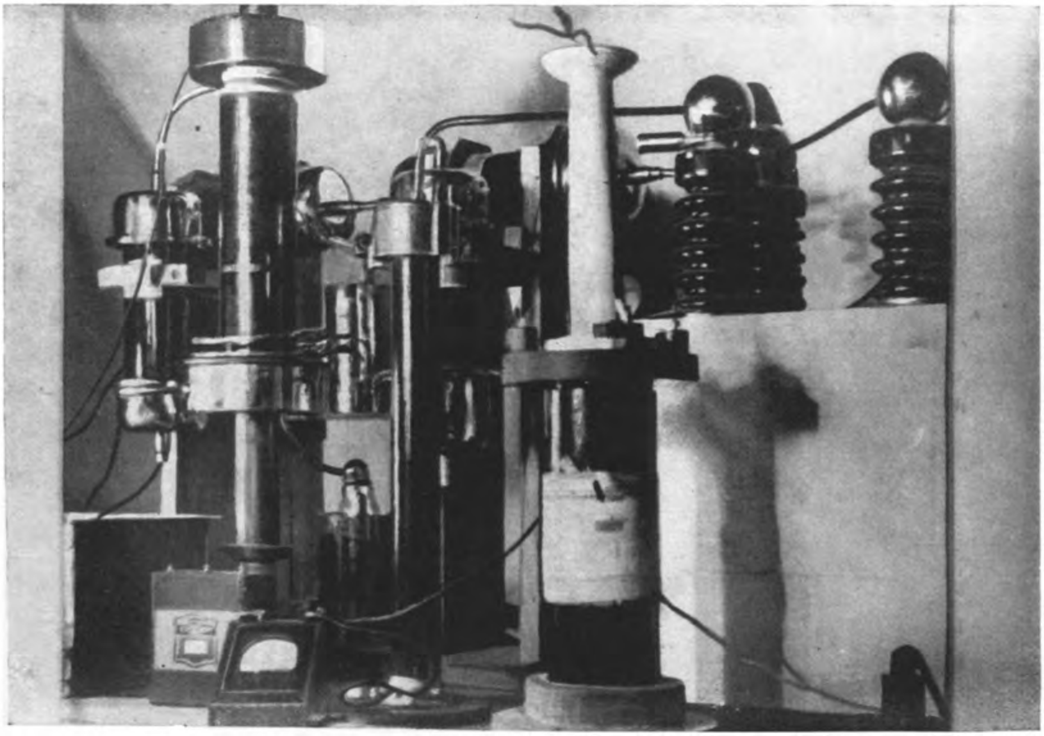


Calcutta University electron microscope in the process of installation (1947).



The completed electron microscope (1948)

G : Electron gun; A : Anode; C, O and P : Condenser, objective and projector lenses; S and F : Specimen and photographic chambers; D : Diffusion pump.



High-voltage system of Calcutta University electron microscope.

microscope had an extra focusing devise (called wobbler), a 50-cycle electromagnetic field, situated between the objective and the condenser, which produced an exaggerated blurring of the off-focus image. This instrument had a 35 mm. camera, with which it was possible to make a large number of exposures in a short time, although at a reduced magnification.

In Japan, Higashi[45] and Tani in the Kyoto University began the early development of the electron microscopes. They had their microscopes in operation soon after 1940.

Dupouy, in France, developed in 1945 a magnetic microscope. The magnification in three stages went up to 60,000 with 90 kV electrons.[46] Prof. Dupouy and his collaborators at the C.N.R.S. laboratories at Toulouse, France, have been very active in the field of high-voltage electron microscopy. They built in 1961 a million-volt electron microscope.[47]

In the Cavendish Laboratory, Cambridge, Cosslett also designed and built in 1965 a 750-kilovolt microscope.[48] A routine resolution of 10–12 A.U. was obtained from Fresnel fringe tests. It must be mentioned, however, that although these super-voltage microscopes have proved useful in studies on solid state physics, e.g. in the investigation of dislocations, precipitates, etc., they did not result in any great gain in seeing the minute details in a biological specimen.

In India, a project to develop an electron microscope was undertaken at the Physics Laboratory of the University College of Science, Calcutta, in 1946, with the kind collaboration of one of the pioneers in this field, Dr. L. Marton, then Professor at Stanford University. Dr. Marton supplied the design data and also helped to get most of the electron optical construction done under his supervision. The vacuum system, the high-voltage and lens power regulators were all constructed and tested in the Science College Laboratory at Calcutta. The installation of this first electron microscope in this country (50 kV, 80 A.U.) was completed in 1948.[49] This microscope was horizontal and consisted of a self-biased electron gun, condenser, objective and projector lenses of electromagnetic type with an over-all electronic magnification of 20,000. Plates I and II show the electron lenses, the microscope in the process of installation, the finished instrument and its high-voltage system. The microscope was used in a large number of biophysical investigations.[50]

COMMERCIAL PRODUCTION OF MAGNETIC ELECTRON MICROSCOPES

No history of the development of the electron microscope will be complete without a reference to the many achievements of the different industrial laboratories in this field. Many of the foremost electronic industrial concerns like Siemens, R.C.A., Philips, Hitachi, A.E.I., etc., have entered into the field of commercial production of electron microscopes. Keen competition amongst these has resulted in quick improvements in design, performance and ease of operation of this instrument. It may be said, quite generally, that without these industrial concerns trying constantly to improve their products, this instrument would not have been so versatile in its applications today. In what follows we have attempted to give a short chronological account of the gradual development and steady improvement in resolution, in different commercially produced electron microscopes.

The production of the first commercial instrument by Siemens in 1939 has already been mentioned. This microscope went through further modification in 1949 and 1954 when the types UM 100 and Elmiskop I (15 A.U. guaranteed resolution) were produced. The last model was again replaced by Elmiskop IA (1964, 8 A.U.) and Elmiskop 101 (1967, 5 A.U.). Siemens also developed a 125 kV instrument: Elmiskop 1A (1966, 10 A.U.).

The development of commercial electron microscopes in the U.S.A. has been done mainly by the R.C.A. Company. Dr. Marton from Brussels and Dr. Hillier of the Toronto group joined the R.C.A. Company in 1940. The first microscope developed was called R.C.A. Type A, but this design was not put into production.[51] The second R.C.A. microscope developed by Zworykin, Hillier and Vance in 1941 (60 kV, 100 A.U.) called R.C.A. Type B was the first R.C.A. commercial model.[52] The first instrument was supplied to the American Cyanamid Company.

The R.C.A. microscope has now gone through many modifications and improvements incorporated in the successive models:[53] the universal EMU (1944–53, 50 kV, 100–30 A.U.), EMD (1948–56, 50 kV), EML (1954–58, 50 kV, 30 A.U.), EMU 3A–F(1953–61, 50 and 100 kV, 20 A.U.), EMU 3G and 3H (1962–65, 50 and 100 kV, 10 A.U.) and EMU 4 (1967, 50 and 100 kV, 5 A.U.). R.C.A. also experimented with a console model of lower voltage EMC (1944–48, 30 kV, 100 A.U.) and a table model with permanent magnet lenses EMT (1950–54, 50 kV, 100 A.U.). However the last two models did not prove very popular.

The R.C.A. Company has now produced more than 1,400 electron microscopes in its several models. It is responsible for many improvements in techniques, which play an important part in the electron microscopy today. Hillier and Ramberg showed in 1947 that the anisotropy of the iron, from which the pole-pieces were made and the lack in mechanical precision, caused the magnetic lenses to be very astigmatic and that was the reason why a resolution of 20 A.U. could not be surpassed by the microscopes in operation at that time. They demonstrated that the correction of the astigmatic error of the electron lens of a modified R.C.A. instrument (EMU type) brought down the resolution to about 10 A.U.[54] Since then, most of the commercial instruments incorporated magnetic and electrostatic stigmators of various types in their own instruments. The other contributions of the R.C.A. are (*a*) reliable and high-speed vacuum system, fitted with mechanical and later with automatic valves and vacuum gauges, (*b*) simplified electronic circuit for production and control of the accelerating voltage and power of the lenses, (*c*) large specimen chambers suitable for dynamic studies of specimens under varying conditions of heat, cold and magnetic fields, (*d*) the combination of image intensification and television system with electron microscopy and (*e*) transistorized power supplies for maximum stability and reliability. All these have contributed greatly to the ease and speed with which the microscope can be operated and maintained today.

The first Philips microscope based on the experimental model of Le Poole was EM 100 (1948, 50 A.U.); the later versions of this unit were EM 100B and EM 100C (20–15 A.U.). Another low-priced instrument, developed by Philips was EM 75 (1955, 100 A.U.) whose B and C versions, produced later, gave a higher performance (50–35 A.U.). The Philips Company has recently introduced the models EM 200 (1958, 10–8 A.U.) and EM 300 (1966, 5 A.U.).[55] An experimental 400 kV electron microscope was also developed by this company in 1948 but this was not commercially produced.[56]

Martin, Whelpton and Parnum constructed the first commercial electron microscope in England in 1937, in the laboratory of Metropolitan Vickers Company. This was called EM 1, but its performance was no better than that of the light microscope.[57] All work had then to be suspended due to the outbreak of World War II. In 1946, Metropolitan Vickers microscope EM 2 appeared, based on the design of Haine. This also had a radio frequency power supply, intermediate lens and was operable at different voltages of 25, 50, 75 and 100 kV.[58] This microscope was followed by the production of EM 3 (1949, 50 A.U.), EM 3A (1955, 25 A.U.) and EM 6 (1958, 15 A.U.). After this date, Metropolitan Vickers became Associated Electrical Industries. In 1964, Associated Electrical Industries introduced the models EM 6G and EM 6B (5 A.U., primarily intended for biological research).[59]

Next to the U.S.A., commercial electron microscopy has developed most in Japan. Based on the work of Tadano, the first commercial microscope in Japan was built by the Hitachi Company in 1942, HU 2 (100 kV, 50 A.U.). This instrument went through several improvements in design and operation as reflected in the models: HU 5 (1949, 30 A.U.), HU 9 (1953, 20 A.U.), HU 10 (1955, 10 A.U.), HU 11A, 11B and 11C (1966, 4·5 A.U.). In addition to the standard 100 kV equipment, Hitachi also developed low-powered instruments HM 3 (1958, 40 kV, 80 A.U.) and the permanent magnet instrument HS 2 (1952, 50 kV, 50 A.U.). The last instrument went through further improvements in design in HS 6 (1958, 15 A.U.), HS 7 and HS 7S (1962, 10 A.U.). Along with Schimadzu, Hitachi has also pioneered in the development of high-voltage instruments and produced the models HU 125 (1966, 7 A.U.), HU 200 (1966, 4·2 A.U.), HU 650 (1966, 10 A.U.) and HU 1000 (1966, 10 A.U.).[60]

In addition to Hitachi, electron microscopes are also being produced in

Japan by three other companies. These are the Japan Electron Optics Laboratory, Schimadzu and Akashi Ltd. Japan Electron Optics Laboratory delivered the first commercial microscope in 1955. The electron microscopes made by this company now comprise the models JEM 7 (100 kV, 7 A.U.). JEM T6S (60 kV, 15 A.U.) and JEM 1000 (a million volt, 7 A.U.).[61] Schimadzu in Japan has been specializing in the commercial production of high-voltage electron microscopes SMH 5B (500 kV, 12·5 A.U.).[62]

ELECTROSTATIC MICROSCOPES

The development of electrostatic lenses and of electron microscopes using such lenses proceeded at first almost side by side with the electromagnetic instruments. Shortly after Busch's work on the focusing action of symmetrical magnetic and electrostatic fields, Davisson and Calbick in the U.S.A.[63] and Bruche and Johannson in the A.E.G. laboratories in Berlin[64] embarked on systematic investigations on electrostatic focusing devices. Davisson and Calbick showed, theoretically, that a hole in a charged plate would act as a lens so far as the electron beam was concerned. Bruche and Johannson published photographs of an electrostatic apparatus forming images of emission cathodes on a fluorescent screen by such aperture lenses. The total magnification obtained was 200 times. During the period when Borries and Ruska were developing their magnetic microscopes in the Siemens laboratory, the A.E.G. was engaged in the development of the transmission type of electrostatic instruments. In 1939, the first successful high-resolution electrostatic instrument was built by Mahl,[65] which was followed by a limited production of the commercial models by the A.E.G. The first of these (built in 1940) was supplied to the Robert Koch Institute in Berlin.

In this microscope the electron source was an electrically heated tungsten wire, surrounded by an apertured grid, biased at about 200 volts with respect to the filament. There was provision for a change of the grid bias voltage, to control the divergence angle and the intensity of the electron beam. The cathode could be kept at 40 to 60 kV negative with respect to the anode which was grounded. There was a projector lens besides the objective, with focal lengths of 3 and 5 mm respectively. Each lens was of the three-electrode system, of which the two outer electrodes were connected to the ground and the central one to the cathode. The total maximum magnification was about 10,000 times with a resolution of about 80 A.U.

After World War II, the development of this microscope continued, first in the Suddeutsche Laboratorien (S.D.L.) in Mosbach-Baden up to 1953 and then in Carl-Zeiss (Oberkochen). This resulted in the production of EM 7 (1948) and EM 8 (1949). The chief improvements were the introduction of a fourth lens, between objective and the two projectors, a diffraction lens for selected area diffraction. However, since 1961, research and development of this electrostatic instrument was given up by Carl-Zeiss (Oberkochen), as it was found out that the theoretically attainable resolution of the electrostatic instrument would be limited to 12–15 A.U. at the maximum. The new microscopes made by Carl-Zeiss (Oberkochen) are all electromagnetic EM 9A (60 kV, 15 A.U.).[66]

After World War II in 1948 Carl-Zeiss (Jena) also started on a programme of development of electron microscopes, with the collaboration of Prof. Recknagel of the Technical University of Dresden. The first electrostatic instrument was produced by this company in 1950: ELMI A (50 kV, 50 A.U.), equipped with the conventional three lenses. This instrument went through further improvements in the Models ELMI B (1953) and ELMI C (1954) (50 kV, 30 A.U.). The latest model in this series was ELMI D produced in 1956. Provided with double condensers and four magnification stages, it could produce an electronic magnification of 35,000X, and 20 A.U. resolution. This was one of the best electrostatic instruments developed so far, but the limit of resolution stopped at 20 A.U. Since 1961, Carl-Zeiss (Jena) also gave up the production of electrostatic instruments and switched on to the electromagnetic ones. The current model is electromagnetic electron-optical plant EF. Besides being a medium-sized transmission electron microscope (65 kV, 30 A.U.), the EF 6 is best suited for emission microscopy of solids with a resolution of about 200 A.U.[67]

Trüb Tauber in Switzerland developed a two-stage hybrid microscope in 1944. This instrument designed by Induni was not of the conventional type. It had a cold cathode and a combination of both electrostatic and electromagnetic lenses in the same instrument. About 30 instruments were built in the period 1945–1960 and resolutions of the order of 20–25 A.U. were reached.[68] However, further development was discontinued in 1960, as it could not compete with instruments with thermionic cathodes and electromagnetic objectives. The new instruments under production in Switzerland are the secondary emission microscopes where the secondary electrons may be released by ultra-violet light (photo emission), by ionic-bombardment or by heat. This microscope named Metioscope (microscope electronique using ions) will be useful in high temperature metallography.[69]

The French electrostatic instrument was developed by the Compagnie Generale de Telegraphie sans Fil (CSF) in 1946 based on the design of Grivet and Bruck.[70] This instrument, a three-stage unit capable of magnification up to 50,000 times and 20 A.U. resolution, has now been discontinued. Thus although both the electromagnetic and the electrostatic instruments started on the race at the same time and place (Germany)—electromagnetic instruments have won the race.

* * *

In tracing the history of development of the electron microscope as outlined above, it will be observed that in every country the initial development was carried out in the research laboratories of the universities or technical institutions and then industry was responsible for further development and production. The combination of the efforts of the academic scientists and the technologists in the industries resulted in this fine instrument that we see today. This microscope has now become a basic scientific instrument in any scientific or technical research and important contributions have been made in many different branches of science with its help. Unfortunately in our country, no serious effort was ever made to produce even a low power instrument. The 40 or more electron microscopes, so far installed in different parts of India, are all imported from abroad. As the imported instruments are built by 10 different companies in different parts of the world, each needs its own set of spares and expert know-how to maintain and service it properly. This creates a problem when something goes wrong. It is the firm belief of the authors that it should not be difficult to produce this versatile and essential equipment in our country at much reduced cost.

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