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Fabrication and characterization of low aberration micrometer-sized electron lenses

E. Steinwand*, J.-N. Longchamp, H.-W. Fink

Institute of Physics, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland

Abstract

Intrinsic spherical aberrations of electron lenses have been the major resolution limiting factor in electron microscopes for several decades. While effective correctors have recently been implemented, an alternative to correct these aberrations is to circumvent them by scaling down lens dimensions by several orders of magnitude. We have fabricated electrostatic lenses exhibiting one micrometer diameter apertures and evaluated their beam forming properties against predictions from numerical ray tracing simulations. It turns out that it is routinely possible to shape a paraxial low-energy electron beam by such micron-sized lenses. Beam profiles have been measured both at a distant detector as well as in a plane close to the lens. It is shown that the lens can form a parallel beam extending no more than 800nm from the optical axes at a distance of 200µm beyond the lens exit. We believe that these findings constitute a prerequisite to derive novel tools for high resolution microscopy using low-energy electrons.

Key words: microlens, spherical aberrations, electron optics, low-energy electrons, field emission

1. Introduction

Back in 1936 already, Scherzer [1] recognized that rotational symmetric electrostatic electron lenses suffer from intrinsic aberrations which have limited the resolution of conventional electron microscopes for more than 50 years. These intrinsic limitations can only be overcome by introducing elaborate electron optical elements, like multi-pole correctors and mirrors, into the path of an elec-
tron beam. Actually building and implementing such correctors has only recently been achieved [2, 3] and revolutionized modern electron microscopy design. An alternative approach towards minimal aberrations relies on the concept of scaling down both, electron source and lens dimensions. In scaling down the size of an electrostatic lens, while keeping the electrode potentials unchanged, the shape of equipotentials and electron trajectories is maintained; they both just undergo the same similarity transformation as the lens geometry. As a consequence, the spherical aberration coefficient, is directly proportional to the lens size. While several attempts have already been undertaken in this direction [4, 5, 6], routine operation of low aberration micron-scale lenses and their application in scientific instruments are still lacking. While we routinely employ electron sources exhibiting an ultimate emission area of atomic dimension [7] it is now a matter of scaling down a lens by about four orders of magnitude and positioning it with nanometer precision in front of the source.

2. Microlens fabrication

2.1. Basic design criteria

The simplest type of electrostatic lens consists of two parallel planar electrodes with two concentric apertures of not necessarily the same size. The electrodes must be separated by an insulating material to maintain a voltage between them, resulting in a focusing electrostatic field distribution at the apertures as illustrated in Fig. 1. A focusing effect is generated independent of the polarity of the applied lens-voltage. A lens size as small as possible appears preferable in order to minimize spherical aberrations. Considering established micro-fabrication techniques and available materials, lens dimensions in the range of one micrometer appear sensible. Micrometer lens dimensions shall also ensure easy positioning of the lens in an electron-optical system using conventional nano-positioning devices based on piezoelectric manipulators.

2.2. Materials and methods

We have developed several lens fabrication methods comprising various microfabrication steps, evaporation methods and materials for the insulating layers and lens electrodes. The result of all methods is a lens structure similar to the one depicted in Fig. 2(d) featuring a 1µm thick insulating layer, two electrodes of several tens nanometers thickness with one micrometer diameter apertures in them. The electrodes must be freestanding around the apertures to avoid charging effects of the insulating walls while the electron beam impinges on the lens. The fabrication
Figure 1: Operating principle of a two electrode aperture lens for an accelerating electrical field between the electrodes. Equipotential lines and electron trajectories have been calculated for $U_1 = 100\text{V}$ and $U_2 = 350\text{V}$ for an initial electron energy of 100eV.

of one particular type of microlens, showing good performance in terms of stability and cleanliness, will be described here in some detail. As a starting material for the fabrication we use commercially available silicon nitride (SiN) membranes of one micrometer thickness. They serve as insulating layers between the two lens electrodes and exhibit a measured breakdown voltage around 320V, high enough to focus a beam of electrons with kinetic energies in the range of 100eV. The initial fabrication step consists in electron beam evaporation of a roughly 30nm thick layer of amorphous carbon on either side of the SiN membrane (Fig. 2(a)). Next, a focused gallium ion beam (FIB)[8] is used to remove the top carbon as well as the SiN layer within a circular region of 5µm in diameter, whereas the carbon layer at the bottom side of the structure remains unchanged (Fig. 2(b)). For the following process step carbon is first evaporated onto a mica sheet. Subsequently, the carbon film is floated off onto a clean water surface [9] and can thus be deposited onto the upper side of the structure (Fig. 2(c)). As the final step, a hole of 1µm diameter is ion-milled through the freestanding parts of both carbon films (Fig. 2(d)). A SEM image of such a final lens structure is shown in Fig. 2(e).

3. Experimental implementation and qualitative tests of the microlens

3.1. Experimental setup

Lenses fabricated as described above have been tested in an ultra-high vacuum system designed for experiments with coherent low-energy electrons. A W(111) field emission tip is used as a source for a divergent electron beam of high spatial and temporal coherence. Typical emitter currents are in the 10 to 200nA range and the kinetic energy of the electrons at the lens entrance is well below 200eV. The electron detector consists of a microchannel plate (MCP) followed by an electroluminescent layer on the vacuum side of a fibre optic plate (FOP). At the ambient
Figure 2: Schematic drawings of the various steps for lens fabrication and an SEM image of the final lens structure. (a) Carbon deposition on either side of a SiN membrane. (b) Removing the upper carbon and the SiN layer within a circular 5µm diameter region using a FIB. (c) Covering of the structure with a carbon flake. (d) Milling a 1µm diameter aperture through the freestanding carbon layers using the FIB. (e) SEM image of the fabricated microlens, recorded at a tilt angle of 30 degrees. The penetration of the 12keV electrons used in the SEM, allows recognizing the 5µm diameter circular region where the carbon electrodes are freestanding. In this case, the lens aperture of 1µm in diameter, is not concentric with the 5µm region but the distance to the SiN walls is large enough to prevent charging effects when implemented as a lens.
pressure side of the FOP a CCD camera collects the emitted light. The detector resolution has been measured to be around 120µm. A dedicated holder allowing for rapid vacuum transfer of microlenses fixes the position of the lens (Fig. 3). The distance between lens and detector amounts to 75mm. The electron source is mounted onto an x-y-z piezo-stage for precise alignment with the lens aperture. For the experiments described here, the source to lens distance varied between 5 and 30µm, leading to kinetic energies of the electrons at the lens entrance between 60 and 150eV.

3.2. Lens operation and overall performance

If the lens electrodes are both at ground potential and a negative voltage is applied to the emitter tip, a projection image of the second lens aperture is visible at the screen. Its magnification can be varied by changing the source-lens distance. Examples of such electron projection images are shown in Fig. 4(a) and (e). Once a voltage is applied between the two lens electrodes, a focusing effect of the lens
is observed. To ensure a field-free region beyond the lens, the second electrode is always kept at ground potential. The voltage applied at the first lens electrode is altered together with the voltage at the emitter tip to maintain the kinetic energy of the electrons at the lens entrance and the emission current constant. The polarity of the voltage at the first lens electrode can either be such that the electrons are decelerated when passing the lens (positive voltage), or such that they are accelerated (negative voltage). The effect of the lens is illustrated in Fig. 4 for both modes of operation. While increasing the voltage between the two lens electrodes, one first observes that the projection image of the lens aperture at the screen decreases (Fig. 4(b) and (f)). A further increase of the lens voltage reduces the divergence angle more and more until the electrons form a minimal spot at the detector (Fig. 4(c) and (g)). With still higher lens voltages, a crossover located between lens and detector is achieved (Fig. 4(d) and (h)). The distance between lens and crossover can even get smaller than the source-lens distance, resulting in an enlarged divergence angle of the beam as illustrated in Fig. 4(d).

Figure 4: Focusing series for the decelerating (top) and accelerating (middle) mode of the lens with corresponding focusing situations (bottom). The distance between the virtual electron source and the first lens electrode amounts to 16µm for the decelerating and 11µm for the accelerating mode with kinetic energies of 93 respectively 95eV at the lens entrance.
4. Quantitative lens characterization

To evaluate whether downscaling the spherical aberrations by scaling down the size of the lens could actually be realized, the magnitude of spherical aberrations must be determined. Two quantities which are directly related to spherical aberrations have been measured. In a second step they were compared to the values obtained from ray tracing simulations, assuming an idealized lens deteriorated only by intrinsic spherical aberrations. The order of magnitude of the spherical aberration coefficients de facto realized in the experiments could thus be deduced.

4.1. Experimental methods

4.1.1. Beam profile at a distant detector

An experimentally easily accessible quantity is the image size of the electron source in the plane of the electron detector which is the smallest achievable spot size at the detector. As the distance from the lens to the detector plane is large compared to the diameter of the lens aperture and to the source-lens distance, a minimal spot size at the detector is achieved when the beam leaves the lens almost parallel. Instead of determining spherical aberrations from the size of the spot obtained when a parallel incoming beam is focused, we did it the other way round. We instead measured the minimal achievable divergence angle when collimating a beam emitted by an almost perfect point source. Thus, the minimal spot size at the detector is directly related to the spherical aberrations of the lens.

The minimal achievable spot size was measured for the decelerating mode of the lens. Each measurement started with taking a projection image of the lens aperture. This allows determining the distance between the virtual electron source and the first lens aperture [10]. Next, the lens voltage was adjusted for obtaining a minimal spot at the distant detector. In order to get the size of the minimal spot and the projection image, the contour line corresponding to half the maximum intensity value in the image was determined. An ellipse was then fitted to the contour line and the spot diameter was taken as the mean of its minor and major axis. It turns out, that the average spot size at the detector varies from 0.5 to 1.1mm measured with a detector resolution of 120µm. Thus, assuming a Gaussian spot profile the broadening of the spot imposed by the finite detector resolution amounts to less than 3% and will not be accounted for in the following. In addition to spherical aberrations there are several other intrinsic effects contributing to the size of the spot visible at the detector, namely chromatic aberrations, diffraction of the beam at the lens aperture and finite source size. For an estimation of chromatic aberrations the energy spread of 0.1% of the electrons [12] must be taken into
account as well as the stability of the lens voltage. Ray tracing simulations show, that this leads to an enlargement of the spot size at the detector by about 15\(\mu\)m. We estimated the influence of diffraction for the decelerating mode of the lens by assuming a parallel beam being diffracted at the second aperture of the lens. This leads to a width of the central maximum of the diffraction pattern of 15\(\mu\)m for 50eV electrons. The magnified image of the virtual electron source contributes with less than 10\(\mu\)m to the spot size, as the size of the virtual electron source is well below 1nm; in fact it has been measured to be of atomic dimension [7]. We can thus conclude that chromatic aberrations, diffraction at the lens aperture and finite source size are negligible contributions to the minimal spot size at the detector.

4.1.2. Beam profile at 200\(\mu\)m distance beyond the lens exit

A more direct way to determine aberrations is to measure the beam diameter in a plane much closer to the lens than the 75mm distant detector plane. This has been done by scanning a sharp edge perpendicular to the optical axis through the beam. The beam diameter in the plane of the edge is given by the displacement of the edge from the position where all electrons are blocked to the position where all electrons pass the edge. We fabricated such sharp edge by ion-milling a rectangular window into a 20nm thick carbon foil, opaque for low-energy electrons. The sample was mounted onto a movable piezo-stage (Fig. 3) and the window was positioned into the electron beam 200\(\mu\)m beyond the lens. Precise motion of the edge perpendicular to the optical axis is realized with a piezo-scanner exhibiting a scan-range of 4\(\mu\)m. While moving the sample with a scan speed of typically 800nm/s, the total intensity at the detector was recorded. The lens voltage was then adjusted for the steepest slope in the intensity versus edge position profile while repeatedly scanning through the beam.

4.2. Ray tracing simulations

Calculation of electrostatic fields and electron trajectories have been done using the software package SIMION 8.0\(^1\) to solve the Laplace equation using the finite-difference method. The lens was modelled as two planar electrodes separated by 1\(\mu\)m and exhibiting concentric apertures of 1\(\mu\)m in diameter with field-free regions on either side of the lens. Cylindrical symmetry reduces the computational effort since the Laplace equation must only be solved in two dimensions.

\(^1\)SIMION 8.0, Scientific Instrument Services, Inc., 2003-2006
The electrical field distributions were calculated on a $15000 \times 1000$ array with a grid size of 5nm. Ray tracing was done with a fourth order Runge-Kutta algorithm implemented in SIMION.

4.2.1. Calculation of spherical aberration coefficients

Spherical aberrations cause paraxial and marginal rays to be focused at different positions, as illustrated in Fig. 5. The distance between the paraxial focus $J$ and the focus $J_n$ of a ray passing the lens at a larger distance from the optical axis is called longitudinal spherical aberration $\Delta J_n$ of the ray, see Fig. 5(a) for denotation. In the case of a parallel incoming beam, the longitudinal spherical aberration of a ray $\Delta J_n$ can be expressed as a power series of the ray’s semi angular aperture $\Theta_n$ (see also Fig. 5(b)). As $\Delta J_n$ is a symmetric function of $\Theta_n$, the odd power terms vanish, which leads to:

$$\Delta J_n = C_s \Theta_n^2 + c_4 \Theta_n^4 + c_6 \Theta_n^6 + \ldots,$$

with the coefficient $C_s$ being the primary spherical aberration coefficient [13]. The latter was calculated by combining ray tracing simulations with a least square fit, similar to methods described elsewhere [14]. Calculations were carried out for a parallel incident ray, both for the accelerating as well as for the decelerating mode of the lens. For this, a parallel beam of 110 electrons has been generated, such that the lens aperture was completely filled. For each particle, the focus position $J_n$ and the elevation angle $\Theta_n$ were computed. The position of the paraxial focus $J$ was approximated by the focus of the ray with an initial distance to the optical axis of 5nm. In this way, the longitudinal aberration $\Delta J_n = J - J_n$ was determined for each particle. A polynomial of sixth order was then fitted to the values $\Delta J_n(\Theta_n)$, yielding the primary aberration coefficient $C_s$. The described procedure was applied to a series of lens voltages for the decelerating and accelerating mode.
respectively. In the following, voltages are always taken relative to the potential where the kinetic energy of the electrons is zero. Thus, the lens is completely described by its geometry and the voltages ratio between the two electrodes [13]. The dependence of $C_s$ on the voltage ratio for the accelerating and decelerating mode are shown in Fig. 6 for voltage ratios related to realistic experimentally accessible values. The aberration coefficients $C_s$ are in the range of millimeters for both modes and decrease with increasing focusing strength of the lens. Here, $C_s$ denotes the aberration coefficient referred to the image side. Thus, the value for the lateral size of the focal spot in the plane of least confusion $d_s$ can be calculated using the relation $d_s = 0.5C_s\Theta^3$, where $\Theta$ is the angular aperture at the image side of the lens [11]. For a crossover several ten micrometers away from the lens, this yields a spot size of several ten nanometers.

![Figure 6: Primary aberration coefficient $C_s$ as a function of the voltage ratio for the decelerating and accelerating mode of the lens.](image)

4.2.2. Calculation of the spot size at a given distance

For comparison with experimental values the size of the image of the electron source was calculated in the detector plane 75mm beyond the lens and in the plane located 200μm beyond the lens. As the main contribution to the finite spot size in a plane distant to the lens is due to spherical aberrations, other factors influencing the spot size, as there are chromatic aberrations, finite source size and diffraction effects, were neglected in the simulations. A monochromatic point source was thus assumed. Since typical experimental tip to lens distances are larger than 5μm, the electrostatic field near the first lens-aperture and the strong field close to the field emission tip do not influence each other, so that they can be treated as two
separated electron-optical components. The electron trajectories in the immediate vicinity of the field emission tip are slightly curved as most of the potential drops in front of the tip. However, further away from the tip, at the position of the lens, the trajectories are straight lines. At the lens entrance they seem to emanate from a virtual source located a short distance behind the physical tip apex [10]. There is thus no need to include the field emission tip in the electrode array. Instead, the region at the entrance side of the lens can be assumed as field-free. Electrons originate at a point corresponding to the position of the virtual source and propagate straight with given kinetic energies and divergence angles towards the lens. As the region behind the lens is field-free, the beam diameter in the planes of interest up to the 75mm distant detector was calculated by extrapolating the trajectories. In accordance with the experimental conditions, a sufficiently large divergence angle was selected to ensure that the electrons completely fill the lens aperture. The distance between subsequent electrons in the plane of the lens aperture was set as close as possible, that is to one grid unit corresponding to 5nm. For several distances between electron source and first lens-aperture the spot size in the plane under consideration was calculated for a set of various lens voltages. In this way, the minimal possible spot size was computed as a function of source-lens distance for both planes evaluated in the experiments, which is at 75mm and 200μm beyond the microlens.

5. Results and discussion

5.1. Minimal spot size at the 75mm distant detector

Measured spot sizes at the detector as a function of source-lens distance are depicted in Fig. 7 together with the corresponding simulated values. Simulations predict a minimal spot size at the detector between 0.2 and 1.1mm in diameter at the detector for source-lens distances ranging from 5 to 30μm. As expected, the increase of the divergence angle with decreasing source-lens distance leads to a larger spot size. The simulated values exhibit some fluctuations which are due to the limited precision in the determination of the lens-voltage required to form a minimal spot. Two series of experimental measurements of the spot size at the detector are also plotted in Fig. 7. For series 1 several measurements have been carried out with one and the same microlens, fabricated in the manner described above. In contrast to this, the eight data points of series 2 have been obtained from measurements with eight different microlenses. Some of those lenses have been produced by methods different from the one described here; however all of them exhibit the same geometry. The measured values for the minimal spot size at the
detector show the predicted dependency. The experimental data points however are shifted by 0.3mm towards higher values compared to the simulated ones. The measured spot sizes assume values between 0.5 and 1.1mm corresponding to a divergence angle of the collimated beam between just 6 and 14mrad. The experimental values of series 2 obtained with different lenses exhibit similar characteristics. This implies that microlenses with comparable quality can now routinely be fabricated in a reproducible way. Moreover, as different lens fabrication methods result in similar lens performances, they appear to be equivalent with respect to the focusing properties of the lenses.

![Graph showing comparison between simulated and experimental values for the minimal spot size at the detector. Data points of series 1 have been obtained from measurements with one individual lens while the data for series 2 correspond to measurements with eight different lenses.](image)

**Figure 7:** Comparison between simulated and experimental values for the minimal spot size at the detector. Data points of series 1 have been obtained from measurements with one individual lens while the data for series 2 correspond to measurements with eight different lenses.

### 5.2. Minimal spot size in a plane 200µm beyond the lens

The simulated spot-sizes in the plane 200µm beyond the lens vary from 3µm diameter for a source-lens distance of 6µm down to 0.6µm diameter for a source-lens distance of 30µm. Experimental values have been obtained as described above (see also Fig. 8(a)). For a source-lens distance of 14µm and 92eV electrons at the lens entrance, a lens-voltage of 48V was found to generate a minimal spot. In Fig. 8(b) the total intensity at the screen, averaged over all pixels of the CCD chip, is plotted versus the position of the edge moved perpendicular to the beam with a scan speed of 800nm/s. From the intensity profile a beam diameter of 1.8µm has been derived. Corresponding simulations assuming identical conditions reveal a value of 1.2µm. As the distance of 200µm is still large compared to
the 1µm diameter of the lens apertures, focusing of the beam towards this plane is impossible. Instead, the beam diameter is minimal when the beam leaves the lens as parallel as possible. Thus, the focusing conditions for a minimal beam diameter are just as in the case of a 75mm distant detector as described and discussed above. In fact, the values for the beam divergence angle obtained by the two methods are in very good agreement; they amount to 9mrad for a source-lens distance of 14µm.

![Figure 8](image_url)

Figure 8: (a) To measure the beam diameter 200µm beyond the lens, a micro-machined edge is scanned through the beam while the total intensity at the screen is recorded. (b) Measured intensity at the screen as a function of edge position. The source-lens distance amounts to 14µm. A beam diameter of 1.8µm is deduced from the width of the step profile.

### 6. Conclusions and outlook

We have shown that electrostatic lenses of micrometer dimensions can readily be fabricated and exhibit reproducible performance. Comparisons with ray tracing simulations show that the concept of scaling down spherical aberrations by decreasing lens dimensions can in fact be realized. Effects like misalignment of tip and lens, residual vibrations and ac-magnetic fields, deviations from perfect lens-symmetry and contaminations of the apertures have not been considered at all in our simulations. Therefore, the experimental values for the spot size are somewhat larger than the values predicted by simulations. Although these effects do reduce lens performance slightly, their magnitude turns out to be small compared to the achieved reduction of spherical aberrations by down-scaling lens dimensions. As a result, a simple micrometer-sized lens exhibits aberration coefficients comparable to those of high performance objective lenses found in modern electron microscopes [15]. While the bare number of the aberration coefficient is just one aspect, an even more important feature of the scaling concept is the fact that
the electron beam is always kept close to the optical axes. The coherent divergent beam originating from the electron point source is modified early on by the lens and thus never spreads out to macroscopic dimensions. The nearly parallel beam beyond the microlens deviates less than one micrometer from the optical axes at a distance of 200µm beyond the lens. This implies that all following electron optical devices, as an objective lens for example, perceive a micron dimension paraxial electron beam with a broadening of just 10mrad. No beam limiting aperture to improve resolution but decrease brightness at the same time would consequently be needed for an objective lens positioned beyond the microlens. Furthermore, since the microlens is combined with a coherent electron point source here, imaging technologies relying on the wave character of electrons, like holography or coherent diffraction, appear feasible. The atomic dimension emission area of the source in combination with the microlens appears to also be favourable when it comes to creating a focus by means of an objective lens. Since the focus is nothing but the image of the primary source, there would be no need to obtain a demagnified image of the primary source. A sharp focussed beam could thus be obtained and directed towards a sample placed at a convenient large working distance. In having shown the performance of such microlenses, it is now a matter of exploring exciting applications in imaging with coherent low-energy electrons.

7. Acknowledgement

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References


