Design of a Multi-Electrode Immersion Lens for Ion-Optical Systems

The present work puts forward an electrostatic optical device for application in an ion-optical system. A design has been achieved computationally for a multi-electrode immersion lens of low relative spherical and chromatic aberration coefficients with the aid of the following suggested expression for the potential field: 

$$U(z) = \left[ \frac{a \cdot z}{z^2 + c} \right] + b$$

where $a$, $b$, and $c$ are constants, $z$ is the optical axis, and $U(z)$ is the axial potential distribution. The potential is constant at the boundaries, therefore the electric field is zero, i.e. there is a field-free region outside the lens where the charged particles travel in a straight line. The lens consists of four electrodes where the terminal electrodes are identical in their geometry. The two inner electrodes have the same shape of a thin disc and their central holes are equal. The lens is not symmetrical about the origin but is rotationally symmetric. The paraxial ray equation has been solved using Runge-Kutta method for the zero and infinite modes of operation. The spherical and chromatic aberration coefficients $C_s$ and $C_c$, respectively have been computed using Simpson’s rule. The following results are obtained for $C_s$ and $C_c$, normalized in terms of the focal length $f$: $(C_s/f)_{\text{min}} = 1.3$ and $C_c/f = 5$ for zero magnification; $(C_s/f)_{\text{min}} = 14.42$ and $C_c/f = 5.73$ for infinite magnification. These results suggest that operating the proposed lens under zero magnification conditions is more favorable. Therefore, the proposed expression for the potential distribution is recommended for representing an electrostatic immersion lens of low relative chromatic aberration coefficient.

Keywords: Electrostatic lenses, Ion-optical system, Spherical aberration, Chromatic aberration

1. Introduction

Electrostatic lenses are finding increasing applications in many areas of science and technology particularly in modern ion implantation instruments. Ion implantation is one of the key technologies in the fabrication of dimensionally controlled semiconductor structures. [1,2].

For the last several decades, many efforts have been made to combine a transmission electron microscope (TEM) with ion implanters [3-5]. This system avoids the problems of transferring samples from the ion implanters to the electron microscope [6]. In situ TEM experiments have the specific advantage that defect clusters produced by heavy ion implantation can be directly correlated to the appearance of highly disordered or amorphous zones for a given ion impact, since the same sample area is monitored during the implantation itself [7]. Ions can be accelerated and introduced into TEM column through an electrostatic system of lenses. This paper aims at investigating what can be theoretically achieved when a proposed rotationally symmetric electrostatic immersion lens is operated in an ion-optical system under zero and infinite magnification conditions with low aberration coefficients.

2. Electrostatic Lens Model

It is often desirable to perform a rapid approximate evaluation of lens properties without actually carrying out a detailed analysis. This can be accomplished with the aid of a simple mathematical model for the lens, i.e. an approximation for the axial potential distribution that is reasonably close to the real one and allows a solution in closed form or an approximation in simple terms. The lens models are basically of two types: The potential distribution is either approximated by a single function for the whole lens (analytical models) or it is divided into a series of intervals and the distribution in each interval is approximated by an elementary function (piecewise models) [8].

It is aimed in the present work to find a more simple analytic expression that would describe the axial potential distribution of an accelerating immersion lens with acceptable aberrations. Since the lens is of the accelerating type, hence the ion...
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beam enters the low potential electrode and emerges from the higher potential electrode.

The following expression is suggested to represent the potential distribution along the optical axis of an immersion lens:

$$U(z) = \left[ a r^2 + \frac{b}{z^2} + c \right]$$

where $a$, $b$, and $c$ are constants, $z$ is the optical axis, and $U(z)$ is the axial potential distribution. Plots of $U(z)$ as a function of $z$ are shown in Fig. (1) for different values of $a$. An increase in the value of $a$ will increase the potential at the middle electrodes while the ratio of the potentials between the outer electrodes changes very slightly. The broken line is the first derivative of the potential distribution when $a=6 V \cdot mm$, $b=1.9 V$ and $c=3 mm^2$. It should be mentioned that the above values of $b$ and $c$ have been maintained throughout the present work since both put limitations to the beam trajectory and the lens aberrations. For instance values of $b$ less than 1.9V will change the lens into a diverging instead of converging one. Furthermore, this value of $c$ will offer the lowest aberrations possible. Figure (1) shows that the potential is constant at the lens boundaries, so its first derivative is zero; this means that there is a field-free region outside the lens where the charged particles travel in a straight line. The potential applied on the electrodes at object plane is $U_0$ and that at the image plane is $U_i$. The different potentials applied on the four electrodes depend on the value of $a$ taken into consideration.

From the values of the axial potential distribution and its first and second derivatives the electrodynamics profile has been obtained as shown in Fig. (2). The radial and the axial dimensions of the electrodes $r$ and $z$ respectively have been normalized in terms of the total lens length $L$ which has been taken in the present work to be equal to 40mm as shown in Fig. (1) by the axial extension of the field $U(z)$. It is seen that the immersion lens consists of four electrodes. The terminal electrodes are identical in their geometry. The inner electrodes have the same shape of a thin disc and their central holes are equal which allow passage for the ion beam. The four electrodes have rotational symmetry about the optical axis. The two halves of the lens have a mirror image.

3. The Trajectory of Charged Particles

The trajectory of charged particles through an axially symmetric electrostatic lens field, in terms of the axial potential field $U(z)$ and its first and second derivatives $U'(z)$ and $U''(z)$ respectively, is given by the following paraxial ray equation [9]:

$$r'^2(z) + r''(z) \frac{U'(z)}{2U(z)} + r(z) \frac{U''(z)}{4U(z)} = 0$$

where $r$ is the radial displacement of the beam from the optical axis $z$, and the primes denote a derivative with respect to $z$.

Figures (3) and (4) represent the trajectories of the charged particles traversing the field of the immersion lens operated under zero and infinite magnification condition respectively. Under zero magnification condition the charged particles enter the lens field parallel to the optical axis. The gradient of the emerging beam increases with the increase of $a$, keeping $b$ and $c$ in Eq. (1) constants at the values 1.9V and 3mm$^2$, respectively. Under infinite magnification condition the charged particles emerge from the lens field parallel to the optical axis. The beam crosses the optical axis within the lens field at the values of $a \geq 3 V \cdot mm$.

![Fig. (1): The axial potential distribution along the optical axis for different values of $a$](image)

4. Spherical and Chromatic Aberration Coefficients

The spherical and chromatic aberration coefficients $C_{so}$ and $C_{co}$ respectively at the object plane have been computed with the aid of the two following formulae [9]:

$$C_{so} = \frac{1}{2} \frac{U_0}{U_i} \frac{z_j}{z_0} \left[ \frac{5}{4} \left( \frac{U'}{U} \right)^2 + \frac{5}{24} \left( \frac{U'}{U} \right)^4 \right]$$

(3)

$$+ \frac{14}{3} \left( \frac{U'}{U} \right)^3 \left( \frac{r'}{r} \right)^2 \left[ \frac{3}{2} \left( \frac{U'}{U} \right)^2 \frac{r'^2}{r^2} \right] \sqrt{U f} dz$$

$$C_{co} = \frac{1}{2} \frac{U_0}{U_i} \frac{z_j}{z_0} \left[ \left( \frac{U'}{U} \right)^2 + \frac{1}{4} \left( \frac{U'}{U} \right)^4 \right] \frac{r}{\sqrt{U}} dz$$

(4)

where $U_0$ is the potential at the object plane. It should be noted that the corresponding aberration coefficients at the image plane could be expressed in a similar form of equations (3) and (4) when $U_0^{-1/2}$ and $r_0^{-1/2}$ are replaced by $U_i^{-1/2}$ and $r_i^{-1/2}$, respectively. The integration given in the above equations have been executed by means of Simpson’s rule. The aberration coefficients have been normalized in terms of the focal length $f$, i.e., the values of $C_{so}/f$ and $C_{co}/f$ have been investigated as figures of merit, which are dimensionless.
Figure (5) shows the relative image-side spherical and chromatic aberration coefficients $C_s/f$ and $C_c/f$, respectively, as a function of $a$ for the electrostatic immersion lens operated under zero magnification conditions. It is seen that as $a$ increases, $C_s/f$ decreases towards a minimum value; $(C_s/f)_{\text{min}}=1.3$ at $a=6\text{V.mm}$ and voltage ratio $U_i/U_0=1.37$. This minimum value is electron-optically acceptable. At this value of $a$ the corresponding relative chromatic aberration $C_c/f=5.0$, which is relatively high from the electron-optical point of view. The figure shows that $C_c/f$ increases with increasing $a$.

The plots of $C_s/f$ and $C_c/f$ as a function of $a$ for the electrostatic immersion lens operated under infinite magnification condition are shown in Fig. (6). In general the behavior of $C_s/f$ and $C_c/f$ is similar
to that shown in Fig. (5). However, the values of the relative aberration coefficients under zero magnification are less than those under infinite magnification, which are \( (C_s/f)_{\text{min}} = 14.42 \) and \( C_v/f = 5.73 \) at \( a=5.3 \) mm and \( U_i/U_0 = 1.32 \).

It is seen that under both magnification conditions the values of \( C_s/f \) are comparable when \( C_v/f \) is minimum. Thus, so far as \( C_v/f \) is concerned it is favorable to operate this lens under zero magnification condition, i.e., the lens would form a focused ion beam on the image side when a beam parallel to the optical axis enters the lens. However, if one is interested in having both relative aberrations as low as possible, then it is possible to reach a compromise. For instance, at \( a=5 \) V mm, Fig. (5) shows that \( C_s/f \) and \( C_v/f \) are equal to 3; a value usually acceptable in practice.

4. Conclusions

It appears that the proposed analytic function of the axial potential field for an immersion lens offers considerable advantages with regard to the relative spherical aberration coefficient, particularly when the lens is operated under zero magnification conditions. This mode of operation is suitable for using the lens as a focusing unit in an ion-optical system. The operation of the proposed immersion lens is limited by its relative chromatic aberration in both zero and infinite magnification conditions. However, this lens may be introduced in various systems such as TEM and ion implanters to focus the beam on the target.

References


This article was reviewed at Woods Hole Oceanographic Institution, Massachusetts, U.S.A and School of Applied Sciences, University of Technology, Baghdad, IRAQ

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**7TH ASIAN INTERNATIONAL SEMINAR ON ATOMIC AND MOLECULAR PHYSICS**

4th to 7th December, 2006
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