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Simulation of an ion Optical Transport and Focusing System

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ABSTRACT:

A simulated ion/electron optical transport and focusing system has been put forward to be mounted on high voltage transmission electron microscope for in situ investigations. The suggested system consists of three axially symmetric electrostatic lenses namely an einzel lens, an accelerating immersion lens, and a decelerating immersion lens, in addition to an electrostatic quadrupole doublet lens placed on the image side. The electrodes profile of these lenses is determined from the proposed axial field distributions. The optical properties of the whole system have been computed together with the trajectory of the accelerated charged-particles beam along the optical axis of the system. The computed dimensions of the final image have been found to be electron-optically acceptable.

محاكاة منظومة نقل وتبئير بصرية أيونية

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الخلاصة:

تم اقتراح منظومة نقل وتبئير ايون/إلكترون بصرية لوضعها مقابل مجهر الانبعاث الالكتروني عالي الفولتية لأجراء البحوث دون الحاجة إلى نقل النموذج المعرض. المنظومة المقترحة تتكون من ثلاث عدسات كهروستاتيكية متماثلة محورياً وهي العدسة أحادية الجهد، عدسة مغمورة مُعجلة وعدسة مغمورة مُبطئة، بالإضافة إلى عدسة مزدوجة كهروستاتيكية رباعية الأقطاب وضعت من جهة الصورة. شكل الأقطاب لهذه العدسات حسب من توزيعات المجال المحوري المقترحة. إن الخواص البصرية للنظام أجمعه حسبت من مسار حزمة الجسيمات المعجلة على طول المحور البصري للنظام. الأبعاد المحسوبة للصورة النهائية وجدت بأنها مقبولة من وجهة نظر بصريات الإلكترون.

INTRODUCTION:

The use of transmission electron microscope (TEM) for performing analytical studies on materials such as irradiation effects has been conducted for more than four decades. For irradiation effects studies two developments are of special importance, (a) the availability of specimen holders in which specimen temperature can be controlled over a very wide range during an experiment and (b) the interfacing of ion accelerators which allows in situ TEM studies of irradiation effects and the ion beam modification of materials by ion implantation. This system avoids the problems of transferring samples from ion implanter to the electron microscope.

The installations throughout the world of TEM with in situ ion beam capability since 1960 have been summarized by Allen and Ryan (1998) and Allen and Dorignac (1998). Their lists include about fifty high voltage instruments with in situ facilities where more than 70% of these are manufactured in Japan and installed in various parts of the world. The most interesting instruments are (a) the 3.5 MV Hitachi ultra high voltage electron microscope which was installed in 1995 at Osaka University in Japan and (b) the 1.25 MV JEOL instrument with in situ two ion beamlines which was installed in 1998 at Hokkaido University in Japan. The majority of the high voltage transmission electron microscopes are employed in the materials science including applications involving electron irradiation studies.

The increased demand in the world for the in situ investigations would first require putting forward a computer-aided design prior to any means of manufacturing or assembling a prototype experimental system. In the present computational investigation it is aimed at putting forward an ion beam transport and focusing system for an ion implanter and TEM. The suggested system consists of various types of electrostatic lenses such as the einzel, immersion, and quadrupole lens where their electrodes configuration and optical properties are determined from suggested hyperbolic mathematical models representing the potential distribution of the different lenses. The system proposed in the present work is intended to be suitable for performing in situ electron and/or ion irradiation to the specimen surface in transmission electron microscopes operated over a wide range of accelerating voltages. In general, it is desirable that ion beams are transported at high acceleration to achieve good dose homogeneity at the specimen. A low ion current of small cross-section is taken into account to eliminate the space-charge effect.

OPTICAL PROPERTIES CONSIDERATIONS OF THE SYSTEM:

Ion/electron optical systems consisting of a series of lenses aligned in the axial direction form intermediate images of an object in the field-free spaces between them. The number of lenses in a system may be three or more depending on their function; for example in particle accelerators, the number of successive focusing, deflecting, and analyzing elements may be large (see for example, Read et al 1987).

If a system consists of two charged-particles lenses of magnifications M′ and M″ then the total magnification M of the system is given by (Szilagyi 1988):

$$M = M' M'' = -(n_1 f_2'') / (n_2 f_1') = -(U_{obj}/U_{img})^{1/2} (f_2''/f_1') \quad (1)$$

where the superscripts ′ and ″ represent the first and second lens respectively, while 1 and 2 represent the object- and image-side respectively, f is the focal length, n is the refractive index, and U_{obj} ,and U_{img} are the object- and image-side electrode voltage respectively.

The spherical aberration coefficient of the system C_{sso} referred to the object side is expressed by the following equation:

$$C_{sso} = C_{so}' + (U_{obj}/U_{img})^{3/2} C_{si}'' / M^4 \quad (2)$$

where C_{so}' is the object-side spherical aberration coefficient of the first lens, and C_{si}'' is the image-side spherical aberration coefficient of the second lens. The presence of the total magnification M in the second term of equation (2) relates the image-side coefficient of the second lens to the object side. The spherical aberration disk diameter d_{ssi} in the image-side for a two-lens system is given by the following equation:

$$d_{ssi} = M'' d_{si1} + d_{si2} \quad (3)$$

where d_{si1} and d_{si2} are the spherical aberration disk diameters of the first and second lens respectively.

The chromatic aberration coefficient of the system referred to the object side C_{sco} is represented by the following equation:

$$C_{sco} = C_{co}' + (U_{obj}/U_{img})^{3/2} C_{ci}'' / M^2 \qquad (4)$$

where C_{co}' is the object-side chromatic aberration coefficient of the first lens, and C_{ci}'' is the image-side chromatic aberration coefficient of the second lens. The chromatic aberration disk diameter d_{sci} in the image-side of a two-lens system is given by the following equation:

$$d_{sci} = M'' d_{ci1} + d_{ci2} \qquad (5)$$

where d_{ci1} and d_{ci2} are the chromatic aberration disk diameters of the first and second lens respectively.

It may be concluded that it is easy to generalize the above relationships for chains of lenses by simply considering combinations of lens pairs as single lenses and using the procedure sequentially (Szilagyi 1988).

In a quadrupole doublet lens, the spherical aberration in the gaussian image plane is given by (Okayama 1989):

$$\Delta x = (P_{CD}\, \alpha^3 + S_{CD}\, \alpha\, \gamma^2) \qquad (6)$$

$$\Delta y = (P_{DC}\, \alpha^2 \gamma + S_{DC}\, \gamma^3) \qquad (7)$$

where α and γ are semi-aperture angles in the image space, the subscript pair CD (i.e. convergence-divergence) refers to the plane in which the first quadrupole lens converges and the second lens diverges; the subscript pair DC (i.e. divergence-convergence) refers to the plane in which the lens performance is exactly opposite. The spherical aberration coefficients of the quadrupole doublet lens P_{CD}, P_{DC}, S_{CD}, and S_{DC} are calculated from the formulas given by Dymnikov et al (1965), and Fishkova et al (1968). The field distribution along the quadrupole lens axis is approximated by a rectangular model due to its accuracy and simplicity (Grivet 1972).

DESCRIPTION OF THE PROPOSED TRANSPORT AND FOCUSING SYSTEM:

The proposed transport and focusing system consists of a series of electrostatic lenses mounted along a common optical axis. A three-dimensional diagram shown in figure 1 illustrates the series of electrostatic lenses mounted between the object-side region and the target. The incoming accelerated charged-particles beam first experiences the field generated by an einzel lens operated at accelerating mode and under infinite magnification condition. As the beam emerges from the einzel lens, it enters a system of two immersion lenses, the first lens being operated in the accelerating mode under zero magnification condition while the second is a decelerating lens operated under finite magnification condition. The beam crossover exists between the two immersion lenses. Finally an electrostatic quadrupole doublet lens succeeds the second immersion lens; its function is aimed at focusing the beam on the target. All electrodes of the einzel and immersion lenses are assumed to be infinitely thin particularly in the immediate vicinity of the optical axis.

Figure 1 shows that the three-electrode einzel lens and the two-electrode immersion lenses are symmetrical about their center in addition to the rotational symmetry. The central electrode of the einzel lens is in the form of a disk. The electrodes of the quadrupole doublet lens have a hyperbolic shape in the vicinity of the optical axis. The electrodes of all the electrostatic lenses system should be constructed from high-melting point materials so that they can withstand the vast amount of heat generated as a result of the direct bombardment of the high energy charged particles with the electrodes. These materials should also be excellent electrical conductors in addition to their low sputtering yield. It should be noted, however, that materials of relatively low melting point such as stainless steel could be used for constructing electrodes provided that they are not subjected directly to the ions bombardment. Under these conditions, stainless steel is widely used for manufacturing the electrodes of quadrupole lenses.

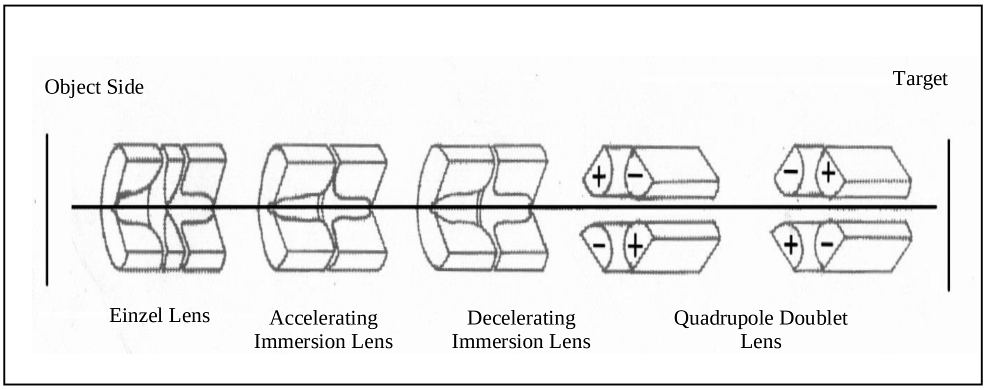

Figure 1: An electrostatic transport and focusing lens system.

Figure 2 illustrates the object-target trajectory of the accelerated charged-particles beam along the optical axis of the system where the electrostatic lenses are assumed to be perfectly aligned. It should be noted that the beam traverses a straight line in various field-free regions. In fact the diagram illustrates the beam trajectory in two orthogonal planes; the trajectory above the optical axis represents the path projection in the xOz plane and that below it is the corresponding projection in the yOz plane. The gaps between lenses are particular parameters so the choice of these gaps is arbitrary. If in a certain field-free region the beam is parallel to the optical axis, then the optical properties of the system will not be affected by varying the width of this region.

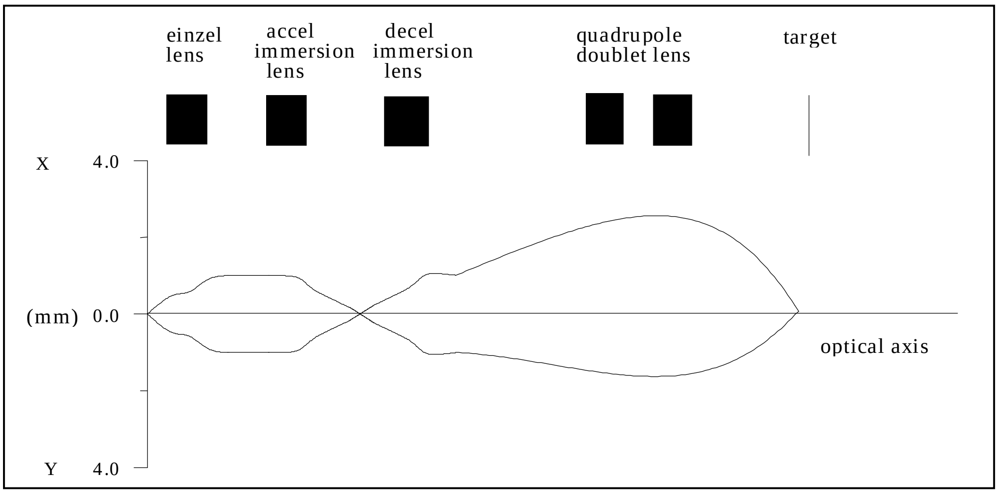

Figure 2: The trajectory of the accelerated charged-particles beam along the optical axis of the system of electrostatic lenses in two orthogonal planes.

COMPUTED PARAMETERS OF THE SYSTEM:

The electrodes potential ratio of the einzel lens has been chosen to be 5.0 in order that the beam experiences a trajectory such that it is originated from a point on the optical axis situated on the object side. This potential ratio is low from the practical point of view which suggests that low power consumption is encountered under these conditions. The electrodes potential ratios of the accelerating and decelerating immersion lenses are 9.14 and 0.11 respectively which are also relatively low. In order to maintain the same beam energy at emergence from the image side for the incoming beam from the object side, the voltage applied on the terminal electrodes of the einzel lens, the first electrode of the accelerating immersion lens, and the second electrode of the decelerating immersion lens is kept the same. The main function of the decelerating immersion lens is to reduce the energy of the charged particles to its initial value.

Since quadrupole lenses are very suitable for forming a fine linear beam and fine round beam (Okayama 1988**,** the suggested design of the quadrupole doublet lens is intended to be suitable for focusing the beam on the target. Since a quadrupole doublet lens has been used for reducing the spherical and chromatic aberrations of round lenses (Hawkes 1970)**,** thus one may suggest for a future work that a new design for the electrostatic doublet lenses could be investigated such that these lenses act as corrector units in focusing and transport systems.

The first- and third-order optical properties computed with the aid of equations (1) - (5) for the first three lenses of the transport and focusing system put forward in the present work are shown in table 1.

The image formed by a three-lens system consisting of the einzel lens, the accelerating immersion lens, and the decelerating immersion lens is an object for the quadrupole doublet lens. In computing the various optical parameters of the three-lens system, the einzel lens and the accelerating immersion lens are considered as a single optical unit forming an image which becomes an object for the decelerating immersion lens. The properties of these first two lenses are listed in table(1) When the beam experiences a path parallel to the optical axis on either the object or image side of any optical element, its focal properties have not been determined. Since the image-side properties are the most significant, the aberration disk diameters d_{so}, d_{co}, and d_{to} on the object side for the three-lens system have not been listed.

A table 1 show that the charged-particles beam energy is maintained constant since Uobj/Uimg is unity. The magnified image of the three-lens system is inverted since M is negative. The chromatic aberration disk diameter d_{ci} on the image side of the three-lens system is lower than the spherical aberration disk diameter d_{si}; a property which could be exploited for special purposes. The spot size diameter d_{ti} in the image side is of the order of the aperture diameter which is in common use in transmission electron microscopes. It is seen that the aberration disk diameter of the combined system is greater than that of the individual lenses forming the system; a result which is quite clear by considering equations (3) and (5). Since equations (1)-(5) show that the aberration is a function of the magnification, hence by a suitable choice of the latter one can minimize the aberration of the system.

Table 1: The optical properties of a three-lens system consisting of an einzel lens and accelerating and decelerating immersion lenses.

Parameter	**einzel**	**Accel imm.**	**einzel+ accel imm.**	**decel imm.**	**3-lens system**
U_{obj} / U_{img}	1.0	0.11	0.11	9.14	1.0
f_i/L	∞	0.74	0.74	3.58	3.58
f_o/L	0.52	∞	0.52	0.74	0.52
C_{ci}/f_i	---	4.91	0.61	High	High
C_{co}/f_o	0.70	---	1.85	5.91	4.45
C_{si}/f_i	---	9.68	4.5	High	High
C_{so}/f_o	3.3	---	13.6	14.36	13.7
M	Infinite	Zero	0.47	-14.74	-6.9
d_{ci} μm	---	3.66	3.83	High	13.36
d_{co} μm	0.36	---	8.15	4.4	---
d_{si} μm	---	4.5	5.0	High	32.12
d_{so} μm	1.07	---	10.64	6.68	---
d_{ti} μm	---	5.8	6.3	High	34.79
d_{to} μm	1.13	---	13.4	8	---

In determining the final spot size of the beam at the target, the image formed by the first three lenses is considered as an object for the quadrupole doublet lens. Hence the total spot size d_t of the first three lenses image is the dimension of the object for the quadrupole doublet. To calculate the final spot size, the following optical properties are required (Grime and Watt 1984):

Object dimensions = 34.8x34.8 μm^2 (Table 1)

Semi-aperture angles: $\alpha = 0.00415$ rad and $\gamma = 0.0665$ rad

Magnification of the quadrupole doublet in x- and y- direction: $M_x = 1.035$ and $M_y = 1.126$

First-order spot dimensions (Grime and Watt 1984):

$x_i = x_o / {}_x = 34.8/1.035 = 33.6$ μm (x-direction)

$y_i = y_o / {}_y = 34.8/ 1.126 = 30.9$ μm (y-direction)

The spherical aberration increases the first-order spot size in the x- and y- direction by the following amounts:

$\Delta x = 0.06$ μm

$\Delta y = 1.06$ μm

Therefore, the final maximum dimensions of the spot are 33.6x32 μm^2. The above results indicate that the quadrupole lens plays an important role in transporting and focusing the accelerated charged particles where the contribution of its aberration is low, in addition to being less than that of the first three lenses. The value of the image size at the target is quite acceptable when compared with the results given in various references (see for example Henke et al 1995). In fact the image spot size is of the order of the aperture diameter which is usually mounted in transmission electron microscopes.

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