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Scanning Electron Microscopy 1928–1965*

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Summary: This article gives an account of the origins of the scanning electron microscope (SEM) and traces its development up to 1965 when the first SEM was marketed by the Cambridge Instrument Company. The survey concentrates on the SEM, as distinct from the microanalytic electron probe instruments that were also being developed during this period.

Key words: scanning electron microscopy, imaging of solid samples, history

Introduction

From the very beginning of electron microscopy the imaging of solid samples was an important goal. This was particularly important since the methods for producing thin samples were only developed later. The first attempt was by Ruska (1933) with the sample surface normal to the viewing direction and illumination by an electron beam at grazing incidence to the surface; he obtained images of copper and gold surfaces but at a magnification of only 10×. A few years later he made a second attempt (Ruska and Müller 1940) with the same geometry and with only marginally better results. Von Borries (1940) was much more successful with his grazing incidence method in the transmission electron microscope (TEM) where the sample surface is at a few degrees both to the viewing direction and to the illuminating beam. This is still an important technique.

A breakthrough in the microscopic imaging of surface topography in the TEM was the introduction of surface replicas by Mahl (1941) and these set the standard for the next 25 years although they were tedious to make and could be subject to serious artefacts. An example of a replica of etched aluminum is shown in Figure 1.

During the 1930s a very different way of imaging solid samples was invented by Knoll (1935) for the study of the targets of television camera tubes— scanning electron microscopy (SEM). Two years later von Ardenne (1938a, b) built an electron microscope with a highly demagnified probe for scanning transmission electron microscopy (STEM) and also tried it as an SEM. And soon afterwards Zworykin *et al*. (1942a) developed a dedicated SEM. The beginning of the general use of the SEM can be accurately dated to 1965 when the Cambridge Instrument Company in the U.K. marketed their Stereoscan 1 SEM, which was followed about 6 months later by the JEOL JSM-1 in Japan. This was 30 years after the initial developments in Germany and the U.S.A., but it was the research project started in 1948 by Oatley at the Cambridge University Engineering Department that led directly to the Stereoscan (Oatley 1982).

The purpose of this article is to trace the development of the SEM up to the sale of the first commercial SEMs in 1965. Incidentally, it will be seen that many of the ideas put forward by the early workers were well ahead of their time, becoming technologically practicable only much later. The development of microanalytic probe instruments is summarised only briefly.

Invention of Scanning

The 1928 starting date in the title of this article is somewhat arbitrary and it was chosen because the first mention of scanning applied to microscopy was made in that year. But it is relevant to start nearly 100 years earlier with the invention by Alexander Bain, a Scottish clockmaker, of the principle of dissecting an image by scanning, and later the granting of a British patent to him (Bain 1843) for the first fax machine (McMullan 1990). At the transmitter of this instrument, a stylus mounted on a pendulum contacts the surface of metal type forming the message, thus closing an electrical circuit, and at the receiver a similar stylus, also on a pendulum, records the message electrochemically on dampened paper. Following each swing of the pendulums, the type and the recording paper are lowered one line; means for starting the pendulums swinging simultaneously and synchronising them magnetically are described in the patent.

Scanning Optical Microscopy

The first proposal in print for applying scanning to microscopy was made by Synge (1928) in Dublin. This was for a scanned optical microscope and his aim was to overcome the

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Abbe limit on resolution by what is now called "near-field microscopy," that is, the production of a very small light probe by collimation through an aperture smaller than the wavelength of the light.

Synge was a scientific dilettante who had original ideas in several scientific fields but did not attempt to put them into practice (McMullan 1990). However, he considered some of the problems that would be encountered with a scanning microscope. He proposed the use of piezoelectric actuators (Synge 1932), as are now used with great success in the scanning tunneling microscope and other probe instruments (including, of course, the near-field optical microscope itself). Synge envisaged fast scanning of the sample so that a visible image could be displayed on a phosphor screen, and he also pointed out the possibility of contrast expansion to enhance the image from a low contrast sample—probably the first mention of processing an image electronically (as distinct from photographically).

Charged Particle Beams

A proposal for using an electron beam in a scanning instrument was described by Stintzing (1929a, b), of Giessen University, in German patents. These patents were concerned with the automatic detection, sizing, and counting of particles using a light beam, or for those of sublight microscopic size, a beam of electrons. Focussing of electrons was at that date unknown to him, as to most others, and he proposed obtaining a small diameter probe by crossed slits. The sample was to be mechanically scanned in the case of a light beam, and electric or magnetic fields would deflect an electron beam. Suitable detectors were to be used to detect the transmitted beam which would have been attenuated by absorption or scattering. The output was to be recorded on a chart recorder so that the linear dimension of a particle would be given by the width of a deflection, and the thickness by the amplitude; the production of a two-dimensional image was not suggested. Stintzing apparently did not attempt the construction of this instrument and there are no drawings accompanying the patent specification.

Electron Beam Scanner

Knoll, the co-inventor of the TEM with Ruska, was the first to publish images from solid samples obtained by scanning an electron beam (Knoll 1935). In 1932, very soon after the building of the first TEM at the Berlin Technische Hochschule, he moved to the Telefunken Company to work on television camera tubes and developed an electron beam scanner for studying the targets of these tubes. The sample was mounted at one end of a sealed-off glass tube (Fig. 2) and an electron gun at the other; the accelerating potential was in the range 500–4000 V. The electron beam was focussed on the surface of the sample and scanned by deflection coils in a raster of 200 lines and 50 frames/s. The current collected by the sample (the difference of the incident and secondary emitted currents) was amplified by a thermionic tube amplifier and intensity-modulated a cathode-ray tube which was scanned by deflection coils connected in series with those on the electron beam scanner. By changing the ratio of the scan amplitudes, the magnification could be varied, a principle which had been demonstrated by Zworykin (1934, 1942a) on an optical microscope fitted with a TV camera. Knoll used unity magnification most of the time, but he could increase it to about 10 times before the resolution was limited by the diameter of the scanning probe.

This apparatus had virtually all the features of an SEM but, surprisingly, in view of his earlier work on the TEM, Knoll did not use additional electron lenses to reduce the size of the probe below 100 µm; however the resolution he obtained was entirely adequate for his purpose. The beam current was relatively high, of the order of microamps, and therefore thermionic tubes could be used to amplify the signal current in spite of the fast scan rate.

Similar images were no doubt produced by others working on the development of TV cameras in the 1930s, but Knoll was the only one at the time who looked at samples other than camera tube targets. For example, he viewed and published images of silicon iron (Fig. 3) and also elucidated the contrast mechanisms: secondary electron coefficient and topography. The images he observed were true secondary electron images

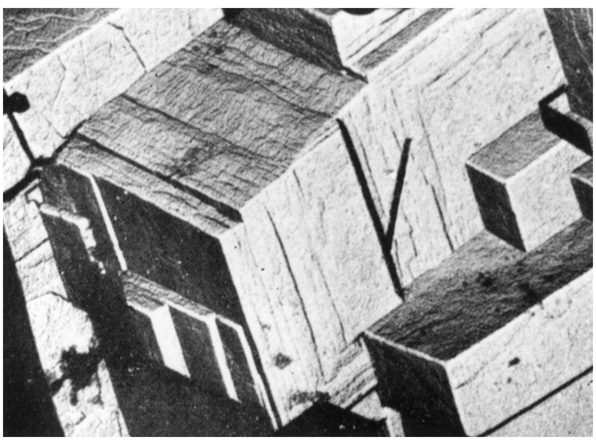

FIG. 1 TEM image of an early oxide replica of etched aluminum (Mahl 1941); horizontal field width = 9 µm.

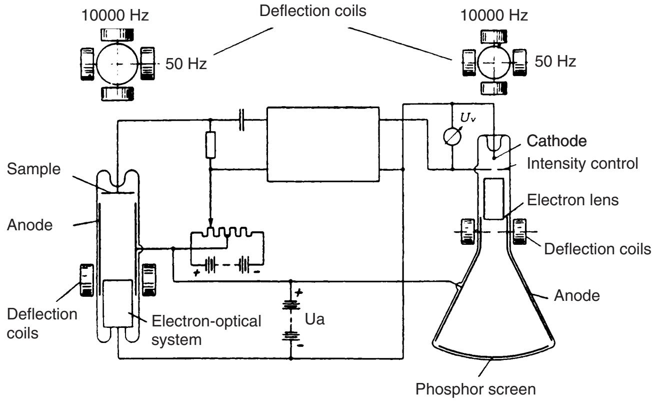

FIG. 2 Schematic diagram of Knoll's (1935) electron-beam scanner.

because the electron gun and sample were enclosed in the highly evacuated and baked glass envelope and there was, therefore, little or no contamination of the surface. It is only comparatively recently that UHV SEMs have been available which can work in this imaging regime.

Knoll continued using his electron beam scanner (which he named "der Elektronenabtaster") for a number of purposes, including the study of oxide layers on metals (Knoll 1941).

Von Ardenne's Scanning Electron Microscope

The first scanning electron microscope with a submicron probe was developed by von Ardenne (a private consultant who had his own laboratory in Berlin) over the very short period of about 2 years. Von Ardenne also had had experience in the development of TV camera tubes (von Ardenne 1985). In 1936 he was contracted by Siemens and Halske A.G. to investigate the possibility of using a scanned electron probe to avoid the effects of objective lens chromatic aberration with thick samples in the TEM. During the course of this work, he laid the foundations of electron probe microscopy by making and publishing a detailed analysis of the design and performance of probe-forming electron optics using magnetic lenses (von Ardenne 1938a, b). The analysis covered the limitations on probe diameter due to lens aberrations and the calculation of the current in the probe. He also showed how detectors should be placed for bright-field and dark-field STEM and for imaging a solid sample in an SEM. He also considered the effects of beam and amplifier noise on imaging.

In order to fulfill the Siemens contract, von Ardenne built the first STEM and demonstrated the formation of probes down to 4 nm diameter, but in the short time available, he was limited to employing only the existing technology. Because there was no suitable low-noise electronic detector available, he used photographic film to record the image. Consequently, there was no immediately visible image. A schematic of the microscope column is shown in Figure 4. In this instrument a demagnified image of the crossover of the electron gun was focussed on the sample by two magnetic lenses, and X-Y deflection coils were mounted just above the second of these lenses. Immediately

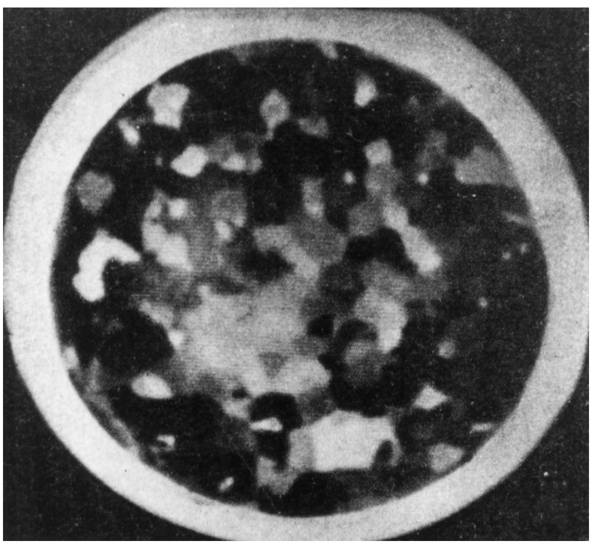

FIG. 3 Electron-beam scanner image of silicon iron showing electron channeling contrast; horizontal field width = 50 mm. (Knoll 1935).

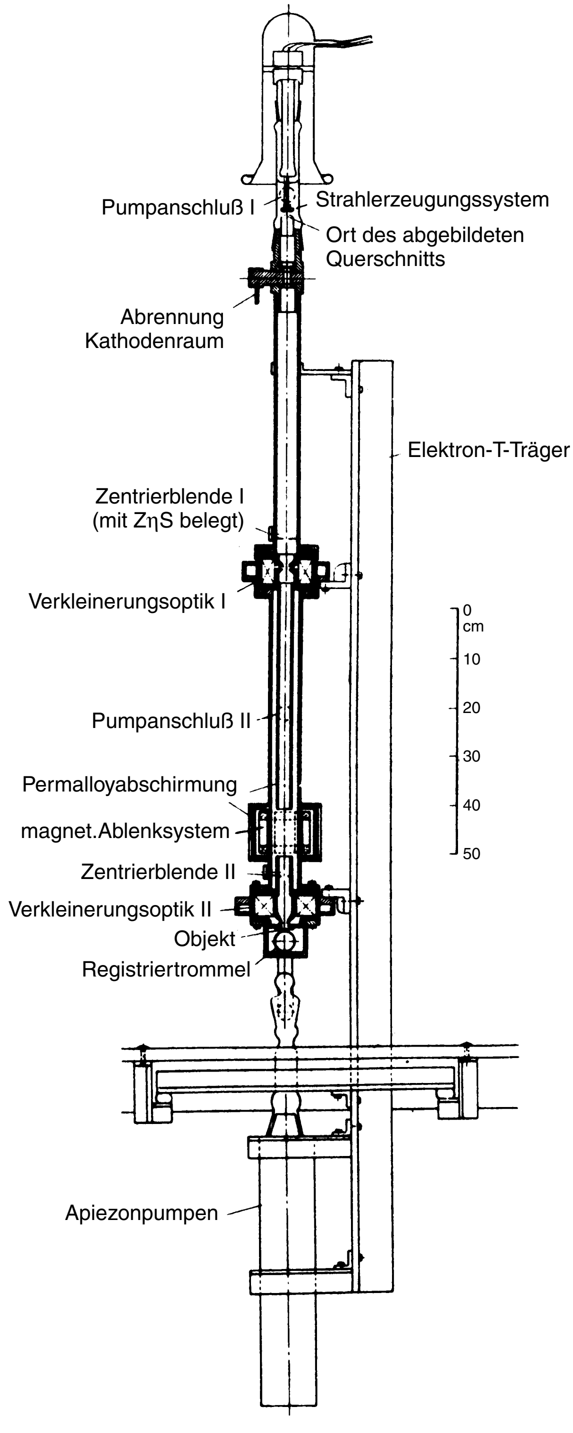

FIG. 4 Cross section of the column of von Ardenne's (1938b) STEM. "Strahlerzeugungssystem" = electron gun; "Verkleinerungsoptik" = reducing lens; "magnet. Ablenksystem" = deflection coils; "Objekt" = sample; "Registriertrommel" = film recording drum.

below the sample was a drum around which the photographic film was wrapped. The image was recorded by rotating the drum and simultaneously moving it laterally by means of a screw while the currents in the deflection coils were controlled by potentiometers mechanically coupled to the drum mechanism. The intensity of the beam was very low (about 10^{-13}A) and it was necessary to record the image over a period of about 20 min. Since the image was not visible until the film had been developed, focussing could only be accomplished indirectly by using the stationary probe to produce a shadow image of a small area of the sample on a single-crystal ZnS screen which was observed through an optical microscope and prism system. The recordings were inferior to those from the TEM that was being constructed by Ruska and von Borries at Siemens, and the hoped-for advantages of STEM with thick samples were not fulfilled.

Von Ardenne spent a short time trying to use the instrument in the SEM mode on bulk samples, but only low-resolution images could be obtained because of the detector problem: the sample current was amplified by thermionic tubes and a large probe current was needed. He did not publish any images.

In total, von Ardenne worked for less than 2 years on scanning electron microscopy before concentrating on the development of his universal TEM (von Ardenne 1985). Then, with the start of the World War II, his work was directed to building a cyclotron and isotope separators for nuclear energy projects. If he had been able to continue, there is little doubt that he would have built an efficient SEM within a year or two: this is evidenced by a patent (von Ardenne 1937) which included a proposal for double-deflection scanning, two papers (von Ardenne 1938a, b), and a book (von Ardenne 1940). Two of the chapters in the book were on scanning microscopy and were based on the 1938 papers but included additional material relating to imaging the surfaces of solid samples. Most important, he proposed a detector using an electron multiplier with beryllium copper dynodes (Fig. 5) which could be opened to the atmosphere and work efficiently under poor vacuum conditions. Measurements of the secondary emitting ratio of beryllium copper and its stability when exposed to the atmosphere were first reported only in 1942 by Matthes of the AEG Research Institute in Berlin (Matthes 1942), but von Ardenne was probably aware of this research a year or two before.

In his book von Ardenne also discussed the interaction between the beam electrons and the sample and suggested that backscattering would cause a loss of resolution, illustrating this with a diagram which has a quite modern look (Fig. 6). He argued that the incident beam electrons produce secondary electrons at or near the surface from an area approximately equal to the beam diameter and give a high resolution image ("nutzbare Strahlung"). The beam electrons then penetrate into the sample and a proportion of them are backscattered and reach the surface where they produce further secondaries. These two signals are now generally referred to as SE-I and SE-II, respectively (Drescher *et al.* 1970, Peters 1982). The backscattered electrons are emitted from an area of diameter comparable with the penetration depth, and the secondaries they produce ("schädliche Strahlung") may impair the resolution (however, he did not consider the case of a sample with small inclusions below the surface). He concluded that good resolution might be obtained either with a very low energy beam (1 keV), or with one having a high energy (50 keV). In the first case the backscattered electrons would emerge from an area of the surface little larger than the incident beam and the resolution would be unaffected. On the other hand, with a 50 keV beam, the secondary electrons would be produced by the backscattered electrons over a very much larger area; moreover, they would be evenly distributed so that their main effect would be to increase the background (reduce the contrast) rather than to affect the resolution.

Von Ardenne's scanning microscope was destroyed in an air raid on Berlin in 1944, and after the war he did not resume his

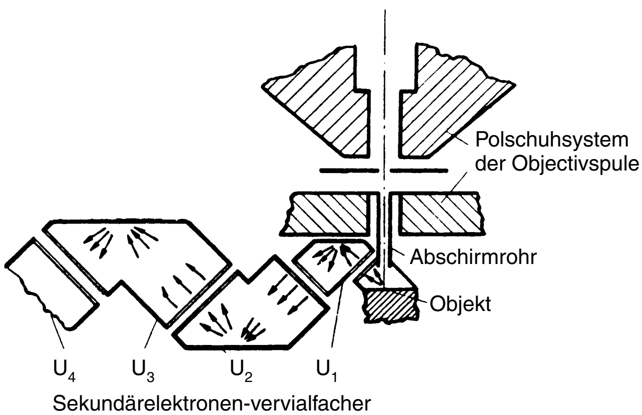

FIG. 5 Electron multiplier with beryllium copper dynodes proposed by von Ardenne (1940) as a secondary electron detector for an SEM. The drawing shows the first three stages of the multiplier and its position relative to the objective lens and sample.

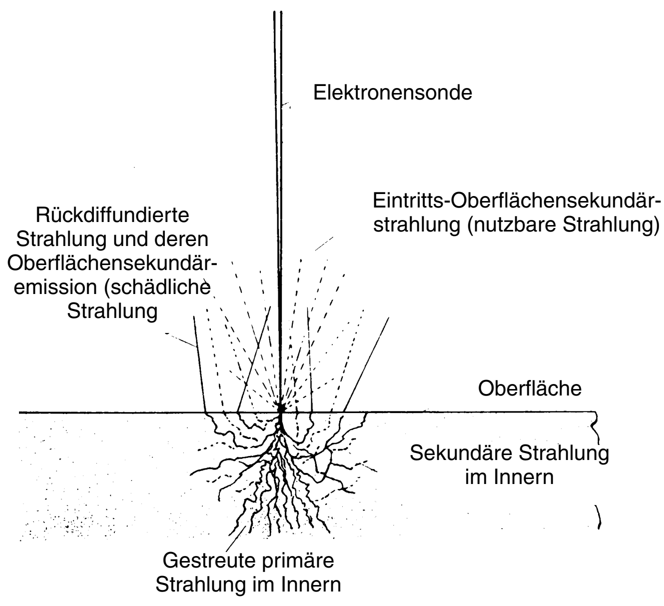

FIG. 6 Diagram illustrating von Ardenne's (1940) discussion of secondary electron imaging of a surface.

work in electron microscopy but researched in other fields: first in Russia, and from 1955 in Dresden, which was then in the D.D.R. Additional information about von Ardenne's scientific work has been given in his autobiography (von Ardenne 1972) and by McMullan (1988).

The RCA Scanning Electron Microscope

Meanwhile in America, Zworykin, Director of Research at the RCA Camden N.J. laboratories, had initiated a development programme on SEM in 1938 (Zworykin *et al.* 1942a) which continued until about 1942. This work was done in parallel with the development of a TEM by the same staff, in particular Hillier, Ramberg, Vance, and Snyder, as well as Zworykin himself.

Although Zworykin had every microscope paper from Germany translated as soon as it was received (Reisner 1989), he was apparently not influenced by von Ardenne's work on the SEM. Instead he started in effect by repeating Knoll's beam scanner experiments using a "monoscope;" this was a pattern-generating cathode-ray tube which had been developed by RCA for television use (Burnett 1938) and was very similar to Knoll's apparatus. He then built an SEM based on the monoscope but with two magnetic lenses to produce a very small focussed probe, and a demountable vacuum system so that the sample could be changed (Zworykin *et al.* 1942a). The scan rate was the U.S. TV standard, 441 lines and 30 frames/s, and the signal was amplified by a thermionic tube video amplifier. For a signal-to-noise ratio of 10 the signal current had to be 3×10^{-8} A which could be reached only if the probe diameter was about 1 μm.

Zworykin next tried to obtain a high current in a smaller probe by use of a field emission gun with a single-crystal tungsten point (Zworykin *et al.* 1942a), presumably based on experience with the point projection microscope that had been built in the RCA laboratories by Morton and Ramberg (1939). To obtain a sufficiently high vacuum he had to return to having the gun and the sample in a glass envelope which was baked and sealed off. A single magnetic lens was used, and fleeting images were obtained at 8000× magnification with scanning at TV rate and a thermionic tube amplifier. Stable images could no doubt have been achieved, but at that time a practical microscope would not have resulted because demountable UHV techniques did not exist.

To overcome the noise problem, Zworykin therefore decided to build an SEM with an efficient electron detector and a slow scan. The detector was the combination of phosphor and a photomultiplier that Everhart and Thornley used nearly 20 years later in an improved form. In order to attract the secondary electrons to the detector he designed an electrostatic immersion lens which retarded the beam electrons and accelerated the secondaries. Figure 7 shows the final electron optical arrangement: electrostatic lenses were used to produce a demagnified image of the source on the sample which was held at +800 V relative to the grounded gun cathode. The electron beam leaving the gun was accelerated to 10 keV in the intervening electron optics. The accelerated secondary electrons diverged as they passed through the fourth electrostatic lens and hit the phosphor screen with an energy of 9.2 keV.

In the first instrument, the scanning was done by moving the sample relative to the beam electromechanically using loudspeaker voice coils and later by hydraulic actuators; it was only in the final version that magnetic scanning of the beam was employed. The scan time was fixed at 10 min by the facsimile recorder which was used for image recording; this recorder also controlled the microscope scans. There was no provision for a faster scan or the production of a visible image on a TV monitor (which seems strange remembering Zworykin's TV background). This may have been because the signal bandwidth was limited by the decay time of the phosphor; the same problem was found in later work at Cambridge (McMullan 1952). The focus setting was determined by maximising the high frequency components in the video waveform observed on an oscilloscope, a method which was originally proposed by von Ardenne (1938b).

Although the intention was to produce contrast by differences in the secondary emission ratio of the surface constituents, and the incident beam energy of 800 eV was chosen with this in mind, contamination of the surface in the rather

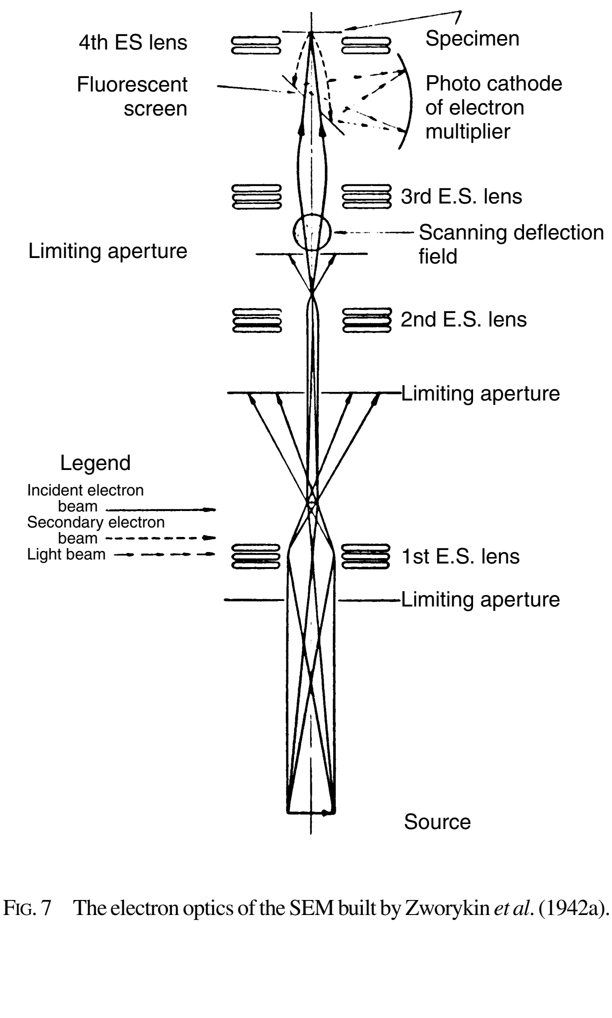

FIG. 7 The electron optics of the SEM built by Zworykin *et al.* (1942a).

poor vacuum prevented meaningful compositional contrast from being obtained. Actually, all of Zworykin's published micrographs were of etched or abraded samples. The contrast was topographic (Zworykin *et al*. 1942b), as shown in the example of etched brass (Fig. 8). The quality of the recorded images was rather disappointing and, together with the lack of a visible image, must have been a factor in RCA deciding to discontinue the project. But another reason was undoubtedly the excellent results that were being obtained with replicas in TEMs, as mentioned in the Introduction. In any event, all available technical effort had to be directed to the highly successful RCA EMB TEM, which was then coming into production (Reisner 1989).

The Cambridge Scanning Electron Microscopes

Apart from a theoretical analysis of resolving power by a French author (Brachet 1946), no other work on the SEM had been reported by 1948. The feeling among electron microscopists appeared to be that it was not worth further consideration in view of the apparent failure of the RCA SEM—if such an experienced team were unsuccessful it was very unlikely that anyone else could produce an effective instrument; a notable exception to this general opinion was Gabor (1945). It was then that Charles Oatley at the Engineering Laboratories of the University of Cambridge decided that another look at the SEM might be worthwhile, although, as he has related, "several experts expressed the view that this [the construction of an SEM] would be a complete waste of time" (Oatley *et al*. 1985). He has explained at some length the reasons that brought him to this decision, but the main technological ones were that "Zworykin and his collaborators had shown that the scanning principle was basically sound and could give useful resolution in the examination of solid surfaces" and "improvements in electronic techniques and components had resulted from work during the war" (Oatley 1982). He was also of the opinion that the RCA detector had a low efficiency and only a small proportion of the secondaries were reaching it. This resulted in images that were noisy in spite of the long recording time. Independently of von Ardenne, Oatley proposed the use of an electron multiplier with beryllium-copper electrodes (Allen 1947) having been promised one by Baxter of the Cavendish Laboratory who was building multipliers of this type (Baxter 1949).

FIG. 8 Micrograph of etched brass produced by the SEM of Zworykin *et al*. (1942a); horizontal field width = 18 μm.

I was selected by Oatley to build an SEM as a Ph.D. project. This was a challenging task because electron microscopy was a completely new subject for everyone in the laboratory. I had had some experience in the radar and television industries, including the development and manufacture of cathode-ray tubes, which was quite helpful. I first completed a 40 keV electrostatically focussed TEM which had been begun by another Ph.D. student, K.F. Sander; he had abandoned it at an early stage and had changed the subject of his research project to electron trajectory plotting (Sander 1951). I converted it to an STEM, and then to an SEM, by the addition of scan coils, the electron multiplier detector, and a long-persistence cathode-ray tube monitor (McMullan 1952).

It was still far from clear how Zworykin's earlier results might be improved upon. A higher incident beam energy could be expected to be beneficial, but it was not clear how image contrast would be formed. Bruining and de Boer (1938) had shown that the secondary emission from a surface is critically dependent on the vacuum conditions. It was plain that a high enough vacuum would not be achieved for there to be meaningful secondary-electron compositional contrast from a polished sample.

As mentioned in the Introduction, images of surfaces had been obtained at grazing incidence and viewing direction (2°) in the TEM by von Borries (1940) and others, and it seemed probable that similar images could be produced in the SEM. I, therefore, mounted a sample of etched aluminum at a rather larger angle (30°, because the backscattered electrons did not have to be focussed) and was rewarded by the now commonplace three-dimensional appearance that is the hallmark of SEM images; this is a consequence of the large depth of focus. One of the first images of etched aluminum is shown in Figure 9. In this figure are shown (a) the direct view image at 1.8 s frame period, and (b) a 5 min recording; the beam energy was 16 keV. The resolution was limited to about 50 nm by astigmatism in the objective lens and insufficient magnetic shielding.

A block diagram of the SEM is shown in Figure 10 (McMullan 1953) and a cross section of the column in Figure 11. There was a relatively fast-scan long-persistence cathode-ray tube display (405 lines, 1.9 fields/s interlaced) and a slow scan (5 min) display for photographic recording; other features included a nonlinear amplifier for gamma control, and beam blanking for D.C. restoration. Double-deflection scanning coils were added later.

The most important differences between this instrument and Zworykin's were the much higher incident beam energy at the sample (15–20 keV) and the contrast that was produced mainly by scattered electrons. The mechanism of contrast formation was investigated and was shown to be topographic. No attempt was made to collect low-energy secondaries and, in fact, I thought that they would be detrimental because of the inevitable contamination on the surface of the sample. I overlooked the increase in signal that is obtained from the low-energy secondaries.

I realised that there was another advantage in using a high-energy scanning beam: this was that in principle atomic number contrast was possible using backscattered electrons. An experimental curve of emission ratio (for 20 keV primaries)

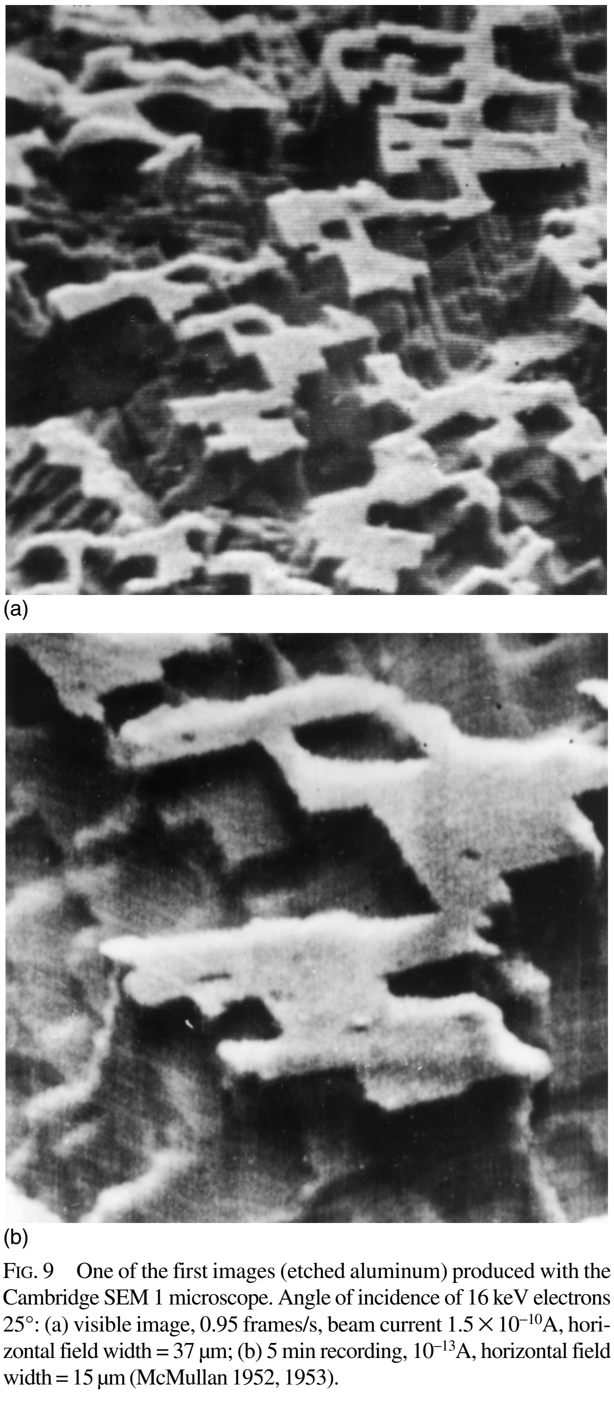

FIG. 9 One of the first images (etched aluminum) produced with the Cambridge SEM 1 microscope. Angle of incidence of 16 keV electrons 25°: (a) visible image, 0.95 frames/s, beam current 1.5×10^{-10}A, horizontal field width = 37 μm; (b) 5 min recording, 10^{-13}A, horizontal field width = 15 μm (McMullan 1952, 1953).

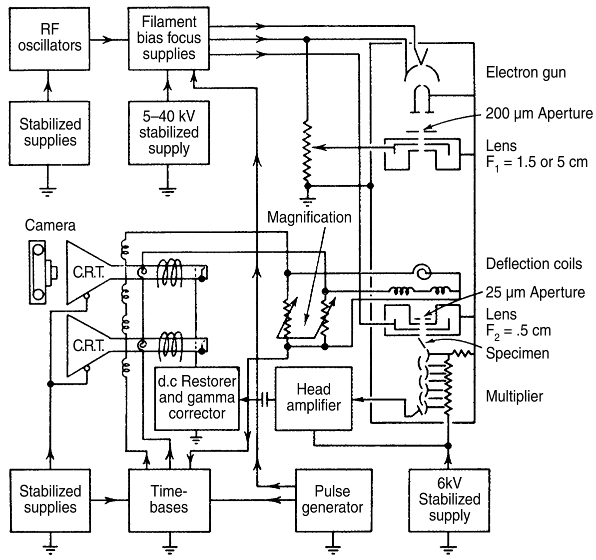

FIG. 10 Block diagram of SEM 1 (McMullan 1952, 1953).

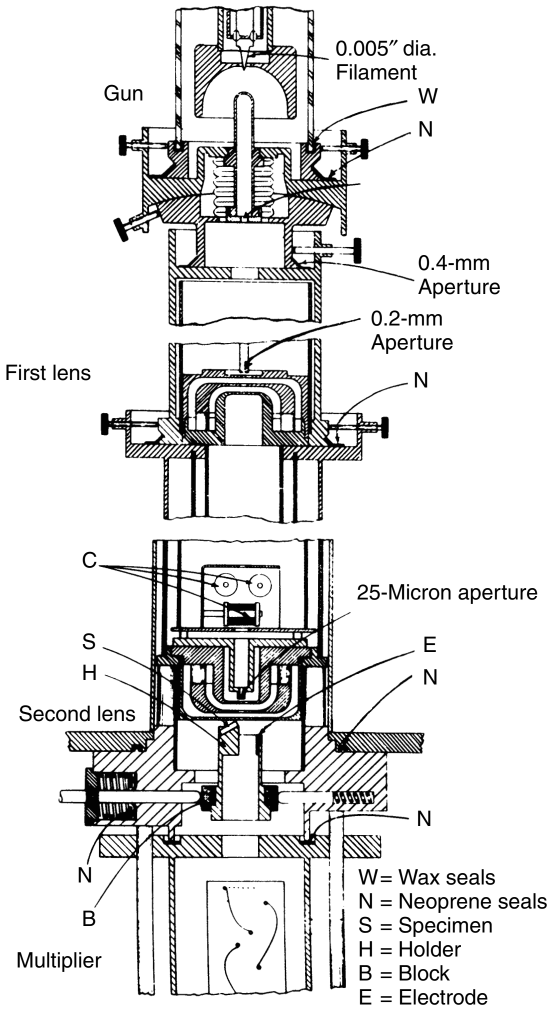

FIG. 11 Cross section of the column of SEM 1 (McMullan 1952, 1953).

versus atomic number had recently been published by Palluel (1947), but an attempt at obtaining atomic number contrast failed; some years later Wells (1957) was more successful. The obvious disadvantage of high-beam energies was that the resolution was limited by penetration of the primary electrons. I suggested low-loss electron imaging (LLE) to minimise this, but was not able to implement it. One other contrast mechanism that I tried was cathodoluminescence and I was able to demonstrate that phosphors which had too long a decay constant to be used to produce a 1.9 s frame time image with a Zworykin-type detector were completely satisfactory when excited at a high-current density by a focussed probe.

Figure 12 is a photograph of the SEM taken in 1953 shortly before K.C.A. Smith assumed responsibility for it and turned this first instrument into an SEM which could produce images comparable with those from modern microscopes. He introduced improvements including a stigmator and a tilting sample stage, and he increased the efficiency of the detection system by moving the electron multiplier nearer the sample so that low-energy secondary electrons could be collected, thus increasing the signal current. He also showed that metallised insulating samples could be imaged, and he examined a wide variety of samples including thermal decomposition of silver azide, germanium point-contact rectifiers, and fungus spores in water vapour in an environmental cell (Smith and Oatley 1955, Smith 1956).

The electron multiplier of this modified instrument was a bulky device, and in 1956 Oatley suggested that an aluminised short-decay-time plastic scintillator plus photomultiplier might be worthwhile investigating. Smith first used this combination to detect high-energy backscattered electrons and later two more of Oatley's students, Everhart and Thornley, developed it as the secondary electron detector that bears their names (Everhart and Thornley 1960).

Altogether five SEMs were built in the Engineering Department: SEM 2 (Wells 1957), SEM 3 (Smith 1961), SEM 4 (Stewart 1962), and SEM 5 (Pease and Nixon 1965). All were used on a wide variety of samples and for the development of new techniques. Other important instrumental advances made by Oatley's group during the remainder of the 1950s and to 1965 included: atomic number contrast (Wells 1957); stereomicroscopy (Wells 1960); voltage contrast (Oatley and Everhart 1957); low-voltage (1 kV) SEM (Thornley 1961); high temperature (1200K) imaging of thermionic cathodes in an SEM (Ahmed 1962); high resolution (10 nm) SEM (Pease and Nixon 1965); etching of surfaces in an SEM by ion bombardment (Stewart 1962); ion etching and microfabrication in SEM (Broers 1965); microelectronics in SEM (Chang and Nixon 1966). In addition, EBIC imaging was first demonstrated by Wells *et al.* (1963), but not in Cambridge. Most of this work is described in papers by Oatley (1982) and Oatley *et al.* (1965, 1985).

Smith completed SEM 3 (Fig. 13) in 1958; this was the first magnetically focussed SEM (Smith 1959, 1961). The lower section of the column below the table consisted of a modified Metropolitan Vickers (later AEI) type EM4 TEM (Page 1954) and contained the electron gun, condenser lens, transmission sample stage, objective lens, and double pole-piece projector lens. For scanning operation, the transmission objective and double projector were used together in various combinations and powers according to the spot diameter required to provide the first stage of spot demagnification. Immediately above the table there was a section of the column containing the scanning coils and the objective lens which was of the pin-hole type (Liebmann 1955) with three adjustable apertures. There was a tilting sample stage, and the secondary electron detector was of the Everhart-Thornley type.

SEM 3, which was the first fully engineered SEM, had been commissioned by Thiesmayer and Atack of the Canadian Pulp and Paper Research Institute and was used for examining wood fibres in their Ottawa laboratories: this was the earliest industrial use of an SEM on a daily basis. They

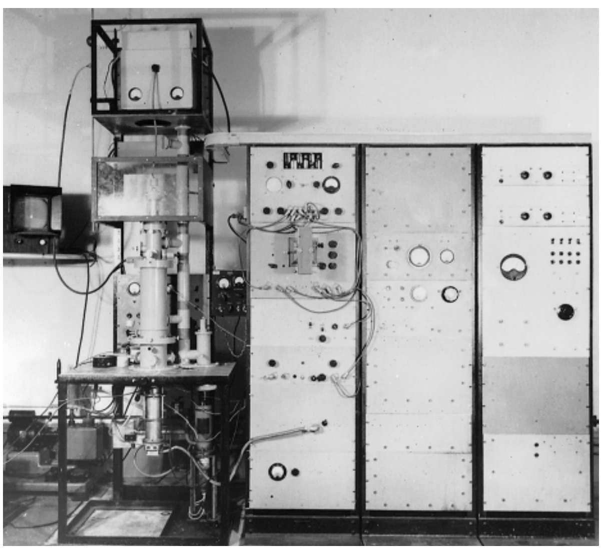

FIG. 12 Photograph of SEM 1 taken in 1953.

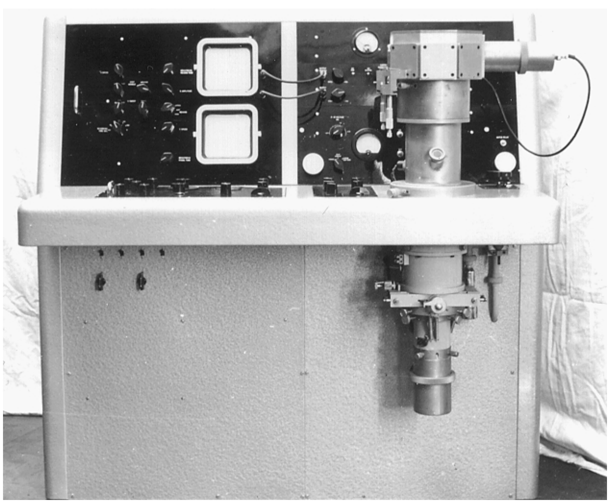

FIG. 13 The first magnetically focussed scanning electron microscope (SEM 3) built by K.C.A. Smith for the Pulp and Paper Research Institute of Canada (Smith 1959, 1961).

were among the very few who at that time saw the great potential of SEM (Atack and Smith 1956): although Oatley's group had produced and published high-quality micrographs from many different samples, there was still considerable resistance to SEM. Over several years Oatley expended much effort in trying to persuade electron microscope manufacturers to market an SEM (Jervis 1971, Oatley 1982), but he was finally successful only in 1962 when the Cambridge Instrument Company decided to go ahead with the production of the "Stereoscan" (Fig. 14) which was based on the instruments developed by Oatley's group (Stewart and Snelling 1965). The prototype went to the Dupont Chemical Corporation in the USA in 1964 and in the following year the first two production models were sold to Thornton at the University of North Wales and to Sikorski at Leeds University in the U.K., and the third to Pfefferkorn at Münster University in Germany. The Japanese firm JEOL marketed their JSM-1 SEM about 6 months later.

Other SEMs up to 1965

SEMs were developed in other laboratories within this time frame as well. An SEM was built in France by Bernard and Davoine (1957) at the National Institute of Applied Science in Lyon: it had a probe size of the order of 1 µm and was used over a period of years mainly for cathodoluminescence studies. In the U.K., AEI, then a major TEM manufacturer, developed an SEM but did not proceed after the first instrument, sold in 1959, turned out to be unsatisfactory (Jervis 1971). In the early 1960s, at the Westinghouse Laboratories in Pittsburgh, Wells, Everhart, Matta and others built an advanced SEM for semiconductor studies and microfabrication and demonstrated EBIC imaging (Wells *et al.* 1965). And in the USSR there was an SEM at Moscow University from about 1960 (Kushnir *et al.*).

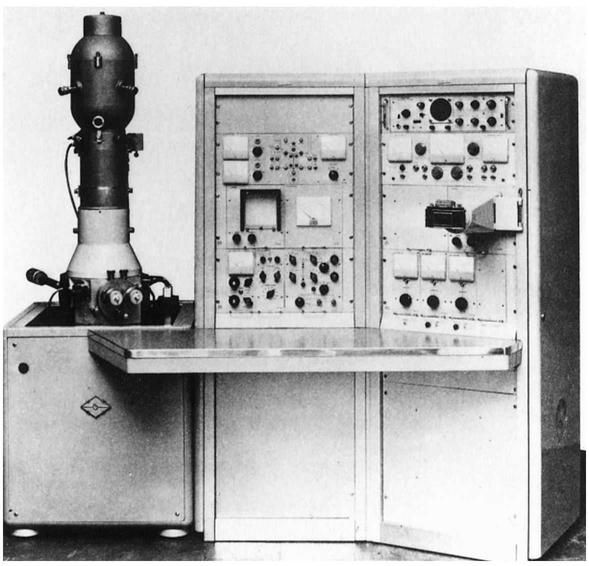

FIG. 14 The prototype of the first Stereoscan SEM, supplied by the Cambridge Instrument Company to the duPont Company, U.S.A. (Stewart and Snelling 1965). Courtesy of Leica Ltd.

There were other groups, especially in Japan, who researched the SEM but did not publish their results.

Electron Probe X-Ray Analysers

Although peripheral to the subject of this article, the salient events in the development of the electron probe x-ray microanalyser will now be briefly summarised. Originally proposed by Hillier in 1947, a static probe instrument was developed by Castaing and Guinier in Paris in 1949 (Castaing and Guinier 1949) and marketed by the French firm Cameca in 1956. Cosslett at the Cavendish Laboratory in Cambridge started a research programme in 1953 which 2 years later led to a scanning microanalyser built by Duncumb (Cosslett and Duncumb 1956). This was further developed at the Tube Investments Research Laboratories near Cambridge (Duncumb and Melford 1960) and was marketed as the "Microscan" by the Cambridge Instrument Company in 1960. In the U.S.A., microanalysers were developed by Birks and Brooks (1957) among others. Firms in several countries were marketing microanalysers by 1965; the probe sizes were generally around 1 µm and electron imaging was only an adjunct technique. A few years later SEMs were being equipped with the newly introduced energy-dispersive silicon diode spectrometers, and x-ray microanalysis on SEM samples is now routine.

Conclusion

This article has described how the development of the scanning electron microscope from concept to the marketing of a commercial instrument in 1965 took 30 years. The foundations were laid in the 1930s by Max Knoll (b. 1897, d. 1969) who first obtained scanned electron images from the surface of a solid, and by Manfred von Ardenne (b. 1906) who established the principles underlying the SEM, including the formation of the electron probe and its deflection, the positioning of the detector, and ways of amplifying the very small signal current. The technology necessary for the realisation of his ideas was only just becoming available and because of the very short time he had for the development of an SEM he was unable to put them into practice.

Vladimir K. Zworykin (b. 1889, d. 1982) and his team at the RCA Research Laboratories built an SEM which had several important original features, but its performance was not adequate to persuade electron microscopists of its usefulness.

The SEM idea was revived in 1948 by Charles Oatley (b. 1904) at the Cambridge University Engineering Department, and over the next 15 years a succession of his research students built five SEMs of increasingly improved performance culminating in the production of a commercial instrument by the Cambridge Instrument Company.

The contributions of Knoll, von Ardenne, Zworykin, and Oatley to the genesis of the scanning electron microscope should be recognised by the many thousands of microscopists who today use this instrument in virtually every field of scientific research.

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