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Cathode lens electron microscopy: past and future

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Abstract
This retrospective sketches the evolution of emission electron microscopy, low energy electron microscopy and related methods from the early stages up to the present state and gives a brief outlook on the future possibilities of these cathode lens electron microscopy techniques. It is concerned mainly with instrumentation, discusses some little known work and emphasizes important steps in the evolution of the field instead of attempting to review it in detail.

1. The early years of emission microscopy

This year photoelectron emission microscopy (PEEM) is 75 years old. It was in 1933 that Brüche used a simple instrument (figure 1) to produce the first PEEM image [1]. It showed at 10 times magnification holes in a Zn plate that was irradiated with UV light. In the same year Zworykin showed that also secondary electrons could be used for surface imaging [2] and a year earlier both Brüche and Johannson [3] and Knoll *et al* [4] had demonstrated imaging with thermionic emitted electrons.

Thus, emission electron microscopy was born in the early 1930s. In the following years, the simple first instruments were increasingly improved and the first studies of electron mirrors were made [5, 6]. The terms cathode lens and immersion lens were introduced and first elementary calculations of the resolution limit of these lenses were made [7, 8] but it was not until the early 1940s that detailed calculations were performed. Recknagel's geometric–optical calculations [9] of the resolution δ for emitted electrons resulted in the famous Recknagel formula $\delta = 4\varepsilon/F$. Here ε is the emission energy divided by the charge of the electron and F is the field strength at the cathode. This formula was later also generally applied to faster electrons, which caused significant problems with the acceptance of the possibility of high resolution imaging with reflected electrons. Subsequent wave optical calculations for the homogeneous acceleration field [10] addressed the various factors affecting the resolution of emitted electrons and came up with the expression $\delta = \lambda_k(\varepsilon/\lambda_k F)^{1/4}$, where λ_k is the wavelength corresponding to the emission energy of the electron from the cathode.

Ten years after the first low magnification images, thermionic emission electron microscopy (THEEM) achieved a better resolution than that of the light microscope [11–14] after Boersch realized that the resolution could be improved significantly by limiting the angular aperture in the back focal plane [11]. However, it took 25 years before PEEM reached a resolution in the 100 nm range [15, 16]. Shortly before that, emission microscopy with secondary electrons (SEEM) produced by ion bombardment had already reached a resolution in the 10 nm range [17]. Another 10 years later, Engel reached in PEEM a point resolution of 12 nm, in SEEM 27 nm and in THEEM 40 nm [18]. Engel not only achieved the best well-documented resolution to date but also made a comparative study of the contrast formation in the various imaging modes (figure 2), including the influence of the wavelength of the light in PEEM. Unfortunately none of his results were published but some images can be found

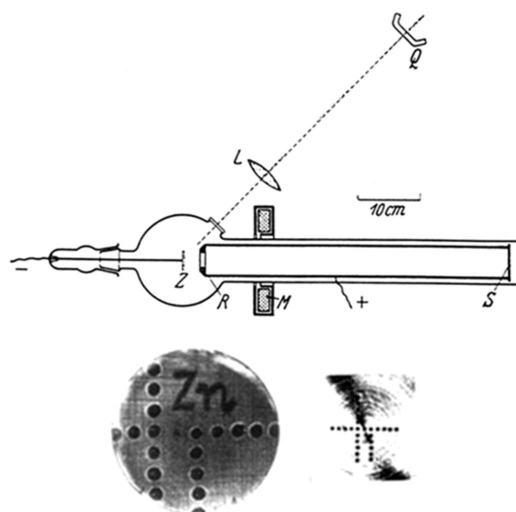

Figure 1. Schematic of Brüche's first PEEM system and first PEEM image of a scraped Zn plate with holes. Magnification 6× and 2×. Reproduced from [1] with permission. Copyright 1933 Springer.

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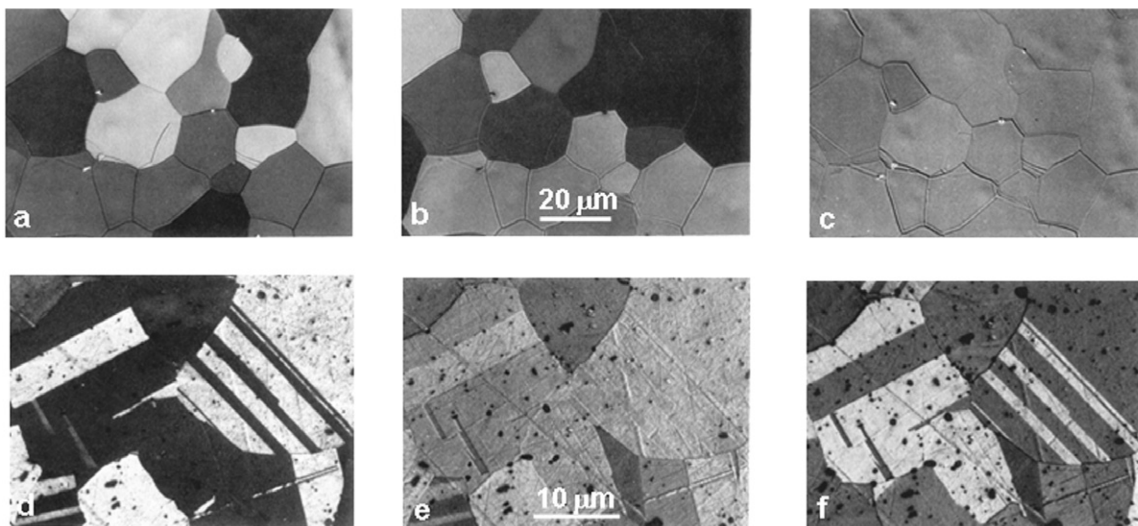


Figure 2. (a) THEEM, (b) threshold PEEM and (c) 'kinetic' SEEM image of polycrystalline Ta. (d)–(f) PEEM images of polycrystalline beryllium bronze taken with increasing photon energy from left to right. Reproduced from [18] with permission.

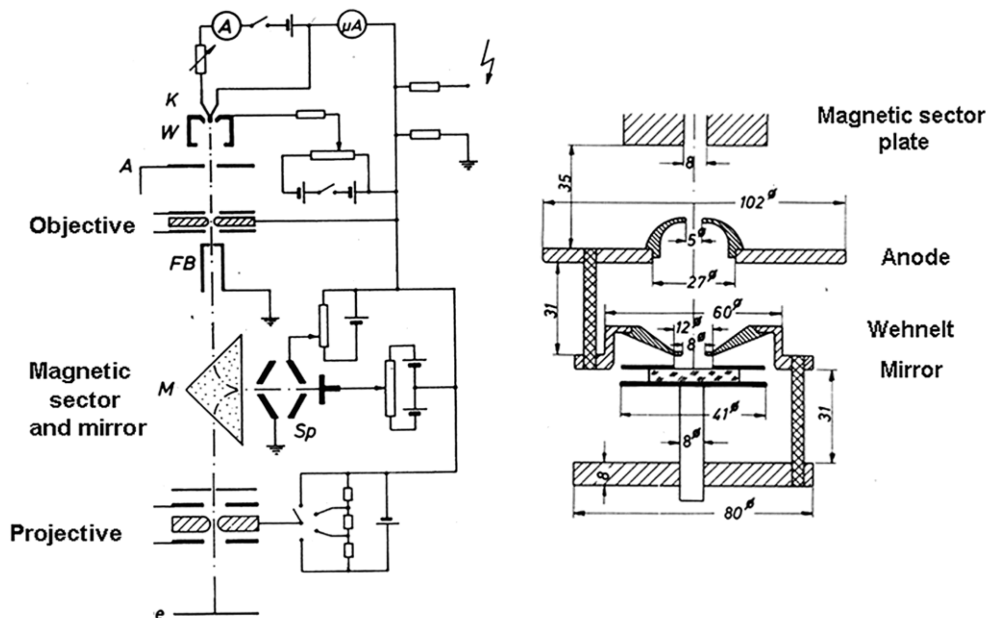


Figure 3. Emission microscope with magnetic prism–electron mirror low pass energy filter. Left: schematic of the instrument as used for measuring the energy distribution of a cathode. For imaging, the specimen was placed above the objective. Right: schematic of the electron mirror used in this instrument. Dimensions in mm. Reproduced from [22, 23] with permission. Copyright 1968, 1971 Optik.

in a review paper [19]. Finally, also the influence of the direction of the polarization of the light on the contrast was demonstrated [20].

2. The maturation of emission microscopy

The years from the 1950s to the 1970s saw considerable activity in surface electron emission microscopy in Europe, predominantly in Möllenstedt's institute in Tübingen.

For example, by 1968 Möllenstedt *et al* had demonstrated that resolution and contrast could be improved by using a Castaign type [21] magnetic prism–electron mirror combination as a low pass energy filter (figure 3) [22, 23]. Also in this period the first commercial instrument, the METIOSCOPE KE 3 was developed [24]. However, the rapid surface contamination in diffusion-pumped instruments seriously limited the application of PEEM. Therefore, mainly ion bombardment, which simultaneously cleaned the surface and caused secondary electron emission ('kinetic emission') was used for imaging (SEEM). Also THEEM was used frequently, in particular in the study of cathodes. Despite the high temperatures, contamination by residual gas adsorption and hydrocarbon cracking could not be avoided.

Surface studies under clean conditions require bakeable oil-free all-metal systems, which became widespread only in the sixties. Actually, the first microscopes of this

type had already been reported in the mid-1960s and early 1970s [25–27] but became fully productive only after improvements in the 1980s [28–30]. One of the first applications was a PEEM study of the doping of semiconductors, which showed that the PEEM contrast was very sensitive to the doping level and that dopant concentrations as low as 10^{16} cm^{-3} could be detected [31]. The new possibilities that metal ultra-high vacuum systems brought to the study of surfaces in the 1990s stimulated the development of more instruments. Small electrostatic UHV flange-on PEEMs with the specimen at ground potential of the type described in [32] were built and commercialized, one of them with retarding field high pass energy filtering [33].

Before turning to low-energy electron microscopy (LEEM) the introduction of two additional light sources in PEEM, which previously used only UV lamps, should be mentioned briefly: frequency-multiplied lasers and synchrotron radiation. Massey *et al* used multiphoton absorption of the 266 nm fourth harmonic of a Nd:YAG laser with 100 ns pulses to image guided waves in a $LiNbO_3$ wafer [34]. With the same laser, Massey found a strong resolution and contrast degradation in images of stainless steel with increasing laser power and corresponding increase of the screen current density from 0.1 to 1 A cm^{-2} (figure 4) [35]. This degradation could not be explained by space charge effects [36] nor by thermionic emission at the higher irradiation power. Later he used an Ar laser to image modes in a silicon nitride optical waveguide [37].

X-ray stimulated photoemission for spectroscopic imaging with a conventional x-ray source had already been proposed in the early 1970s [38] but not with submicron resolution as expected on the basis of intensity estimates [19, 39]. These estimates showed that the much higher photon flux density of synchrotron radiation, in particular from undulators, would be needed for meaningful magnifications. The feasibility of imaging with synchrotron radiation was demonstrated in the late 1980s by Tonner *et al* [40–42]. They did not use photoelectrons for imaging but secondary electrons whose yield depends strongly upon the x-ray absorption cross section (XSEEM). This imaging mode, which does not require an energy filter for spectroscopic imaging, was subsequently also used in some significantly improved electrostatic PEEM instruments installed at synchrotron radiation sources [43, 44]. In particular, the magnetic dichroism contrast at the 2p absorption edges of 3d transition metal atoms, which gives information on the magnetic state of the specimen together with chemical information, was introduced in the early 1990s [45] and in 2001 the x-ray absorption near edge structure (XANES) contrast, which provides information on the chemical bonding [46], was introduced. Hemispherical analyzers [47], Wien filters [48] or time-of-flight energy selectors [49] were added to allow imaging with photoelectrons (XPEEM), which requires a band pass filter. Time resolution was achieved in 2004 [50, 51], by using pulsed excitation correlated to pulsed detection, provided by proper operation of the synchrotron light source. Finally aberration-corrected instruments were designed and built. This is the present state of the art, which will be briefly discussed later in connection with LEEM.

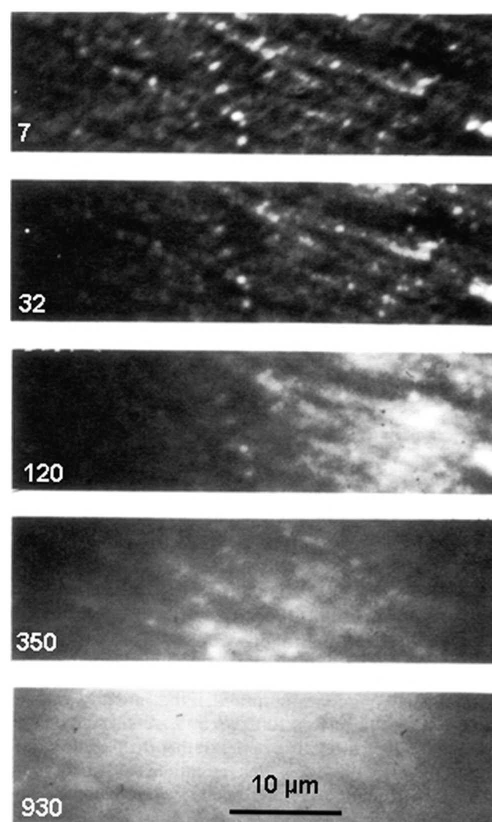
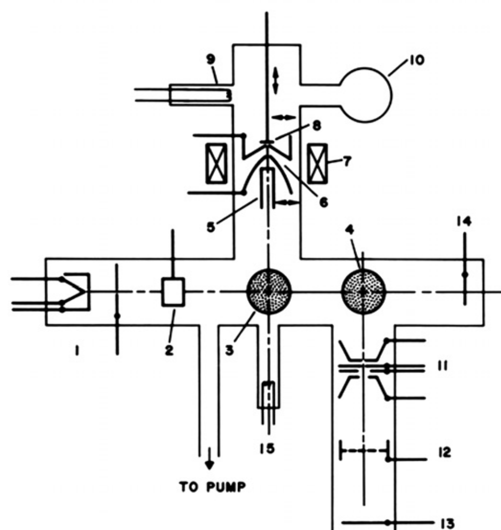


Figure 4. Degradation of the PEEM image with increasing power of the illuminating laser. The numbers are the current densities on the screen in mA cm^{-2}. Reproduced from [35] with permission. Copyright 1983 IEEE.

3. The early years of low energy electron microscopy (LEEM)

Although the first good LEEM images were not published until 1985, the idea to use diffracted low energy electrons for imaging was first conceived 50 years ago in connection with the writing of a book on electron diffraction, which also contained a chapter on transmission diffraction microscopy and low energy electron diffraction [52]. At that time LEED systems were glass systems and the diffraction pattern was acquired by scanning with a Faraday cup [53]. Using diffracted electrons for imaging was completely unrealistic and not even mentioned. This changed a few years later when Germer and collaborators demonstrated that there was enough intensity in a LEED pattern to display it on a fluorescent screen [54, 55]. They interpreted their LEED patterns in terms of single scattering by the topmost layer of atoms [56], while the author of this paper knew from writing his book on electron diffraction [52] that several layers were involved in the diffraction process and that multiple scattering had to be taken into account [57]. The resulting dispute stimulated the development of an instrument for imaging with diffracted electrons. The first system was a glass system (figure 5) [58] because the glass blower convinced management that he could build it. However, repairs soon made the system unusable and permission was given for construction of a metal system, which could be presented a few years later in 1964 [59].



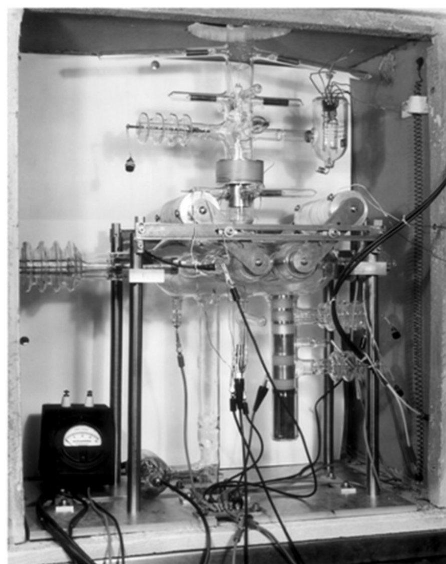


Figure 5. The first short-lived LEEM system [58].

Parallel to this instrument development work, two problems were addressed which were important for the viability of LEEM: lateral resolution and elastic backscattering cross section. If the Recknagel formula $\delta = 4\varepsilon/F$ were to be valid at higher energies, then low energy reflection microscopy would have a lower resolution than emission microscopy. More detailed calculations of the resolution after Recknagel's original work all gave the same ε/F dependence of δ. Only the prefactor 4 was reduced to 0.6–1.2 when δ was calculated for the disc of least confusion instead of the Gaussian image plane and when the angular and energy distribution was taken into account. All this work was naturally focused on emission microscopy. The only expression for δ which predicted a slight improvement with increasing energy was obtained by Recknagel from wave mechanical calculations for the homogeneous acceleration field mentioned before [10]. It predicts $\delta \sim \varepsilon^{-1/8}$, but is valid only for very low energies because of the assumption that $\varepsilon/F \leqslant \lambda_k$. It should be noted that the poor predicted resolution of emission microscopy of about ε/F is due to the fact that all electrons, including those emitted parallel to the surface ($\alpha = 90°$), are used for imaging. Much better resolutions had already been achieved with angle-limiting apertures [11–18]. The reason for this can be seen easily: the spherical aberration of the homogeneous acceleration field gives $\delta = 2\sin\alpha(1 - \cos\alpha)\varepsilon/F$, which results for small α in $\delta \approx \alpha^3\varepsilon/F$ instead of $\delta = 2\varepsilon/F$ for $\alpha = 90°$. Of course α cannot be made too small because of diffraction at the aperture and loss of intensity.

For LEEM it was evident from the beginning that small apertures could be used because in LEED the intensity of the reflected electrons is confined into narrow beams. Elementary calculations for the homogeneous acceleration field including spherical, chromatic aberration and diffraction at the aperture clearly showed that resolutions comparable and better than in PEEM could be achieved [60]. This was confirmed by calculations for a simple three electrode immersion lens [61] which were made using a new method [62] particularly well suited for low energies, later called the boundary element method. The results were published in detail only much later [63] in order to overcome the widespread persistent opinion, based on Recknagel's formula, that LEEM would have poor resolution. After the usefulness of LEEM was demonstrated in 1985, these results were confirmed by many more detailed calculations for various immersion lens types. For example, it was shown that the electrostatic tetrode and the magnetic triode had a significantly better resolution, mainly due to the higher field strength at the specimen than in the electrostatic triode (figure 6) [64].

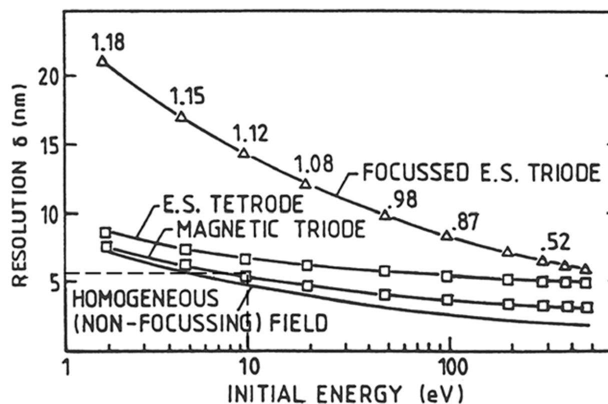


Figure 6. Resolution of various cathode lenses as a function of energy for an energy width of 0.5 eV and field strength at the specimen of 10 kV mm^{-1}, except for the triode in which the field varies from 0.58 to 1.18 kV mm^{-1} under focusing conditions. Reproduced from [64] with permission. Copyright 1989 Optik.

The second question that needed to be answered before embarking on the construction of a complicated instrument was: is there enough intensity for imaging at sufficiently high magnification? This was answered by calculating the elastic backscattering of slow electrons by atoms, which cannot be described in the first Born approximation used for the

forward scattering of fast electrons in transmission electron microscopy. The initial calculations for free atoms [65] showed that the angular distribution of the scattered electrons depended strongly on the long range potential. Therefore, subsequent calculations were made for potentials used in band structure calculations and truncated atomic potentials to take account of their overlap in condensed matter, which leads to the mean inner potential. Attempts to take account of exchange and correlation were given up because of the resulting complications and the lack of evidence of strong influence on the qualitative aspects of the backscattering. The results, some of which were published only much later [66, 67] clearly showed that for all atoms studied the backscattering was strong enough at low energies for imaging, in particular when focused into diffracted beams, specifically into the specular beam.

This theoretical backing justified instrument development. For the beam separator in the metal system a 60° sector field was chosen because more was known about its optical properties than for 90° deflection, which the glass blower had to choose in the glass system for technical reasons. Because the resolution calculations had shown that chromatic aberration limited the resolution, a cold W field emitter was initially used as the electron source but attempts were given up after repeated losses by arc-over. Next a zirconia-coated W(100) thermal field emitter was developed with which most tests were made. The detector was initially a simple fluorescence screen until the first channel plate multipliers became available from the Fort Belvoir Night Vision Laboratory. Most of them did not survive the bakeouts. With all these problems there was still no image by 1966 and management became impatient. Therefore it was decided to disassemble the instrument and temporarily use it in a straight setup for emission microscopy in order to produce some images [68]. After reassembly as LEEM, further technical problems and dwindling support did not bring success. In 1968 George Turner, who had done all the instrument work, was finally transferred to another department which brought the work more or less to a standstill and in 1969 the instrument was transferred from the Michelson Laboratory, China Lake, California, to the Technical University Clausthal, Germany, when the author of this paper moved there.

Rebuilding it there, in part with some modifications, for example by replacing the unreliable electrostatic UHV pump with a sputter ion pump, took some time because it was done by a series of inexperienced masters students, but by 1972 the instrument was rebuilt again [69]. Subsequently a few more masters students got some training in UHV and electron optics on the instrument but it was not until Wolfgang Telieps took over the system in the late 1970s that real progress was made. He succeeded in keeping the W field emitter alive long enough to produce the first LEEM images in the early 1980s [70]. He also demonstrated the usefulness of combining PEEM with LEED for structural characterization of regions with different PEEM contrast. In 1985 the first impressive LEEM images showing atomic steps on Mo(110) were published (figure 7) [71]. Telieps reached a resolution of 20 nm in LEEM, 50 nm in PEEM and 100 nm in mirror electron microscopy (MEM). The images of the Si(111) surface, which showed the

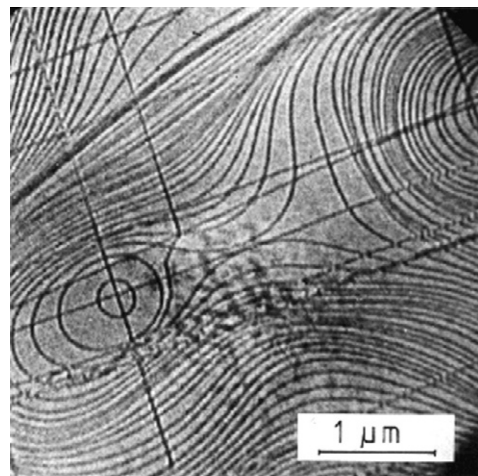


Figure 7. The first high resolution LEEM image showing atomic step contrast. Specimen: Mo(110). Electron energy 14 eV. Reproduced from [71] with permission. Copyright 1985 Elsevier.

coexistence of the (7 × 7) and (1 × 1) structure, and movies of the kinetics of the (1 × 1) ↔ (7 × 7) transition [72] finally convinced the scientific community of the power of LEEM for surface studies and stimulated others to develop and use this technique too.

4. The maturation of LEEM

In the late 1980s several groups started to build LEEM instruments, some following the original design [73, 74], others based on different designs [75, 76]. One design [73] was very successful, others were less for various reasons such as termination of the project before completion [75] or unsuitable specimens despite good instrument design [76]. This latter instrument was built for the study of biological specimens from which backscattering is diffuse. Contrast in this case is mainly due to the topography of the surface. The LEEM images from a biological sample obtained with this instrument at an energy of several electronvolts [77] are very probably mirror images caused by charging of the specimen.

The success of the first LEEM in Clausthal lead to the Volkswagen Foundation's support of the long-envisaged (references in [39]) extension of LEEM to spectroscopic imaging. After Telieps' untimely death in 1987, Lee Veneklasen took over the design of this instrument [78]. The basic instrument without an energy filter (LEEM II) was completed and exhibited at an international conference in 1989. Subsequently a hemispherical energy analyzer was added and in 1994 beamtime became available at BESSY where the first spectroscopic photoelectron images were acquired [79]. In this period also imaging with Auger electrons was tested (figure 8) and in 1995 a comparison between photoelectron and Auger electron imaging was presented [80] which demonstrated the usefulness of Auger electron emission microscopy (AEEM) for chemical imaging, at least at high primary electron current densities [19, 39]. After the instrument was transferred to the Sincrotrone Trieste in 1996, x-ray-excited imaging, both in the XSEEM and in the XPEEM mode was complemented

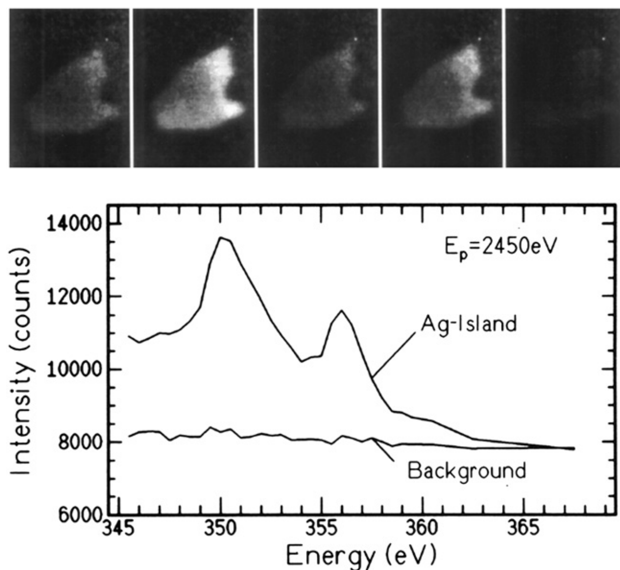


Figure 8. Selected AEEM images of Ag on Si(111) and spectra obtained from them by measuring the intensity in 1.5 μm^2 areas on the flat, (111)-topped Ag crystal and on the Ag monolayer. Primary energy 2450 eV, energy window 1 eV. The images were taken with 346, 350, 354, 356 and 360 eV electrons. Image acquisition time 20 s. Reproduced from [80] with permission. Copyright 1997 Kluwer–Academic.

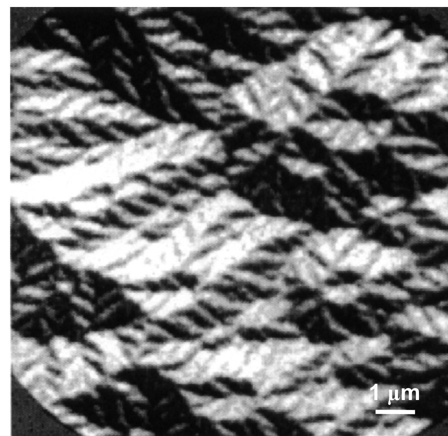


Figure 9. SPLEEM image of the magnetic closure domains on the Co(0001) surface. Reproduced from [83] with permission. Copyright 1991 *MRS Symp. Proc.*

by photoelectron diffraction and band structure analysis from micron size regions on the sample.

An improved commercial version of this spectroscopic LEEM/PEEM ('SPELEEM') can be found today in most third generation synchrotron radiation sources and has become one of the most versatile surface analysis systems, thanks to the combination of many characterization techniques. A second result of this success was support for a collaboration between several complementary groups (Darmstadt, Clausthal, Brno, Berlin) with the goal of improving the resolution of cathode lens electron microscopy by aberration correction. This effort was led on the theoretical side by Rose [81] and led finally to the instrument described in this and previous [82] workshops. Another extension of LEEM to spin-polarized LEEM (SPLEEM) for the study of magnetic materials was stimulated in the late 1980s by Poppa from IBM Almaden and developed in a joint effort in Clausthal. The field emitter was replaced by a cesiated GaAs surface, followed by a 90° deflector. Spin-polarized electron emission was excited by illumination of the photocathode with circular-polarized laser light. One of the first magnetic images is shown in figure 9 [83].

A second phase of the instrument development started in the mid-1990s. With the goal of reducing the costs of LEEM and to attach it to other surface analysis instruments, two flange-on instruments were developed by the Arbeitsgruppe Bauer in Clausthal [84, 85], one of them specifically for IBM for SPLEEM [86], which was later transferred to Berkeley, where it is used now very successfully. Tromp *et al* improved the 90° beam separator considered previously in Clausthal [87, 88] and built a significantly improved LEEM with a field emission gun, which allowed them to approach the theoretical resolution of LEEM [89]. Finally, a completely different beam separation method using a Wien filter was attempted in a commercial instrument [90] but, as a consequence of the difficulty of achieving simultaneously normal incidence and reflection, this has led to little use of this instrument for LEEM. An instrument in which the incident beam is produced by specular reflection of an electron beam perpendicular to the optical axis from a W single crystal tilted 45° against the optical axis [91] has experienced a similar fate.

Finally, at the beginning of this century, the efforts to correct the aberrations of the cathode lens began to bear fruit. Scherzer [92] and Zworykin *et al* [93] had already pointed out in the 1940s several ways to achieve this goal. One of them was the use of an electron mirror, whose aberration constants have the opposite sign to that of the electron lenses. There were many studies of the optical properties of electron mirrors before the first aberration-corrected instrument designs were proposed [76, 81, 94]. One of them, the SMART instrument, has been developed over the years [82, 95, 96] and is now in operation at BESSY II (Berlin). A second one, which uses a design similar to Rose's [81] but without LEEM possibilities, is in development at ALS (Berkeley) [97].

While these developments aim at the ultimate resolution and high transmission of cathode lens electron microscopes, the needs of the microelectronic industry for fast inspection has led to a revival of mirror electron microscopy (MEM), which allows much faster image acquisition than the usual scanning electron microscopes due to the parallel image acquisition [98–100]. In these MEMs the requirements are quite different from those of ordinary cathode lens microscopes: a very large field of view, the possibility of charge compensation, which is particularly important in MEM, a large specimen table, to mention a few of them. As a consequence, a good inspection system using MEM is considerably more complex than a standard LEEM.

5. An outlook at the future of cathode electron microscopy and its application

Before taking a look at the future of the field, it is useful to examine its present state, not only the instrumental aspects that have been discussed so far, but also the applications for which the instruments were used. In addition to the home-built LEEM, SPLEEM and flange-on LEEM instruments there are now two excellent commercial LEEM/PEEM instruments, one of them with an imaging energy filter, which is in widespread use, mainly in synchrotron radiation sources. There is the aberration-corrected instrument spectroscopic LEEM/PEEM SMART in operation at BESSY (Berlin) and PEEM in the testing phase at ALS (Berkeley). ALS also has the most productive high resolution PEEM (PEEM II) [44]. Similar instruments are commercially available and in use. Finally, there are many small PEEM instruments, some of them in very sophisticated versions such as those using time-of-flight energy filtering. The following questions arise: what has been done so far with these instruments so that we know what we can expect from them in the future and what needs to be improved or developed in instrumentation to broaden the applications?

Until the early 1990s the information obtained from the images was mainly qualitative, both in PEEM and LEEM. The reason for this is simple: in order to extract quantitative information from the images, for example of the time or temperature dependence of surface processes, a huge amount of data has to be stored and analyzed which needs digital data acquisition and storage, fast computers and good theoretical support. This did not exist before the early 1990s. In addition, on the experimental side, the experimental parameters such as temperature or deposition rate have to be controlled precisely. Take for example LEEM experiments. In the early work—and to a large extent still today—it was difficult to measure the temperature of the specimen, which sits at high potential. Image acquisition was made with video recorders on video tapes and the conversion into digital format was expensive and cumbersome. Thus, while for example the anisotropic growth of Si on Si(100) (figures 10(a)–(c)) [101] or the sublimation of Si(100) via 'Lochkeim' formation (figures 10(d)–(f)) [102] could be followed at video rate, the extraction of the kinetics of the processes and of the basic physical processes underlying them was not possible.

The situation changed in the early 1990s with the improvements of data acquisition, via digital cameras, and of the computer technology. Quantitative studies were then pioneered by Tromp *et al* at IBM and soon also used by other groups such as Kellogg's at Sandia or Altman's in HKUST. Today data acquisition, storage, processing and analysis is no longer a limiting factor for quantitative studies. For example, in pump–probe experiments, which have been developed during the last five years for magnetic studies, millions of images have to be acquired, stored and analyzed. Today the factors that limit quantitative studies are the precise control of the experimental conditions and, in the case of studies with synchrotron radiation, the beamtime available for the experiment. The first factor depends not only on the quality of the instrumentation but equally upon the quality of the experimentalist, the second is determined by science policy and the competition for beamtime. Science policy is the major uncertainly in predicting the future: promising projects may be terminated by management as happened with one of the LEEM instruments [75] and nearly happened to the first LEEM development; or they may be stopped by termination of the research grant. Beamtime limitations will hopefully decrease with increasing number of synchrotron radiation facilities. What may become more critical with decreasing funding of the field is the quality of the experimentalist. Looking back at the last decade, many good instruments have become available but most of the scientific output has come from only a few research laboratories with permanent personnel and postdoctoral students, a few university groups excepted. This is not surprising because only very good Masters and PhD students become scientifically productive within their training period.

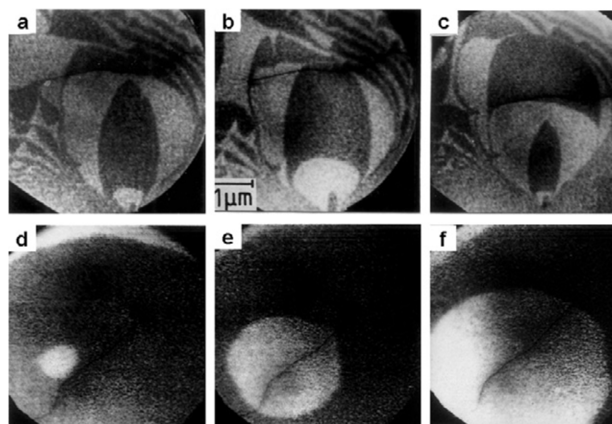


Figure 10. Video frames of the anisotropic growth of Si on Si(100) (reproduced from [101] with permission. Copyright 1991 Elsevier.) and of the Lochkeim formation and growth during sublimation of Si(100) (reproduced from [102] with permission. Copyright 1990 Elsevier.). Electron energy 5 eV.

The only factor that is not uncertain is instrumentation. The present arsenal of cathode lens electron microscopes allows a wide field of applications, some of them not or little used up to now. Further instrument developments, for example simpler (partially) aberration-corrected systems with high transmission, laboratory soft x-ray light sources or direct electron detection with complementary metal oxide semiconductors (CMOSs), will lead to new applications. LEEM instruments are, for example, well suited for area-selected LEED-IV structure analysis, either with small apertures in the illumination systems in the LEED mode for a full structural analysis or by taking many LEEM images with the (00) beam as a function of energy (LEEM-IV) if only the periodicity normal to the surface is of interest. In the case of surface alloys consisting of atoms with sufficiently different backscattering amplitudes and phases, even the layer composition can be determined at the lateral resolution of LEEM [103]. AEEM, which at present is not used for chemical characterization because of the low transmission, will become powerful in aberration-corrected systems and will allow in-house spectroscopic imaging, thus eliminating the need for synchrotron radiation. The same is true for appearance

potential electron microscopy (APEM), which has not been used up to now in LEEM instruments in chemical imaging. It will be particularly useful for materials with a high density of unoccupied states such as the 3d transition metals. This method, which is the counterpart to x-ray XANES imaging mentioned in section 2, has the advantage over AEEM in that it does not require an energy filter and that it makes use of the high intensity of secondary electrons. The transmission gain by aberration correction will also make secondary electron emission microscopy (SEEM) a viable technique and extend the application of LEEM instruments from single crystals to fine-crystalline and amorphous materials, using backscattering cross section differences for contrast formation.

As for PEEM, only two examples for simple extensions of its present use should be mentioned. One is imaging with polarized light, which at present is used nearly exclusively in magnetic studies, for the determination of the lateral distribution of the orientation and chirality of adsorbed molecules, exploiting the orientation dependence of the ionization cross section or polarization. Another one is the use of ring-shaped contrast apertures, which have higher transmission at equal or better energy discrimination [104]. Once affordable tunable UV sources become available, resonant PEEM may become a useful method for the study of systems with sharp occupied energy levels and unoccupied levels above the vacuum level, such as the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels in many organic systems, for example in large biological molecules. Most of the past PEEM work was concerned with metals and semiconductors. With the high transmission of aberration-corrected instruments, radiation-sensitive samples will become more accessible to XPEEM without excessive radiation damage. There are numerous other small extensions of PEEM but a major one, PEEM excited by free electron laser radiation (FEL-PEEM) [105] with high power density in the laser pulses, will very likely be disappointing. Resolution and contrast degrade strongly at high power or current densities as already noted some time back with an optical laser [35] and also observed more recently with undulator radiation and in LEEM. Therefore the goal for the future is not high flux density of the photon beam but high transmission of the microscope if high resolution is to be achieved. Of course, if high resolution is not needed, the high electric fields associated with high intensity may allow imaging of interesting nonlinear phenomena including surface modification.

With all the possibilities which cathode lens electron microscopy offers, one limitation has to be kept in mind for future applications: the surface roughness. For simple geometric surface features the image can be calculated. An experimental example is the square grid of holes shown in figure 11 [106]. In focus there is no contrast, out of focus the structure looks completely different depending upon focus. It is also a good illustration that rough surface features such as scratches cannot be used for resolution determination as has been done occasionally. The deduction of an unknown structure from the image is difficult if not impossible. Perhaps the application of deconvolution or maximum entropy methods

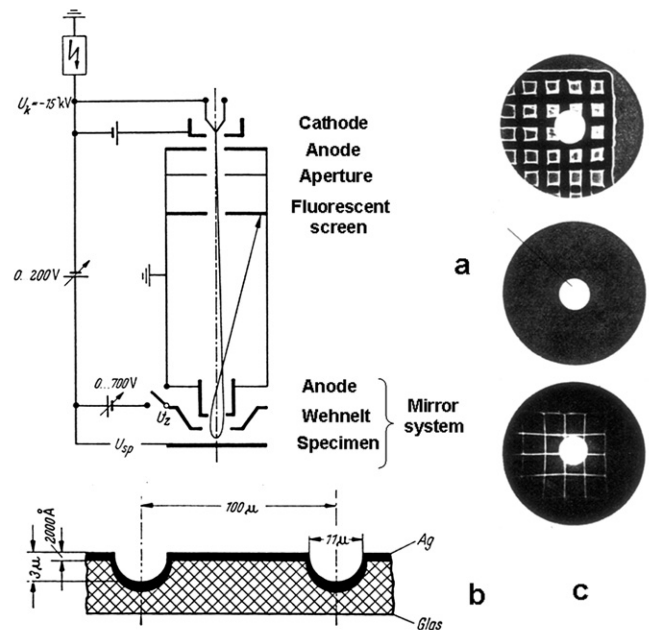


Figure 11. Demonstration of the influence of focusing on image appearance in MEM. (a) Schematic of an MEM instrument, (b) cross section through the specimen, (c) images at different foci; the line points to the hole in the screen [106].

will provide a solution. With this problem in mind, the question arises: in which research fields are there opportunities for cathode lens electron microscopy? If the dream of molecular computing and data storage should become true, then one of the major driving forces of past and present research for this microscopy, semiconductor and micromagnetic technology, would be gone and the beautiful methods developed for magnetic studies would fade away. Resonant PEEM may then become important. The growing environment and energy problems will very likely strengthen research in catalysis, energy conversion and old-fashioned fields such as corrosion. The problems in these fields involve rough interfaces, sponges and nanoparticles, all of which are not accessible to cathode lens microscopy. However, as surfaces play an important role in these fields, there are numerous basic science problems that can be studied with the methods discussed here. Therefore, as long as pressing societal problems do not suppress basic research, cathode lens electron microscopy should have a bright future.

6. Summary

This retrospective of cathode lens electron microscopy has been mainly concerned with the evolution of the instrumentation. Methods have only briefly been mentioned, with some important steps in their evolution missing, for example magnetic PEEM using x-ray magnetic circular and linear dichroism (XMCD/XMLD-PEEM). Applications have been mentioned only occasionally as examples. All this information may be found in more or less thorough reviews, which cover the 75 years [107–123]. They show the evolution and the wide range of applications of cathode lens electron microscopy and its contributions to the understanding of

surface phenomena and provide a good background for future work. In particular, references [113–115, 118, 119, 121, 123] illustrate the wealth of information that has been obtained on the statics and dynamics of magnetic microstructures.

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