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Abstract

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PHYSICS

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ON THE REALIZATION OF THE THEORETICAL LIMIT OF THE RESOLVING POWER OF AN ELECTRON MICROSCOPE

(Presented by Academician A. A. Lebedev, June 19, 1968)

We have developed the EMV-100L electron microscope with a guaranteed resolving power of 3 Å. The instrument has been used to compare the realized resolution with the theoretical limit determined by the optics of the instrument. At present the EMV-100L microscope is being put into production by industry.

The theoretical limit of resolving power is determined by the spherical aberration of the objective and by diffraction phenomena ([1]):

$$\delta_{\mathrm{t}} = A\sqrt[4]{C_{\mathrm{sph}}\lambda^3}. \tag{1}$$

It is realized at the optimum aperture of the objective

$$\alpha_0 = B\sqrt[4]{\frac{\lambda}{C_{\mathrm{sph}}}}, \tag{2}$$

where C_{sph} is the coefficient of spherical aberration of the objective, and λ is the electron wavelength. The coefficients A and B depend on the aperture of the condenser, on the form of the electron-scattering function in the object, on the adopted resolution criterion (the ratio between the maximum and the minimum of the intensity-distribution curve of the particle image), and on the focal plane (Gaussian or optimum). For the optimum focal plane the following values have been found for these coefficients: $B = 1.4$, $A = 0.4$ (0.43), and $A = 0.6$. The last value refers to the case when the condenser aperture $\alpha_{\mathrm{B}} \ll \alpha_0$.

For a number of reasons, the actual resolving power of electron microscopes differs from the theoretical limit. The principal causes worsening the resolution are as follows: thermal drifts and drift caused by mechanical stresses in the structural elements of the specimen stage and other units of the instrument, insufficient vibration resistance of the microscope, disturbance of the adjustment of the optical system by stray magnetic fields arising when the lenses are

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Fig. 1. Iridium particles on a carbon substrate. Electron-optical magnification 305,000. Total magnification 2,200,000

Figure 1: Fig. 1. Iridium particles on a carbon substrate. Electron-optical magnification 305,000. Total magnification 2,200,000

switched on, residual astigmatism of the objective, inaccuracy of focusing of the image, contamination of the object by hydrocarbon deposits, instability of the high voltage and of the lens excitation currents, etc.

Recently, as a result of careful refinement of instrument designs, errors caused by the factors listed above have been significantly reduced, as a result of which the resolving power of the best instruments has approached the theoretical limit. Microscopes with a guaranteed resolution of 5 Å are now being produced, and in individual cases a record resolution of 2.8–3 Å has been achieved, close to the theoretical resolution limit ([2]).

In the EMV-100L electron microscope, the above-listed causes that reduce resolution have been practically completely eliminated. Thermal stabilization of the entire column of the instrument has been introduced, and the na-

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Fig. 1. Iridium particles on a carbon substrate. Electron-optical magnification 305,000. Total magnification 2,200,000.

heating of its individual parts by the heat released in the excitation windings of the lenses. On the basis of theoretical and experimental investigations of the mechanism of the specimen stage, drift of the carriage with the specimen holder was eliminated. A rigid design of the microscope column was created. To eliminate stray fields, the microscope column was made of permalloys of various grades—precision alloys which, in the most important parameters, surpass the best grades of pure iron used in instrument making. The rate of contamination of the specimen was sharply reduced as a result of the use of high-quality vacuum materials. The brightness of the illuminator was increased, and the possibility of reliable operation at high electron-optical magnifications (300–450 thousand times) was ensured, which makes it possible to correct the astigmatism of the objective lens and focus the image with sufficient accuracy. A power supply was developed for the microscope with high-voltage stability of $2 \cdot 10^{-6}$ min^{-1} and objective-lens current stability of $1 \cdot 10^{-6}$ min^{-1}. The magnetomotive force of the objective lens was increased to 5000 ampere-turns, as a result of which the coefficient of spherical aberration of this lens decreased to $C_{\text{sph}} = 1.5$ mm. According to (1), the theoretical limit of the resolving power of the EMV-100L microscope is, at an accelerating voltage of 100 kV, 2.1 Å; at 75 kV, 2.3 Å; and, if $\alpha_B \ll \alpha_0$, $\delta_t = 3.5$ Å.

Work on the instrument was carried out at a voltage of 75 kV. The aperture angle of the objective in the experiments was optimal; the aperture of the illumination

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system was almost an order of magnitude smaller than the objective aperture. On a microscope with a good yield percentage (20–25%), a resolution of 3 Å and better was achieved. In a number of cases a resolution of 2.5–2.3 Å was recorded, and in isolated cases 2.2 and 2.1 Å. At such high resolutions, when only a small number of electrons participate in the formation of the image of small particles, fluctuations of the electrons in the beam inevitably have an effect, as a result of which, in individual rare cases, a resolution better than the actual one may be recorded (3). Therefore one can state with sufficient confidence that a resolution of 2.5–2.3 Å, which was obtained repeatedly, was realized.

Thus, on the EMV-100L microscope it proved possible to compare the data of theory with experiment. According to the theory, one could expect a resolution close to 3 Å, since we worked with $\alpha_B \neq \alpha_0$. In fact, a higher resolution was obtained (see Fig. 1). Such a resolution is not unexpected, since the angular distribution of the electrons and the resolution criteria adopted in the theory lead to overestimated values of δ_t (Fig. 1, see inset to p. 75).

In conclusion, the authors express their gratitude to the staff members who took part in the development, manufacture, and adjustment of the new microscope.

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CITED LITERATURE

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Note: Figure translations are in progress. See original paper for figures.

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