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Practical Integrated Design of a Condenser-objective Lens for Transmission Electron Microscope

Li Wen-ping 1, Wu Jian1, Zhou Zhen1, Gui Li-jiang1, Han Li2

1 Beijing University of Aeronautics and Astronautics, Beijing 100191, P.R.China
2 Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, P.R.China
liwp@buaa.edu.cn

Abstract. A condenser-objective lens is designed through combination of separating and integrating to consider the effect of the front condenser field on its objective performance. A practical lens model including magnetic pole piece, magnetic circuit and coil windings is built to optimize its rear field. The front field can be integrated into the rear one by simply adjusting the position of the specimen and the excitation on the condenser-objective lens. Optical performance of the integrated lens is researched as both a condenser lens and an imaging one. The total aberrations at the specimen plane are 0.01nm under STEM operation mode and its spherical aberration coefficient is 1.5mm when being an imaging objective lens, which can meet for high resolution microanalysis and TEM imaging.

1. Introduction
With the development of nanotechnology, it becomes important to improve the resolution of transmission electron microscope (TEM) in nano-metrology. The resolution of electron microscope is limited by the aberrations of its objective lens, so the popular so-called condenser-objective lens according to Riecke[1] has been the researching focus in this field[2-3]. Condenser-objective lens differs from conventional objectives in that the specimen is arranged in the middle of the pole piece gap. Its front field disposed above the specimen works as a condenser lens and the rear one disposed below the specimen as an objective lens. The condenser-objective lens is the most important lens in both the illumination system and the imaging system. However, most authors have concentrated their efforts on its objective performance either searching for optimized field distributions with minimum aberrations or considering the effect of the current density of coil windings on the objective lens design [3-5]. Chen Wen-xiong developed a program to calculate both condenser and objective performance of such a lens with a given model in 1988[6], but little attention has been paid to the effect of the front condenser field on its objective performance especially in modern field-emission TEM [3]. Furthermore, the specimen is disposed at very high field of the condenser-objective lens and its position is sure to affect its ultimate performance [6]. A more accurate simulation model is needed to obtain higher precise in its optical performance.

In this paper, a condenser-objective lens is designed through combination of separating and integrating the front and rear field. The practical lens model and its rear field are first optimized to achieve the resolution, then its front filed is designed to obtain better illumination. At last, the performance of the integrated lens is researched as both a condenser lens and an imaging lens.
2. **Separate design of the condenser-objective lens**

The condenser-objective lens works in TEM as shown in Fig.1. A beam path denoted by solid lines in Fig.1 represents a standard TEM illumination mode. A beam path denoted by dotted lines without activating the condenser lens in Fig.1 represents the STEM operation mode. The illumination system and the imaging system have different optical principles and different performance, so it is impractical to design the whole lens according to the united criterion.

2.1. **Theoretical design of the rear field**

The rear field is theoretical designed according to resolution in CTEM imaging. According to reference [7], for an optimum defocus value of

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\Delta f_{opt} = -\frac{3}{2} \Delta f_{Sch} = -1.22\left(C_s \lambda \right)^{1/2} \quad (\Delta f_{Sch} \text{ is Scherzer defocus, } C_s \text{ is the spherical aberration coefficient, } \lambda \text{ is the wavelength of the electron})
\]

and optimum aperture size \( \alpha_{opt} = 1.4\left(\frac{\lambda}{C_s}\right)^{1/4} \), the typical value of resolution is \( \delta = 0.66C_s^{1/4} \lambda^{3/4} \). In our 200kV TEM, the spherical aberration coefficient should be smaller than 1.5 mm to get the resolution better than 0.25 nm. According to the conclusions in reference [3], we choose Fig.1 Principle of a condenser-objective lens the gap \( S \) between the pole pieces as 6 mm and the bore diameter \( D \) as 3 mm. When the excitation on the lens is 9976.212NI (\( NI / \sqrt{V_c} = 20.4 \), where \( V_c \) is the corrected voltage when taking into account relativistic effects), its spherical aberration coefficient will be 1.38 mm with 1.8 mm focal length.

2.2. **Practical optimization of the lens model**

![Figure 2: Optimized model of a condenser-objective lens](image)
In order to obtain higher precise simulation, our lens model not only includes magnetic pole piece, magnetic circuit and coil windings but also consists of structures for mechanical assembling. Permendur alloys 1J22 and high purity electrical iron DT4C are chosen as the materials of the magnetic pole piece and magnetic circuit respectively. Better pole pieces structure means smaller fringe field beyond the pole gap. We refer to the conclusions in [8] when designing its magnetic circuit and coil windings and the optimized model is shown in Fig.2. We place the S.A. aperture below the centre of its pole pieces 200mm to leave enough space for other units. Only if the excitation on the lens is above 10377.7NI, the lens will have a spherical aberration coefficient of less than 1.5mm. Its spatial field distribution is shown in Fig.3 and the current densities of coil windings are 221.6 NI/cm². Judged from Fig.3, larger magnetic field (B>2.2T) is situated in the pole piece, so the magnetic circuit is unsaturated. The focal length of the lens is less than 1.92mm, the specimen is disposed below the centre of its pole pieces 0.15mm or farther and the magnification is more than 105.

3. Integrated design of the condenser-objective lens
The author gave an optimized ratio of the upper bore diameter to the lower one (D1/D2) in [6].However, the whole field will be changed greatly once we change the upper bore diameter. Then our above optimization of the rear field may become useless. Here we integrate the front condenser field into the rear one by optimizing the position of specimen and the excitation on the condenser-objective lens.

3.1. Integrating its front field into its rear one
In Fig.1, both the condenser lens and the front field work at the TEM illumination mode, but in STEM mode the front field works solely. The STEM mode is chosen to optimize the front field. The intermediate image plane at STEM mode should have a distance from the objective lens to supply enough space for auxiliary units in TEM. In addition, the aperture at the specimen may be larger than 2.5mrad being necessary for high resolution observation. Better illumination beam is obtained by placing the specimen below the gap centre 116.1µm. The excitation on the condenser-objective lens is 10382.0 NI (current densities of coil windings are 221.7NI/cm²) and its spatial field distribution will
be similar to that shown in Fig.3. The beam current density contours at the specimen is shown in Fig.4 if the energy spread of the field-emission gun is chosen 0.6eV. It can be seen from Fig. 4 that the total aberrations including spherical aberration and chromatic aberration are 0.01nm, which can be used in high resolution microanalysis.

![Fig.4 Beam current density contours at the specimen plane](image)

**Fig.4 Beam current density contours at the specimen plane**

3.2. Performance of the integrated lens

![Fig.5 Electron trajectory under different mode](image)

**Fig.5 Electron trajectory under different mode**
Under the STEM mode, electron trajectory is shown in the upper part of Fig. 5. Its illumination performance is detailed in part 3.1. The integrated lens has a spherical aberration coefficient of 1.5mm, a chromatic aberration coefficient of 1.4mm and a focal length of 1.91mm in the imaging system, which can meet for the ultimate resolution. The focal plane of the pre-field was studied before we get the electron trajectory under TEM mode as shown in the lower part of Fig. 5. In order to obtain the illuminated field, the lower part of Fig. 5 gives the electron trajectory when the focal plane of the pre-field is chosen as the object plane. The diameter of the illuminated field at the specimen plane is about 1.8um when the illumination aperture is 5 mrad. Compared to STEM mode, the same transmission electron trajectory is obtained under TEM mode as the excitation on the condenser-objective lens and the specimen plane keep fixed under both modes. Therefore, the same imaging performance has been obtained under TEM mode.

4. Conclusions
A condenser-objective lens is designed through combination of separating and integrating to consider the effect of the front condenser field on its objective performance. The practical model not only includes magnetic pole piece, magnetic circuit and coil windings but also consists of structures for future assembling, which improves the simulation precision greatly. Optical performance of the integrated lens shows that it can be used in high resolution TEM and STEM.

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