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ACCURACY IN LINEAR DIMENSIONS MEASUREMENT IN SCANNING ELECTRON MICROSCOPES IN MICROTECHNOLOGY AND NANOTECHNOLOGY

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A study has been made on the effects of scanning electron microscope parameters on the accuracy in measuring the linear dimensions in microtechnology and nanotechnology. Definitions are given of the errors with which these parameters should be known for using such microscopes in such technologies.

Key words: *scanning electron microscope, relief-structure linear dimensions.*

Scanning electron microscopes (SEM) are widely used [1–4]. Their technical and economic parameters are governed by the characteristics of the electron probe, of which the most important are the geometrical ones: focused electron beam size (diameter), convergence and divergence angles, and focal depth. That information is important in SEM design and upgrading and also in using the microscope in research and industry.

Knowledge of the electron-probe geometrical characteristics is not an independent purpose. One needs a correct understanding of the physical significance of the parameters characterizing narrow electron beams and their effects on the SEM parameters and the focusing systems, as this enables one to build microscopes with new properties and focusing systems, which provide marked reduction in the electron-probe dimensions.

However, exact measurement of probe parameters is not restricted to the needs of SEM upgrading. The probe dimensions have a large effect on the determination of microstructure linear dimensions [5–7], particularly in the nanometer range.

We consider what probe parameters and what measurement accuracy are required at present and will be necessary in the near future for measuring the linear dimensions of microstructure and nanostructure elements.

Relief Structures Used in Microtechnology and Nanotechnology. These have a fairly complicated profile (Fig. 1), and the details of electron-probe interaction with such a surface [8] (relation between structure and probe parameters) indicate that there are four main groups of structure:

1) rectangular, which are not usually encountered. They have been made especially for use as standard measures [9] for calibrating SEM [10] and are characterized by $\varphi < \varphi_d/2$, where φ_d is the convergence-divergence angle of the electron probe;

2) trapezoidal with small angles of inclination in the side walls, which are the basic form of structures:

$$d > s = h\tan\varphi; \qquad (1)$$

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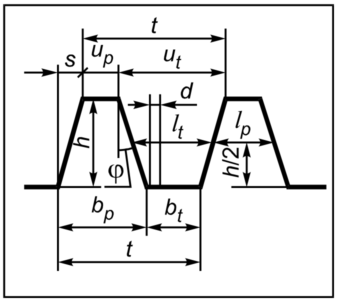


Fig. 1. Scheme for trapezoidal stepped structure with characteristic parameters.

3) trapezoidal with large inclinations, which are fairly often used in that area and are characterized by $d \ll s = h \tan\varphi$; the most important point for these structures is their use for calibrating scanning electron and atomic-force microscopes [11];

4) trapezoidal with negative slopes of the side walls ($\varphi < 0$). These structures are encountered fairly rarely and are not used to calibrate SEM.

Measuring Microstructure and Nanostructure Linear Dimensions.

Recent fundamental researches [8] have served to define the positions of the reference points on video signals obtained in slow secondary electron collection. Figures 2*a*, 3*a*, and 4*a* give the actual shapes of the signals, while Figs. 2*b*, 3*b*, and 4*b* show schemes for the signals and the reference points selected on them. These points correspond to signal maxima or are points of intersection between straight lines approximating individual signal parts (the base level of the signal and the flanks). Figures 2*b*, 3*b*, and 4*b* also show the reference segments (distances between certain reference points). The sizes of the segments are linearly related to the sizes of the relief structures:

- for rectangular structures,

$$l = L/M - 2\delta; \tag{2}$$

$$l = G/M + d; \tag{3}$$

- for structures with small angles of inclination of the side walls,

$$t = T/M; \tag{4}$$

$$l_p = (u_p + b_p)/2 = L_p/M; \tag{5}$$

$$l_t = (u_t + b_t)/2 = L_t/M; \tag{6}$$

$$u_p = (2L_p - G_p)/M + d; \tag{7}$$

$$b_p = G_p/M - d; \tag{8}$$

$$u_t = (2L_t - G_t)/M - d; \tag{9}$$

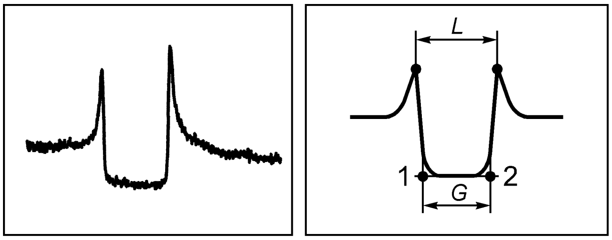
$$b_t = G_t/M + d; \tag{10}$$

- for structures with large angles of inclination of the side walls,

$$t = T/M; \tag{11}$$

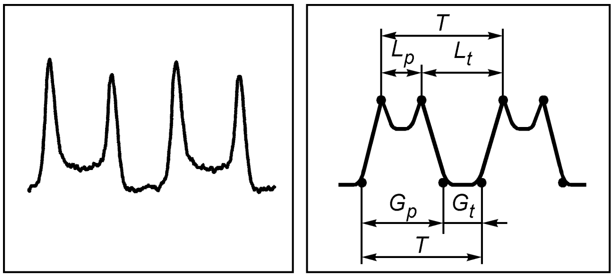
$$s = S/M; \tag{12}$$

$$d = D/M; \tag{13}$$



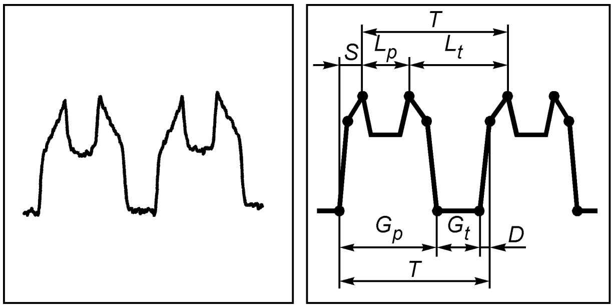
a *b*

Fig. 2. *a*) Shape of actual SEM signal obtained in slow secondary electron collection on scanning a slot-type groove; *b*) scheme for signal with measurable parameters.



a *b*

Fig. 3. The same as Fig. 2 but for a stepped structure with small angles of side wall inclination.



a *b*

Fig. 4. The same as in Figs. 2 and 3 but for a stepped structure with large side wall inclination angles.

$$u_p = L_p/M + d; \tag{14}$$

$$b_p = G_p/M - d; \tag{15}$$

$$u_t = L_t/M - d; \tag{16}$$

$$b_t = G_t/M + d. \tag{17}$$

The parameters of the linear equations have a clear-cut physical significance, which has been considered in [8].

Measuring rectangular-structure linear dimensions. For rectangular grooves, parameter G of the video signal (VS) (Fig. 2*b*) is related to the width l of the groove by (2), while the distance L between VS maxima is given by (3). The physical meanings of the d and δ in these formulas have been determined after lengthy and difficult researches [8].

The effects of probe diameter on the accuracy of measuring the dimensions of rectangular structures (RS) have been dealt with in some detail in [8, 12–14], and the effects on the accuracy of measurement for RS width can be defined by the following:

$$(\Delta l/l)^2 = (1 - d/l)^2[(\Delta G/G)^2 + (\Delta M/M)^2] + (\Delta d/l)^2. \tag{18}$$

Measuring the linear dimensions of trapezoidal structures with small side wall inclination angles. For these structures (typical structures used in microelectronics), the linear equations relating the parameters of structure and signal have the form of (4)–(16). The geometrical meanings of the quantities in those equations are indicated by Figs. 1*b* and 3*b*. The parameters in linear equations (7)–(10) are the magnification M of the microscope and the diameter d of the electron probe. These equations have been checked out by measurement of the sizes of the ridges and grooves in a unit with trapezoidal profile [6, 7] on various SEM and various probe electron energies and probe diameters (including variation by defocusing [7]).

Equations (7)–(10) indicate that the probe diameter is important in measurements of linear dimensions for relief structures. We may estimate the contribution from the error in probe diameter measurement to the total error in determining microstructure linear-element sizes. From (7)–(10), we readily get the following expressions:

- for ridges

$$\left(\Delta b_p / b_p\right)^2 = \left(1 + d / b_p\right)^2 \left[\left(\Delta G_p / G_p\right)^2 + (\Delta M / M)^2\right] + \left(\Delta d / b_p\right)^2; \tag{19}$$

$$\left(\frac{\Delta u_p}{u_p}\right)^2 = \left(1 - \frac{d}{u_p}\right)^2 \left[\left(\frac{2\Delta L_p}{2L_p - G_p}\right)^2 + \left(\frac{\Delta G_p}{2L_p - G_p}\right)^2 + \left(\frac{\Delta M}{M}\right)^2\right] + \left(\frac{\Delta d}{u_p}\right)^2; \tag{20}$$

- for grooves

$$\left(\Delta b_t / b_t\right)^2 = \left(1 - d / b_t\right)^2 \left[\left(\Delta G_t / G_t\right)^2 + (\Delta M / M)^2\right] + \left(\Delta d / b_t\right)^2; \tag{21}$$

$$\left(\frac{\Delta u_t}{u_t}\right)^2 = \left(1 + \frac{d}{u_t}\right)^2 \left[\left(\frac{2\Delta L_t}{2L_t - G_t}\right)^2 + \left(\frac{\Delta G_t}{2L_t - G_t}\right)^2 + \left(\frac{\Delta M}{M}\right)^2\right] + \left(\frac{\Delta d}{u_t}\right)^2. \tag{22}$$

Measuring the linear dimensions of trapezoidal structures with large side wall inclination angles. Equations (14)–(17) define the dimensions of the bottom base of the ridges and grooves, so the error in measuring the base is found from (19) and (21) and that for the top from

$$\left(\Delta u_p / u_p\right)^2 = \left(1 - d / u_p\right)^2 \left[\left(\Delta L_p / L_p\right)^2 + (\Delta M / M)^2\right] + \left(\Delta d / u_p\right)^2; \tag{23}$$

$$\left(\Delta u_t / u_t\right)^2 = \left(1 - d / u_t\right)^2 \left[\left(\Delta L_t / L_t\right)^2 + (\Delta M / M)^2\right] + \left(\Delta d / u_t\right)^2. \tag{24}$$

Linear-Dimension Measurement Error Analysis. Equation (18) for a rectangular groove is a consequence of (21) for the trapezoidal case, while (23) and (24) for trapezoidal structures with large side wall slopes correspond to (19) and (21) for trapezoidal structures with small side-wall slopes, apart from change in the variables and sign in the first bracket. Therefore, the two expressions have identical analyses.

The error in measuring the distances $G_{p,\,t}$ and $L_{p,\,t}$ on the video signals is very much affected by the noise component and by the algorithms for searching for the corresponding reference points (Fig. 3*b*), but with reasonable constraints (noise contribution not more than 10% of the signal amplitude) and automatic image signal processing in current experiments imply that $\Delta G_{p,\,t}/G_{p,\,t} \sim \Delta L_{p,\,t}/L_{p,\,t} \sim 10^{-3}$, so on the basis of the condition

$$b_{p,\,t},\, u_{p,\,t} \gg d \tag{25}$$

we get that (19)–(22) can be simplified:

$$\left(\Delta b_{p,\,t} / b_{p,\,t}\right)^2 \approx (\Delta M / M)^2 + \left(\Delta d / b_{p,\,t}\right)^2; \tag{26}$$

$$\left(\Delta u_{p,\,t} / u_{p,\,t}\right)^2 \approx (\Delta M / M)^2 + \left(\Delta d / u_{p,\,t}\right)^2. \tag{27}$$

Current methods of calibrating SEM allow one to obtain relative errors in the magnification $\Delta M/M$ in the range 0.2–0.7% [10], while Δd usually does not exceed 1–2 nm. Then in the range of dimensions for microstructure elements $b_{p,\,t},\, u_{p,\,t} > 10$ μm, the error in measuring the probe diameter Δd can be neglected. Then the errors in measuring the top and bottom bases of the trapezium are determined only by $\Delta M/M$ on calibration:

$$\Delta b_{p,t} / b_{p,t} \approx \Delta u_{p,t} / u_{p,t} \approx \Delta M / M. \tag{28}$$

In the range 10 μm > $b_{p,\,t},\, u_{p,\,t}$ > 1 μm, the contribution from Δd can be neglected only for small probe diameters (d < 100 nm). In that case, one uses (27). For large diameters, one must use (26) and (27).

In the range 1 μm > $b_{p,\,t},\, u_{p,\,t}$ > 100 nm, one cannot neglect Δd or ΔM for any probe diameters, and it is necessary to use (26) and (27). Then the contribution to the error in measuring the probe diameter to the total error in determining the linear dimensions of relief structures may attain 80%.

For microstructure element sizes $b_{p,\,t},\, u_{p,\,t}$ < 100 nm, the contribution from the magnification error on calibration in (26) and (27) can be neglected. Then we get $\Delta b_{p,\,t} \approx \Delta u_{p,\,t} \approx \Delta d$.

This means that the error in measuring the linear dimensions of relief structures in the nanometer range (less than 100 nm) is completely determined by the error in measuring the electron probe diameter. Also, the microscope can be used to measure the sizes of microstructure elements in ranges greater than 1 μm for probe diameters up to 100–200 nm, while for the range less than 100 nm one requires probes of diameter 30 nm and less. Such probe sizes at present occur only in new microscopes. After 3–5 years of extensive use (e.g., in industry), the probe dimensions increase to 50 nm and more. Then the SEM cannot provide for measuring linear dimensions in the nanometer range. It is therefore necessary to develop new microscopes with smaller probe dimensions. These microscopes should provide automatic focusing, i.e., maintenance of the probe size with an error less than 1 nm when the SEM parameters vary widely.

The following feature occurs in measuring linear dimensions of microstructure elements by the use of (4) and (5) [6]. In that case, the probe diameter has no effect on the measurement of sizes for middle lines (Fig. 1) of trapezoidal ridges l_p and grooves l_t (with conditions (1) and (25) met). These features have been confirmed in special experiments [6–8] on SEM working with primary electron energies $E \geq 15$ keV in slow secondary electron collection. Then the error in measuring the middle line of a structure element is determined in the main by the magnification error:

$$\Delta l_{p,\,t}/l_{p,\,t} \approx \Delta M/M, \tag{29}$$

while the probe diameter and the error in measuring it have little effect (apart from conditions (1) and (25)).

For small probe diameters $d \ll l_{p,\,t}$, (29) applies also for the nanometer range, but this does not introduce any advantage, since in microelectronic and nanoelectronic technologies it is necessary to know the linear dimensions of the microstructures and nanostructures at the top and particularly at the bottom of the ridges and grooves, and such dimensions can be determined only if the probe diameter is known.

An exact knowledge of the probe size thus guarantees measurement in the SEM of linear dimensions for rectangular and trapezoidal structures over a wide range down to tens of nanometers. The error in such measurements is largely determined by the error in measuring the electron probe size. An important specification for the latest microtechnologies and nanotechnologies is thus an SEM with a probe of diameter less than 20 nm.

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