Design of a high brightness multi-electron-beam source

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Abstract

An electron optics design is presented for forming 100 high brightness beamlets from a single “Schottky” type “thermal field emission” source, such as used in present day electron microscopes and lithography machines. The footprint of the whole system is only 1.5×1.5 mm, so that it can be used as one element in an array of many elements for application in high throughput maskless lithography or high throughput electron beam inspection. Novel electron optical components are used such as an array of electrostatic aperture lenses with an 85% filling factor and a zero-strength electrostatic decelerating lens. For a source brightness of 10^8 A/m^2srV, each beamlet can deliver 15 nA without an increase of the spot diameter by lens aberrations. © 2008 Elsevier B.V. Open access under CC BY-NC-ND license.

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1. Introduction

In order to increase the throughput of electron beam lithography systems (EBL), several single-source multi-beam systems [1-4] have been proposed. The difficulty for the single-column systems is that the source provides enough current, but the brightness is too low. To achieve the high throughput of 1cm^2/s as defined by Pease [5], an excessive number of beams are required.

An alternative approach is multi-source multi-beam systems, with one beam per source. In the DEAL concept proposed by Baylor [6], an array of vertically aligned carbon nanofibres (VACNF) is used as electron sources. The VACNF has high brightness, but not sufficient stability. Arrayed micro-columns [7] with Schottky sources, which are bright and stable, are under development. The throughput, however, is severely limited by the number of columns.

Another approach is multi-source multi-beam systems, with multiple beams per source.

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In this paper, we propose a high brightness multi-electron beam source with arrayed Schottky emitters, where the diverging beam emitted from each source is split into 100 beamlets with a tight control of aberrations. Thus, with an array of 200 Schottky sources, it is possible to produce 20,000 high brightness beams. Aberrations, especially the off-axial aberrations, are analyzed. The total current transmitted is evaluated. Although our objective was to design a 100-beam unit that has a small enough footprint to be part of an array, the 100-beam unit itself is also expected to have applications, for instance in multibeam SEM [8], inspection, or nanolithography.

2. The Multi-electron beam source configuration

The Multi-electron Beam Source (MBS) is designed for a multi-source multi-beam system, with multiple beams per source. The system is aiming for the 22 nm half pitch node, with a throughput of 5-10 WPH. The Schottky source array comprises 200 Schottky emitters, arranged in a pitch of 1.5 mm. Each source provides the current for 100 beams with a beamlet current of 10-20 nA. The total number of beamlets delivered to the substrate is 20,000.

The configuration of the MBS is shown in Fig. 1.a, including a Schottky emitter array, a macro lens array (MLA), an aperture lens array (ALA), a current limiting aperture array (CLAA) and a deflector array (DA). Because the beams from neighbouring sources must be close together, it is not possible to use a collimating lens for obtaining parallel beams. The filling factor (defined as the ratio of beam diameter in the lens plane and the lens diameter) of a normal electron lens is typically no larger than 20%, so the collimating lens would be much larger than the array of 100-beam units. Therefore, an array of deflectors is used to collimate and enable neighbouring groups of beams.

![Fig. 1: (a) The configuration of the multi-electron beam source; (b) the cross-sectional view and c) the top view of the aperture lens.](image)

To reduce the deflection aberration in the deflector array, an aperture lens array projects multiple source images at the centre of the deflecting electrodes. These source images serve as secondary sources for the reduction optics. Aperture lenses are preferred because they have smaller spherical aberration coefficients and they are more compact than Einzel lenses. Details will be illustrated in section 3 and 4.

When the deflectors are used as a collimating lens, large deflection angles up to tens of mrad are required for the off-axial beamlets. The deflection voltage required can be calculated using the formula below:

\[ V = \frac{2d}{l} l E \alpha \]
where \( E \) is the potential of the beam at the deflector array, \( \alpha \) is the deflection angle, \( d \) and \( l \) are the separation and length of the deflecting electrodes. To reduce the deflection voltage, the potential of the deflector array must be kept below 1000 V. Thus, the aperture lens effect must be formed from a deceleration field between the tip and the aperture lens, instead of an acceleration field between the aperture lens and the deflector array. The potential of the aperture lens and the deflector array is designed to be equal. Supports for the thin aperture plate may be put in this field free region.

To avoid beam broadening and transverse chromatic aberration due to the deceleration field, a three-electrode macro lens is introduced in front of the aperture lens array. The aperture lens holes are facing the macro lens, as shown in Fig. 1.b, and the current limiting apertures are on the backside of the plate, in a field free region. The field between the macro lens and aperture lens holes forms the aperture lens effect.

The key component in the MBS is the aperture lens array, which should focus inclined beamlets with minimized off-axial aberrations. At the same time, the off-axial aberrations in the macro lens should be minimized.

3. Aperture lens

The aperture lens is the most elementary electrostatic lens, comprising a single circular aperture in a plane electrode separating two regions of different uniform field. Aperture lenses are often characterized as inferior to unipotential Einzel lenses because of large chromatic aberrations. The chromatic aberrations of an acceleration field have been studied by Bauer [9]. Despite the notorious chromatic aberrations caused by the uniform field, which will be dealt with in Section 5.1, aperture lens potentials are expected to have smaller spherical aberration coefficients.

An aperture lens and an Einzel lens are simulated for comparison. The geometry and potentials are shown in Fig. 2. They have the same focal length of 1.312 mm in the image side. The spherical aberration coefficients are evaluated when the source is at infinity.

The spherical aberration of the aperture lens is 91 mm, coming from the only focusing effect in the lens aperture, as shown in Fig. 3.a. The spherical aberration integral of the Einzel lens is shown in b, where not only the focusing effects in the first and last electrodes, but also the diverging effects in the central electrode (as shown in Fig. 2.b) contribute to a positive spherical aberration coefficient of about 1400 mm per part. The total spherical aberration coefficient of the Einzel lens is 5458 mm, 60 times larger than that of the aperture lens. When the filling factors of
the two lenses are the same, the convergence angle is the same, and the spherical aberration disk of the Einzel lens is 60 times larger than that of the aperture lens.

![Fig. 3: (a) The spherical aberration integral for the aperture lens; (b) the spherical aberration integral for the Einzel lens.](image)

Because the aperture lens has a smaller spherical aberration coefficient, a larger filling factor can be used. For the multi-beam source with fixed number of beamlets, the total current transmitted to the reduction optics is proportional to the square of the filling factor. Thus the aperture lens is desired because the filling factor is approximately 4 times larger \((60^{1/3})\) than that of the Einzel lens. And the total current transmitted from an aperture lens array is approximately 16 times larger than that from an Einzel lens array.

4. The Aperture Lens Array

The schematic of an outer aperture lens in the aperture lens array is shown in Fig. 4. The origin is located at the centre of the central aperture lens. The trajectory of the beam is curved due to the deceleration field. The current limiting aperture is in a field free region and shifted to reduce off-axis aberrations, as proposed by Kurihara [11]. The virtual aperture is symmetrical with the optical axis and sits in the centre of the lens plane.

![Fig. 4: An outer lens in the aperture lens array with a shifted current limiting aperture](image)

The geometry of the aperture lens is the same as that in Fig. 2.a. The potential in the objective plane is 6621 V and 500 V in the image plane. With an objective distance of 3.976 mm, the electrical field in front of the aperture lens is the same as that of the aperture lens discussed in the previous section, so the aperture lenses have the same strength. The optical properties for the central aperture lens are calculated using ELD [10] and listed in Table 1. Note that \(C_s\) here is not the \(C_s(\infty)\) discussed in the previous section: the \(C_s\) at the image side for a situation in which the object is magnified is always larger than \(C_s(\infty)\). For a half opening angle of 1.28 mrad at the source, the filling factor of the aperture lens is 80%. The image-side spherical and chromatic FW50 disks, the minimum aberration
disk containing 50% current of the probe, are calculated using formulas in [12].

Table 1
The optical properties of the central aperture lens.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective distance (mm)</td>
<td>3.976</td>
</tr>
<tr>
<td>Image distance (mm)</td>
<td>5.585</td>
</tr>
<tr>
<td>Magnification</td>
<td>-3.258</td>
</tr>
<tr>
<td>Angular magnification</td>
<td>-1.117</td>
</tr>
<tr>
<td>Focal length (mm)</td>
<td>1.312</td>
</tr>
<tr>
<td>Spherical coefficient at image side (mm)</td>
<td>29276</td>
</tr>
<tr>
<td>Axial chromatic coefficient at image side (mm)</td>
<td>16.96</td>
</tr>
<tr>
<td>Half opening angle at the source (mrad)</td>
<td>1.28</td>
</tr>
<tr>
<td>Spherical aberration FW50 (nm)</td>
<td>15.13</td>
</tr>
<tr>
<td>Chromatic aberration FW50 (nm)</td>
<td>8.24</td>
</tr>
</tbody>
</table>

To evaluate off-axial aberrations of the aperture lens, the deviation from the paraxial trajectory in the Gaussian image plane are calculated using the formulas in Table 2, where $A_i, K_i, F_i, A_i, D_i, D_i$ and $T_i$ are aperture dependent aberration coefficients [13,14]. These aberration coefficients of the aperture lens are obtained in ELD [10]. The aberration coefficients for a uniform deceleration field, the same as the deceleration field in front of the aperture lens, are also listed for comparison. It is shown that the transverse chromatic aberration, distortion and coma are mainly due to the deceleration field, instead of the aperture lens itself.

Table 2
The deviations from the paraxial trajectory in the Gaussian image plane.

<table>
<thead>
<tr>
<th>Type</th>
<th>Aberration</th>
<th>Coefficients</th>
<th>Deviations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Aperture lens</td>
<td>DECL</td>
</tr>
<tr>
<td>Geometric</td>
<td>Spherical</td>
<td>1.25E4</td>
<td>$-3.00E1$</td>
</tr>
<tr>
<td></td>
<td>Coma</td>
<td>7.72</td>
<td>4.80</td>
</tr>
<tr>
<td></td>
<td>Field curvature</td>
<td>1.31</td>
<td>$-7.70E-1$</td>
</tr>
<tr>
<td></td>
<td>Astigmatism</td>
<td>$-6.39E-2$</td>
<td>$-7.70E-1$</td>
</tr>
<tr>
<td></td>
<td>Distortion</td>
<td>1.23E-1</td>
<td>1.23E-1</td>
</tr>
<tr>
<td>Chromatic</td>
<td>Axial</td>
<td>7.70E1</td>
<td>$-3.00E1$</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>4.80</td>
<td>4.80</td>
</tr>
</tbody>
</table>

The deviations in the Gaussian image plane are plotted in Fig. 5 as a function of the height of the aperture lens. The total aberration (square root sum square of spherical aberration, coma, astigmatism and chromatic aberration - C+A+S+Chro) is also shown. The field curvature can be compensated by microlens strength variation, which will be illustrated in section 5.2. Distortion can be corrected by adjusting the lens positions. The total aberration disk is dominated by the transverse chromatic aberration. The transverse chromatic aberration will be greatly reduced by introducing a three-electrode macro lens in section 5.1. Here we will only analyze the uncorrectable geometrical aberrations, e.g., spherical aberration, coma and astigmatism.

The spherical aberration, coma and astigmatism of the aperture lens are evaluated by the FW50 disk. The FW50 disk is determined through ray tracing in SIMION [15], by recording the through focus series of 500 electrons emitted from an infinitely small source with zero energy spread.
The through focus series of the central aperture lens is shown in Fig. 6a. For each beam profile, the aberration disk containing 50% current is determined by increasing the diameter until 250 electrons are included in the disk. The FW50 is determined from the plot of aberration disk versus image position, as shown in the fourth image. The second image shows the FW50 disk, which has a diameter of 16.4 nm, as indicated by the circle. The first and third images are at 50 μm before and after the FW50 disk. The beam profile changes rapidly with the image position and only spherical aberration is present in the probe. The theoretical spherical FW50 disk is 15.13 nm, as listed in Table 1. The theoretical FW50 disk and the FW50 disk determined from ray tracing are in good agreement. The through focus series of the aperture lens at a height of 375 μm is plotted in b. The FW50 disk is determined using the same method and it is 23.0 nm. Astigmatism and a small coma aberration appear in the series.

Fig. 6: The through focus series and FW50 disk: (a) the central aperture lens; and (b) the aperture lens at 375 μm away from the axis.
The FW50 disk versus the height of the aperture lens is shown in Fig. 7, the incident angle on the aperture lens is also plotted. It is shown that for the aperture lens up to a height of 375 µm, the FW50 disk increases from 16.9 nm to 23.8 nm and the incident angle on the aperture lens increases from 0 mrad to 110 mrad. Assuming a virtual source size of 50 nm, the geometrical source image is 162.9 nm. The total spot size increases from 163.8 nm to 164.6 nm. An aperture lens array with the outermost lens no larger than a height of 375 µm shows acceptable off-axial aberrations. Thus the aperture lens array is a good candidate for the MBS, if the transverse chromatic aberration and the field curvature can be reduced.

5. The off-axial aberrations of the macro lens

In order to reduce the transverse chromatic aberration and field curvature, and prevent beam broadening due to the deceleration field, a three-electrode macro lens is used. The 3-electrode macro lens configuration and electrode potentials are shown in Fig. 8. The aperture lens plate and the deflector array plate (not shown in Fig. 8) are both at 500 V.

The field between the macro lens and the aperture lens has three functions:

- The potential difference between the last macro electrode and the aperture lens plate forms a deceleration field, which is necessary for the aperture lens effect. The electrical field in front of the aperture lens is equal to that of the aperture lens in section 3.

- Comparing the equipotential lines in Fig. 9.a (without aperture plate) and b (with aperture plate), the focusing effect in the last macro electrode is suppressed by the aperture lens plate, as circled in b. As a result, the diverging effect in the central electrode is larger than the focusing effect and the beam diverges in the last part of the macro lens. If the beam half opening angle is 100 mrad, the beam diameter in the aperture lens plate is 300 µm. From the ray tracing result in c, the macro lens operates in a ’zero strength’ mode: a ray emitted with an angle of 100 mrad hits the aperture lens plate with 85 mrad.

- The field for the central aperture lens is stronger than that of the outer lenses. This field variation induces microlens strength variation, which may be used for field curvature correction.
5.1. Transverse chromatic aberration of the macro lens

By introducing the macro lens, the deceleration field is limited between the last macro electrode and the aperture lens plate. By adjusting the potentials and distance between the macro lens and the aperture lens plate, the transverse chromatic aberration of the deceleration field can be compensated by the focusing effect in the first two macro electrodes.

The transverse chromatic deviation of the MBS for an energy spread of 0.5 eV is evaluated in the virtual Gaussian image plane using the method of ray tracing. The transverse chromatic deviations seen by aperture lenses are plotted in Fig. 10, as a function of the height of the aperture lens. The deviation is 3 nm for the outermost aperture lens. The magnification of the macro lens is 1.612, so assuming a virtual source size of 50 nm, the virtual image of the source is 80.5 nm. Thus the transverse chromatic aberration can be neglected.

5.2. Field curvature correction using microlens strength variation

The field curvature of the MBS can be categorized as two parts: the geometrical field curvature and the field curvature due to the macro lens aberration, as shown in Fig. 11. The geometrical field curvature is intrinsic for the MBS due to the outer beam travelling with an angle. The macro lens aberration shifts the virtual source seen by the outer lenses further, resulting a longer objective distance and thus a positive field curvature in the image side.
The field curvature can be corrected using microlens strength variation. The electrical field in front of the aperture plate is plotted in Fig. 12.a as a function of the height of the aperture lens. The focal length of the aperture lens is inversely proportional to the electrical field, calculated using formula $f = \frac{4U}{E}$, where $U$ is the potential in the centre of the aperture lens and $E$ is the electrical field in front of the aperture lenses. The focal lengths of the aperture lenses are plotted in Fig. 12.b, where the central aperture lens has a smaller focal length. The objective distances seen by the aperture lenses are determined from simulation. The image distance is then calculated and plotted in c, which shows the field curvature is within 13 $\mu$m. The shape of the field curvature is due to leftover higher order aberrations. The image distance without field curvature correction (assuming the focal length of outer lenses are the same as that of the central lens) is plotted in d for comparison, where the field curvature is 403.8 $\mu$m.
The transverse chromatic aberration and field curvature are greatly reduced. The beam broadening effect of the deceleration field is compensated by the focusing effect of the macro lens and thus a larger half opening angle at the source can be used for the same filling factor.

6. System performance

The total column length from the tip to the deflector array is 7.5 mm. 100 aperture lenses are arranged in hexagonally with a pitch of approximately 25 μm. The macro lens and the aperture lens array project multiple source images in a pitch around 105 μm at the deflector array. The magnification of source unit comprising the macro lens and the aperture lens is –5.1.

Generally speaking, the aberrations are proportional to the refraction power of a lens. For the ‘zero strength’ macro lens, the aberrations are expected to be small. Thus it is appropriate to assume the off-axial aberrations of outer aperture lenses with macro lens are smaller than that of outer aperture lenses with a deceleration field. From the FW50 plot in Fig. 7, we can assume the FW50 (spherical aberration, coma and astigmatism) for the outermost lens is around 50% larger than the central lens in the MBS. The best image plane is taken in the middle of the field curvature shape. The primary aberrations of the central aperture lens and the outermost lens are listed in Table 3, assuming a virtual source size of 50 nm and a half opening angle of 5 mrad (equal to a filling factor of 85%). The transverse chromatic aberration for the outermost lens is equal to the product of the transverse chromatic deviation in the virtual Gaussian image plane of the macro lens and the magnification of the aperture lens. Distortion, which can be compensated by adjusting the aperture lens position, is not listed in the table.

Table 3
Primary aberrations for the central and outermost aperture lenses.

<table>
<thead>
<tr>
<th></th>
<th>Central</th>
<th>Outermost</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW50 (spherical aberration, coma, astigmatism)</td>
<td>13.2 nm</td>
<td>19.8 nm</td>
</tr>
<tr>
<td>Field curvature</td>
<td>9.0 nm</td>
<td>1.2 nm</td>
</tr>
<tr>
<td>Axial chromatic aberration</td>
<td>10.4 nm</td>
<td>10.4 nm</td>
</tr>
<tr>
<td>Transverse chromatic aberration</td>
<td>-</td>
<td>9.4 nm</td>
</tr>
<tr>
<td>Geometrical spot size</td>
<td>254.4 nm</td>
<td>254.4 nm</td>
</tr>
<tr>
<td>Total spot size</td>
<td>255.1 nm</td>
<td>255.6 nm</td>
</tr>
</tbody>
</table>

Assuming the source brightness of 10⁸ A/m²srV and an extraction voltage of 1 kV, the angular current density is 200 μA/sr. The current per beamlet is 15.7 nA and the total current transmitted from each Schottky source is then 1570 nA. Coulomb interactions will be calculated in the near future.

The deflection voltage can be calculated as \( V = 2d/l \cdot Eα \). Assuming the aspect ratio of the deflector is 8, the maximum deflection voltage is 10.625 V.

7. Conclusion

Novel electron optical components have been presented with very promising results. The aperture lens is capable of having a filling factor of 85% due to small spherical aberration. The aperture lens array allows skewed incidence up to 110 mrad with very small off-axial aberrations. Together with the macro lens operating at ‘zero strength mode’, the transverse chromatic aberration and field curvature of the MBS are greatly reduced. From each Schottky source, these optical components produce 100 beamlets with a beamlet current of 15.7 nA.

Multibeam sources designed with similar principles can be found in reference [16] and [17]. They may be used to increase the throughput of different electron optical systems.
References