Energy dependence of proximity parameters investigated by fitting before measurement tests

L. I. Aparshina, S. V. Dubonos, S. V. Maksimov, A. A. Svintsov, and S. I. Zaitsev[a)]
Institute of Microelectronics Technology, Chernogolovka 142432, Russia

(Received 28 May 1997; accepted 26 August 1997)

Some years ago a method for fast and accurate experimental evaluation of the proximity parameters α, β, η was suggested [S. V. Dubonos *et al.*, Microelectron. Eng. **21**, 293 (1993)]. The method, called the *fitting before measurement* procedure, is used for regular measurements of β and η in a wide energy range for different bulk substrates (Si, SiO_2, mica, ZrO_2, Al_2O_3, InAs, GaAs) and of α as function of resist thickness and energy. An empirical relation from the fitting procedure allows one to extrapolate the β and η values to other substrates and energies. It is demonstrated that a resist of micron thickness can remarkably reduce the resolution of e-beam lithography. It is important that the reducing could not be improved by accurate focusing of the beam but could be overcome only by using a higher accelerating voltage. A phenomenological relation helps to predict resolution as function of resist thickness and electron energy. © *1997 American Vacuum Society.*
[S0734-211X(97)17406-6]

I. INTRODUCTION

The proximity effect in e-beam lithography is quantitatively described by the two Gaussian formula (proximity function)

$$I(r)=\frac{I_1(r)}{(1+\eta)}+\eta\,\frac{I_2(r)}{(1+\eta)}$$

$$=\frac{1}{(1+\eta)}\left(\frac{\exp\left(-\dfrac{r^2}{\alpha^2}\right)}{\pi\alpha^2}+\eta\,\frac{e^{-(r^2/\beta^2)}}{\pi\beta^2}\right),\quad r^2=x^2+y^2,$$

where α is a beam ''spot,'' β is a proximity distance determined by electrons backscattered in the substrate, and η is the ratio of a dose contribution of backscattered electrons to a dose contribution of incident electrons. To handle the proximity effect it is essential to know the ''proximity parameters'' α, β, and η. Usually for parameter determination special patterns are exposed, for which the proximity function can be solved analytically, allowing one to fit experimental results.[1–7] Such patterns need measurements close to heavily overexposed areas, where the result can be influenced by development processes. This could be one reason for the widespread use of measured parameters for identical substrates.[6,7] Using such methods it is also very difficult to get information about possible measurement errors. Usually α is less than 0.1 μm, a value which is very difficult to measure precisely. As a consequence, low accuracy of α causes a large error in η due to normalization of the proximity function.

Generally speaking, the beam spot α, the proximity distance β, and the dose ratio η are determined by cross sections of elastic and inelastic scattering of fast electrons in a resist and a substrate and, therefore, depend on electron energy E, atomic number, atomic weight, density of the substrate (resist), and resist thickness, h. Exact values of the parameters are very important for successful correction of the proximity effect in practical e-beam lithography. The desire to provide experimenters with these values for different substrates was one of the sources of motivation for the measurements.

Besides this we have one more goal in mind. The practical range R_{pr} and the backscattered coefficient η_{BC} are notions widely used in scanning electron microscopy.[8] The practical range R_{pr} determines the spatial resolution of scanning electron microscopy (SEM) diagnostics whereas the backscattered coefficient η_{BC} is related to SEM image contrast. There is a close correlation between β, η and R_{pr}, η_{BC}. From a fundamental point of view interaction of fast electrons with media can be investigated via the dependence of the practical range on accelerating voltage and material properties. But experimental measurement of the practical range is difficult and includes measurement of the transmission coefficient of a set of films with different thicknesses.[8] The film thicknesses should be comparable to and less than the practical range, so two obvious difficulties with this method are the preparation of films with controllable thickness in the micron and submicron range and (even) the possibility of preparing these films. On the other hand, the practical range R_{pr} and the proximity distance β are related by linear dependence so we suggest using the proximity distance for characterization of the interaction of fast electrons with matter instead of the practical range. Such a fast and easy way to measure the proximity parameters paves a way to investigate elastic and inelastic cross sections for different materials.

II. ALPHA, BETA, AND ETA TESTS

Some procedures for evaluation of the proximity parameters were suggested. The common feature of the methods is a consequence of measurement fitting. As mentioned earlier, such methods need to measure distances in nanometers, which leads to unacceptably low accuracy of η and α. Sev-

a)Electronic mail: zaitsev@ipmt-hpm.ac.ru

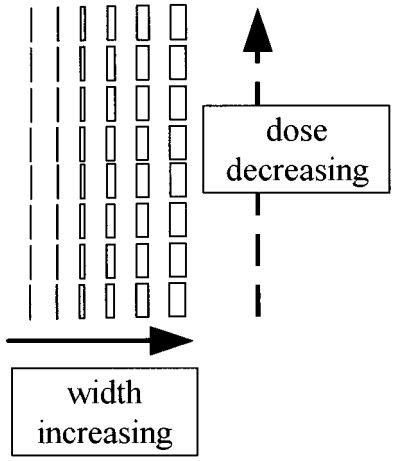

FIG. 1. Test pattern used for α determination.

eral years ago a method[9] for fast and accurate experimental evaluation of the parameters α, β, and η was suggested and some results for Si and GaAs were obtained. The method can be characterized as the fitting before measurement method. Here we used the method for measurement of β and η in the wide energy diapason for different bulk substrates and for different resist thicknesses.

A. Fitting before measurement method

Special patterns have been designed where the doses of all the features are numerically calculated by PROXY[10,11] (a PC software package for proximity correction) using a given set of parameters. If the used parameters are ''true,'' the pattern developed will show a special boundary as a straight horizontal line. If this line is bent, the parameters used are not correct. Along this line all features have just the right dose which avoids any effects caused by the development process due to overexposure.

Fortunately such tests can be done specifically for α and also for β, allowing measurement of these parameters independently by comparing several exposed patterns (preferable after ''lift off'') calculated with different parameter values. η can be measured by patterns which were calculated by using a true value for β.

Looking just for straight horizontal lines in different patterns also gives a clear impression of the accuracy of the measured parameter values.

The test patterns were generated by special procedures implemented in PROXY. Lithographic data of the patterns were exposed with JSM840 under PROXY control as well.

B. Test pattern for α

This pattern consists of many isolated vertical lines with increasing widths ranging from values less than α up to approximately 5α. Each line is split into small vertical elements separated by a gap of 0.1 μ (see Fig. 1).

Along all line elements in one vertical level the required dose for a full exposure is numerically calculated by PROXY using a given α value. Values used for β and η are not critical, but β must be large compared to α, which is normally the case. In the vertical direction all doses are scaled down, e.g., by a factor of 0.95, from step to step. Assuming the bottom ends of all the lines are overexposed and the top ends are underexposed there must always be a clear boundary in between. The gaps between the vertical elements are used for making the lift off process easier.

Where the value used for α is correct, the boundary between fully exposed and underexposed vertical elements will form a straight horizontal line! If the true α is smaller than the one used for calculation, the narrow lines will be longer than the wide ones and visa versa.

The parameters β and η will just move this line up and down, if β is very large compared to α', if not, the left side of the pattern will still indicate whether α is too high or too low.

A PMMA based resist of 0.5 μm thickness was used in the experiments. Figures 2(a)–2(c) show only three patterns from several exposed on a substrate after development and lift off, calculated with α values between 60 and 100 nm. The straightest and most horizontal boundary can be assigned to be just between the two patterns of Figs. 2(b) and 2(c) and this gives a true α value of about 75 nm. The comparison of the patterns makes it clear that this method allows an α determination within approximately 10%.

C. Test pattern for β

While the calculation of the test pattern for α mainly considers the loss of dose in each line due to forward scattering, the test pattern for β is also based on the gain of dose in a probe line by backscattered electrons from the overexposed pattern.

Figure 3 shows this test pattern where a small probe line is positioned in the middle between two wide and overexposed lines. Numerical calculation is done in such a way that half of the probe line dose is exposed by the incident beam while the other half has contributions by backscattered electrons from the areas as well. The total test pattern contains many such vertical line groups. In the horizontal direction the gaps between the overexposed lines are increasing while in the vertical direction the lines are again separated into small elements where the doses are scaled down in the same way as before.

Where the β value used for calculation is correct, all probe lines will end up the same height, again forming a straight boundary (note: this is just a boundary for the inner probe line; the outer overexposed lines have to be ignored). Changes in α or η will move this straight horizontal boundary only up or down but will not influence the straightness and the angle, therefore this test pattern depends on β only.

If the boundary decreases to the right, it shows that the real β value must be smaller than the assumed one and vice versa.

Figure 4 shows such a pattern for Si again after lift off, calculated for a β value equal to 3.9 μm, which turned to be the most horizontal boundary, formed by the upper ends of

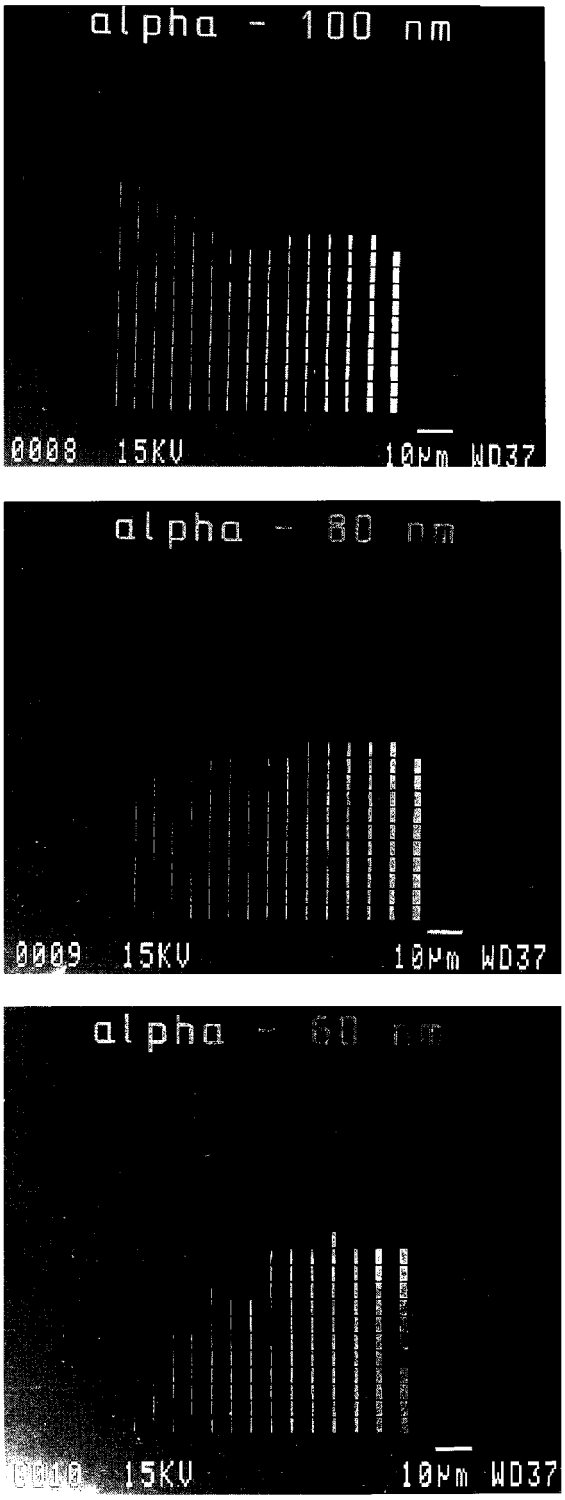

FIG. 2. (a) Part of an experimental image with the α pattern designed for a beam spot equal to 100 nm. It is seen that real beam spot is smaller. (b) Part of an experimental image with the α pattern designed for beam spot equal to 8 nm. The real beam spot is very close to the one used in the calculation. (c) Part of an experimental image with the α pattern designed for a beam spot equal to 60 nm. There is no a straight line and the real beam spot is higher.

all the inner probe lines. So it was concluded that 3.9 μm was the β value for the Si substrate at 30 keV. Also, here it was assumed that the accuracy achievable is approximately 10%.

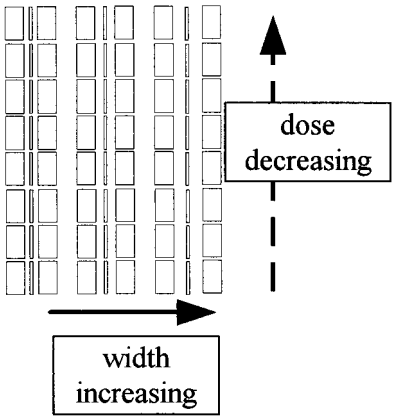

FIG. 3. Test pattern design for β determination.

D. Test pattern for η

This test pattern is very similar to the test pattern for α (see Fig. 1), but the linewidth ranges from less than β to approximately 5β.

With this pattern the result depends strongly on η and on β and the two effects cannot be clearly separated. Therefore it is important that the dose distribution in this pattern is calculated with a true β value, which was measured before. The left side of this pattern (Fig. 5) depends mainly on β whereas the right side is more related to η. Using a true β value the height of the horizontal boundary is already given. The true η value will now correspond to that pattern, where the boundary on the right side is the same height as that on the left side. A higher boundary on the right side indicates that the true η value is higher than the one used for the calculation and visa versa.

III. ENERGY DEPENDENCE OF BETA

Due to the small thickness of the resist and its low density the contribution by the resist in the scattering of fast electrons and in proximity distance β is considered negligible. Beta values were measured for different substrates, most of

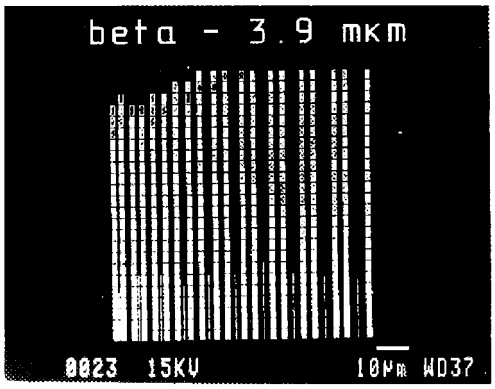

FIG. 4. Experimental image of the test pattern designed for $\beta = 3.9$ μm (Si) demonstrates the coincidence of expected and real values.

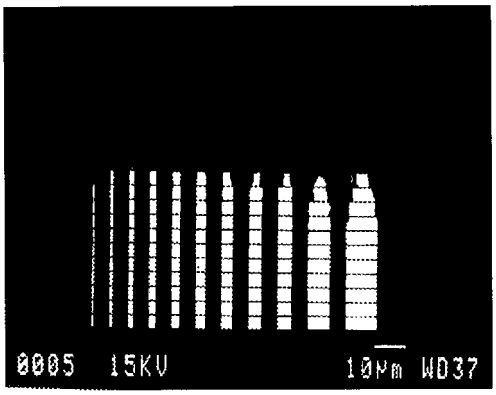

FIG. 5. Experimental image of the test pattern allows the conclusion that parameter η is equal to 0.7.

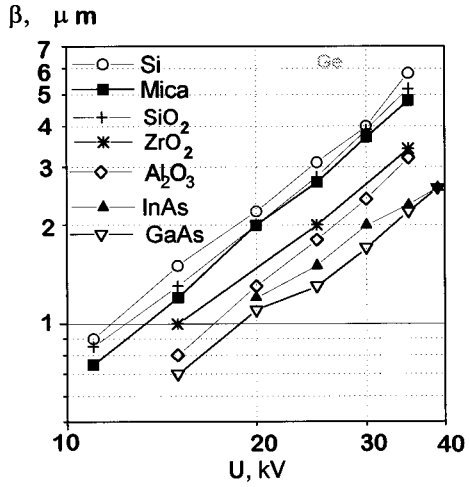

FIG. 6. Dependence of proximity distance β on the energy (accelerated voltage) of electrons for several bulk substrates.

which are of particular interest for microelectronics. The results are shown in Table I. In Table I results of fitting to the power law $\beta = K^* E^p$ are presented. The energy of the electrons is measured in keV and values $K(K_{\max}, K_{\min})$ are given in microns. Exponent p is dimensionless. The standard fitting procedure gives the confidence interval $(p_{\min}, p_{\max})$ for p and $(K_{\max}, K_{\min})$ for prefactor K at a confidence level of 95%. The power law was expected due to the similarity of the proximity distance to the practical range (diffusion depth) known from SEM diagnostics.[8] The exponent values are close to those measured for the practical range but much easier to measure. The data are shown in graph form in Fig. 6.

A backscattering coefficient η_{BS} is a ratio of the backscattered electrons to the number of incident electrons. It is a well known fact that the coefficient is independent of electron energy in the range 5–100 keV. The proximity parameter η is a ratio of absorbed dose induced by backscattered electrons to an absorbed dose related to incident electrons. One could expect a close similarity between these two coefficients. Indeed, measurement of η by the method showed energy independence of parameter η in the range 10–40 keV. The η values are shown in the Table I.

IV. ENERGY AND RESIST THICKNESS DEPENDENCIES OF ALPHA

Now, after developing methods of the proximity effect, the correction spatial resolution is frequently determined by spot diameter of an electron beam, α. The spot diameter is

TABLE I. Proximity parameters β (as function of electron energy E) and η for different substrates. The fitting procedure based on the formula $\beta = K^*(E/1\,\text{keV})^p$ gives the mean values of p and K with the confidence interval $(p_{\min}, p_{\max})$ and $(K_{\min}, K_{\max})$ at a confidence probability of 95%.

E (keV)	Si	SiO_2	Mica	Al_2O_3 β (μm)	ZrO_2	InAs	GaAs
11	0.9	0.85	0.75	⋯	⋯		
15	1.5	1.3	1.2	1	0.8	0.7	⋯
20	2.2	2	2	⋯	1.3	1.1	1.2
25	3.1	2.8	2.7	2	1.8	1.3	1.5
30	4	3.9	3.7	⋯	2.4	1.7	2
35	5.8	5.2	4.8	3.4	3.2	2.2	2.3
39	⋯				⋯	2.6	2.6
				$\beta = K^* E^p$			
p	1.55	1.56	1.6	1.61	1.5	1.36	1.34
$p_{\min}$	1.46	1.48	1.55	1.56	1.36	1.22	1.22
$p_{\max}$	1.65	1.64	1.64	1.67	1.65	1.5	1.46
K	0.0185	0.0193	0.016	0.0102	0.0166	0.0189	0.0185
$K_{\min}$	0.0126	0.0151	0.014	0.0086	0.0104	0.0119	0.0126
$K_{\max}$	0.0273	0.0246	0.0182	0.0121	0.0266	0.03	0.0273
The accuracy of the η measurement is about 20%.							
η	0.7	0.5	0.5	0.8	1	1.4	1.4

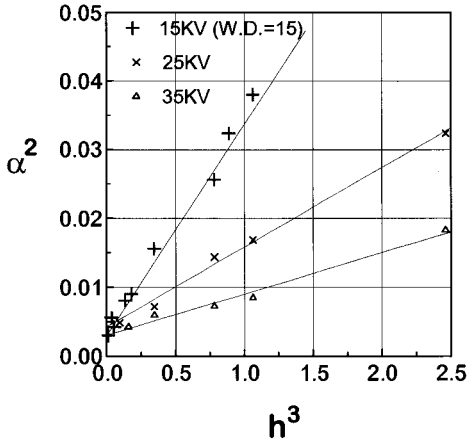

FIG. 7. Dependence of electron beam spreading α^2 as function of resist thickness h^3 measured for three different electron energies shows the power dependence expected from the theory of small-angle scattering.

determined in turn by an initial beam spot, α_0, and by beam spreading due to small-angle scattering in resist, d:

$$\alpha^2 = \alpha_0^2 + d^2 = \alpha_0^2 + h^3/L_{\text{eff}},$$

where h is the resist thickness and L_{eff} is proportional to a so-called transport length l_{tr} of fast electrons. The transport length l_{tr} is determined by elastic (low-angle) scattering of the electrons in the resist and it is known that it is related to electron energy by parabolic dependence $l_{\text{tr}} \propto E^2$. It is seen that even for an infinitely narrow beam there is a physical reason for finite beam size. There are some theoretical estimates of beam spreading in resist but it is very interesting to measure the value experimentally.

The above mentioned alpha test was used for systematic investigation of spreading as a function of the resist thickness and electron energy. A remarkable feature of the method is that it allows the measurement to be carried out in the submicron and nanometer range using an ordinary SEM (and even an optical microscope) with relative accuracy (not less than 10%) due to the special form of the test pattern. A PMMA based resist of varying thicknesses (0.07–1.35 μm) was used at three different electron energies (15, 25, and 35 keV). All the data sets (Fig. 7) demonstrate the expected power dependence on resist thickness h and energy E. A fitting procedure based on the formula

$$\alpha^2 = \alpha_0^2 + A^* h^3/E^2$$

gives values of the initial beam spot α_0 and a phenomenological constant A listed in Table II. Extrapolation of the dependence to zero thickness gives the value of the initial beam α_0 as about 55–60 nm. Additional conclusions about the correctness can be made from the independence of fitting parameters α_0 and A on electron energy.

TABLE II. Parameters α_0 and A extracted from the formula for spreading of the electron beam due to small-angle scattering in resist, $\alpha^2 = \alpha_0^2 + A^* h^3/E^2$.

E (keV)	α_0 (μm)	A
15	0.055	7.43
25	0.061	7.58
35	0.059	7.65

From a practical point of view it is important (to point out) that a resist of micron thickness can remarkably reduce the resolution of e-beam lithography. It is important that the reducing could not be improved by accurate focusing of the beam but could be overcome only by using higher accelerating voltage. The measured spreading provides a quantitative tool for estimation of the resist thickness and energy influence on electron lithography accuracy.

Such experiments are of fundamental interest because they pave the way for measurement of the elastic scattering cross section of fast electrons with matter and could provide unique and important information.

ACKNOWLEDGMENTS

The authors are obliged to the anonymous referees who reviewed this paper for their comments which led to the improvements of both the style and the presentation of this article. This work was supported in part by the Russian Foundation of Fundamental Research (Grant Nos. 96-02-19798 and 97-02-17318).

[1] R. J. Hawryluk, J. Vac. Sci. Technol. **19**, 1 (1981).
[2] C.-H. Shaw, J. Vac. Sci. Technol. **19**, 1269 (1981).
[3] V. V. Aristov, S. V. Babin, A. I. Erko, and L. V. Dorozhkina, Proceedings of the International Conference ''ME '83,'' Cambridge, 1983, p. 57.
[4] L. Stevens, R. Jonkheere, E. Froyen, S. Decoutere, and D. Lanneer, Proceedings of the International Conference ''ME '86,'' Zurich, 1986, p. 98.
[5] V. V. Aristov, S. V. Babin, A. V. Davydov, A. I. Erko, A. A. Svintsov, and S. V. Redkin, Proceedings of the International Conference ''ME '87,'' 1987, p. 129.
[6] S. A. Rishton and D. P. Kern, J. Vac. Sci. Technol. B **5**, 135 (1987).
[7] S. J. Wind, M. G. Rosenfield, G. Pepper, W. W. Molzen, and P. D. Gerber, J. Vac. Sci. Technol. B **7**, 1507 (1989).
[8] L. Raimer, *Scanning Electron Microscopy* (Springer, Berlin, 1985).
[9] S. V. Dubonos, B. N. Gaifullin, H. F. Raith, A. A. Svintsov, and S. I. Zaitsev, Microelectron. Eng. **21**, 293 (1993).
[10] V. V. Aristov, A. L. Erko, B. N. Gaifullin, A. A. Svintsov, S. I. Zaitsev, R. R. Jede, and H. F. Raith, Microelectron. Eng. **17**, 413 (1992).
[11] V. V. Aristov, B. N. Gaifullin, A. A. Svintsov, S. I. Zaitsev, R. R. Jede, and H. F. Raith, J. Vac. Sci. Technol. B **10**, 2459 (1992).