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Properties of the cathode lens combined with a focusing magnetic/immersion-magnetic lens

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ABSTRACT

The cathode lens is an electron optical element in an emission electron microscope accelerating electrons from the sample, which serves as a source for a beam of electrons. Special application consists in using the cathode lens first for retardation of an illuminating electron beam and then for acceleration of reflected as well as secondary electrons, made in the directly imaging low energy electron microscope or in its scanning version discussed here. In order to form a real image, the cathode lens has to be combined with a focusing magnetic lens or a focusing immersion-magnetic lens, as used for objective lenses of some commercial scanning electron microscopes. These two alternatives are compared with regards to their optical properties, in particular with respect to predicted aberration coefficients and the spot size, as well as the optimum angular aperture of the primary beam. The important role of the final aperture size on the image resolution is also presented.

1. Introduction

The cathode lens (CL) is an electron optical element used in emission electron microscopes like the photoemission electron microscope (PEEM) and the low energy electron microscope (LEEM), together with the scanning version of the LEEM, the scanning low energy electron microscope (SLEEM) [1]. In its simplest version, the SLEEM method can be introduced in a conventional scanning electron microscope (SEM) via a feasible adaptation [2]. Lenc and Müllerová [3,4] studied the basic optical parameters of the CL alone as well as in combination with a magnetic focusing lens, and derived approximate analytical expressions for the axial aberration coefficients in both cases. For the combination of lenses, the sequential arrangement of electrostatic and magnetic fields was considered. Numerical computations comparing several cathode lens configurations for the LEEM as regards the optimum resolution were performed by Chmelík et al. [5].

Several authors have declared the aberration coefficients for overlapping electrostatic and magnetic fields of lenses under combination smaller than for their sequential arrangement. Optical properties of combined electric and magnetic fields for low landing energy (down to 100 eV) has been established both in terms of theory and experiment for quite sometime now, starting with a paper in 1981 [6]. An added immersion lens effectively extends the range of operating of an ordinary SEM down to 300 eV is demonstrated in Ref. [7]. Comparison of three types of cathode lenses showed the immersion-magnetic objective lens (OL) improving the overall behavior of the compound lens at low current density [8]. The resolution limits for immersion-magnetic field, retarding electric field and mixed fields were calculated by Khursheed [9,10] with the same result favoring overlapping fields.

2. Software and methods of simulation

Calculations of the electron optical properties, i.e. the spherical and chromatic aberrations in the object and image planes, focal length, angular magnification, image rotation, etc., were made using the program EOD (Electron Optical Design) [11]. EOD is based on potential computation with the first order finite element method enabling one to solve for 2D potential distributions, and gives aberration coefficients with high accuracy. We studied the aberration coefficients as functions of the landing energy of electrons varying from 10 keV to 1 eV by means of their retardation within the CL for a primary beam energy of 10 keV. The spot size was calculated in the Matlab environment from individual confusion discs by two methods, namely via convolution of these discs described by Gaussian functions ($d_{P\text{-}G}$) (see Eq. (1)) [12] and by using the algorithm providing a diameter encircling 50% of the total current in the spot ($d_{P\text{-}BK}$) (Eq. (2)) [13].

Contributions to the spot size included the demagnified cross-over of the gun $d_G=(4I/\pi^2\beta)^{0.5}\alpha^{-1}$, the spherical aberration disc $d_S=K_S C_S \alpha^3$, the chromatic aberration disc $d_C=K_C C_C \alpha \Delta E/E_L$, and the core diameter of the diffraction pattern $d_D=K_D \lambda \alpha^{-1}$ (with I as the beam current, β the gun brightness, α the angular aperture of the primary beam in the specimen plane, C_S the coefficient of the spherical aberration, C_C the coefficient of the chromatic aberration, ΔE the energy spread of the primary beam, E_L the landing

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energy, λ the wavelength of electrons, and K_S, K_C, and K_D are numerical coefficients dependent on the summation rule of the spot size: K_S=0.5, K_C=1, and K_D=0.6 for Eq. (1), and K_S=0.18, K_C=0.34, and K_D=0.54 for Eq. (2))

$$d_{P\text{-}G}^2 = d_G^2 + d_S^2 + d_C^2 + d_D^2 \quad (1)$$

$$d_{P\text{-}BK}^2 = [(d_S^4 + d_D^4)^{1.3/4} + d_G^{1.3}]^{2/1.3} + d_C^2. \quad (2)$$

A key element governing the properties of the primary electron beam is the final aperture restricting the beam angle, i.e. the angle α of a marginal ray in the beam with respect to the beam axis. A specific feature of the CL equipped columns is that within the CL field the beam aperture increases as the radial velocity of electrons is preserved while the axial velocity is lowered. In order to determine the optimum beam aperture, we calculate the minimum of the function $d_P(\alpha)$, which appears at α_{opt} that can be transformed into a bore diameter of the final aperture diaphragm (D_a). Eq. (3) gives us the (optimum) object side aperture α_o while the image side aperture α_i is given by Eq. (4) incorporating the angular magnification M_α of the system (see Fig. 1)

$$\frac{\partial d_p}{\partial \alpha} = 0 \quad (3)$$

$$\alpha_i = M_\alpha \alpha_o = M_\alpha \operatorname{arctg} \frac{D_a/2}{|z_o - z_a|}. \quad (4)$$

Incorporation of the demagnified crossover introduces one more degree of freedom in the problem, namely choice of the electron gun, i.e. its type and performance. However, our task does not require specifying the electron source, which can be avoided by putting the crossover at infinity in front of the objective lens. Then we specify the aperture illuminated with a parallel beam, the angular magnification diverges and we can neglect the d_G term in the summation rules.

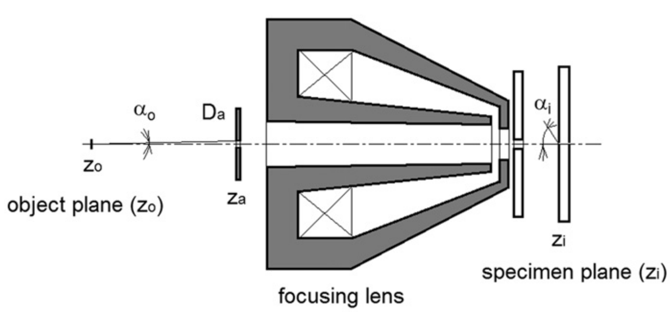

Fig. 1. Definition of terms connected with the primary beam trajectory: object plane at $z_o = -10{,}000$ mm (i.e. at the infinity), the final aperture diaphragm situated at $z_a = -180$ mm, and the image plane at z_i=5 mm or 8 mm.

Simulated combinations of objective lenses with the cathode lens are schematically presented in Fig. 2. The CL consists of two electrodes of diameter 20 mm and thickness 1 mm, separated by a distance of 3.5 mm, with the anode bore diameter of 0.3 mm. The "focusing magnetic lens" is an objective lens traditionally used in the SEM, with the magnetic field confined between the pole pieces and only a little field leaking on to the specimen surface—we will call it the "closed OL". In order to simulate a "focusing immersion-magnetic lens", i.e. a modern OL improving the beam formation performance by immersing the sample in a strong magnetic field, we have cut the lower pole piece of the previous lens with the plane of the upper pole piece nose—this OL is hereinafter called the "open OL". The magnetic circuits of both OLs were optimized to minimize aberrations and avoid saturation effects, their axial magnetic field distributions are given in Fig. 3. The magnetic field strength in the specimen plane for working distance 5 mm is 1.2 and 128.0 mT for the focusing magnetic lens and focusing immersion-magnetic lens, respectively. These two configurations incorporate different relations between the magnetic and electrostatic fields of the compound lens. The closed OL have the fields arranged sequentially while in the open OL they are mutually overlapping. When describing the simulation results we use abbreviations SQ for the sequential fields and OV for the overlapped fields.

The aberration coefficients for the cathode lens alone and for its combination with a sequentially arranged focusing lens can be estimated using approximate analytical equations derived by Lenc and Müllerová [3,4]. For the sequential combination these relations are as follows:

$$C_S = \frac{l}{(1+k)^{3/2}} \left\{ \frac{k^2}{[(1+k)^{1/2}+1]^3} \left[1 + \frac{l/D}{(1+k)^{1/2}+1} \right] + \left[\frac{3(1+k)^{1/2}-1}{2(1+k)^{1/2}} \right]^4 C_S^m \right\} \quad (5)$$

$$C_C = -\frac{l}{(1+k)^{3/2}} \left\{ \frac{k^2}{[(1+k)^{1/2}+1]^3} - \left[\frac{3(1+k)^{1/2}-1}{2(1+k)^{1/2}} \right]^2 C_C^m \right\}. \quad (6)$$

Here C_S and C_C are the aberration coefficients of the complete compound lens while C_S^m and C_C^m are those of its magnetic focusing part, l is the length of the cathode lens field (i.e. distance between anode and cathode of the CL), and D is diameter of the anode bore. Our aim is to verify these estimations by comparing the

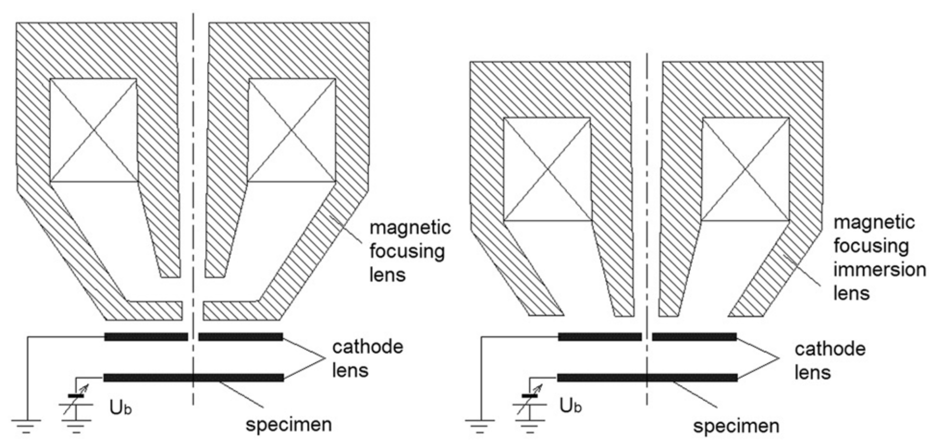

Fig. 2. Arrangements chosen for simulations: the sequential fields of the focusing magnetic lens combined with the cathode lens (left), and the overlapped fields of the focusing immersion-magnetic lens and the same cathode lens (right). The negatively biased specimen is the cathode of the cathode lens while the anode is on the ground potential.