Accuracy of proximity correction in electron lithography after development

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The established methods after Parikh [M. Parikh, IBM J. Res. Dev. **24**, 438 (1980)] allow a dose correction using the "Two Gaussian Model" by considering the parameters α, β, and η. A guaranteed accuracy after development cannot be given for these methods because the development process, depending on resist type, thickness and contrast, is not taken into account. In order to calculate a final guaranteed accuracy considering α, β, η, and the full resist development process, we did a calculation in following steps. First, we calculated the proximity correction just for backscattered electrons by the method of "simple compensation" [V. V. Aristov, A. A. Svintsov, and S. I. Zaitsev, Microelectron. Eng. **11**, 641 (1989)]. In the second step, we simulated the proximity effect after development (modeling) with the before corrected dose distribution, but now considering all parameters: α, β, η, thickness H, and contrast γ of positive resist. This leads to a guaranteed accuracy δ (maximum structure deviation) for a given design rule L using the correction method of simple compensation. This guaranteed accuracy can be expressed in dimensionless coordinates $\delta/\alpha = f(L/\alpha, H/\alpha, \eta, \gamma)$. So the accuracy of the electron lithography in this approach is determined by the beam size, characterized by α. Simple compensation results in the accuracy equal to a fraction of α. A better proximity correction below the guaranteed accuracy is possible by using simple compensation in iteration and by correcting for α inside a small structure frame.

I. INTRODUCTION

Proximity correction means to calculate a required primary exposure dose distribution in order to obtain an even absorbed dose inside all structures considering the contribution of backscattered electrons, beam size, and forward scattering.

Many studies have been done in this field, suggesting different correction methods. But no method allows to calculate a guaranteed final accuracy especially by taking into account the process of resist development, except the method of simple compensation which was introduced by Aristov *et al.*[1,2]

This work describes the method of simple compensation in detail and a theoretical proof of its guaranteed accuracy.

II. FORMULATION OF THE PROBLEM OF PROXIMITY EFFECT CORRECTION

The general problem proximity correction can be defined as follows. Given is a two-dimensional (2D) x,y structure consisting of nonintersecting regions Q_i, $i=1,2,\ldots,N$, shown in Fig. 1 by solid lines. Exposure doses are

$$T(x,y) \geqslant 0, \quad x,y \in Q,$$
$$T(x,y) = 0, \quad x,y \notin Q.$$

After development during time t the resist projection onto the substrate surface (plane x,y) represents structure Q^* comprising the elements Q_i^* shown in Fig. 1 by dotted lines. We suggest that the error δ should be defined by the maximum distance between the boundaries of structures Q and Q^*.

The problem of the correction is to find such distribution of exposure doses $T(x,y)$ that after exposure and development the errors of the whole lithographic process δ would be less than a prescribed or desirable value.

III. EXPOSURE AND DEVELOPMENT MODELS

Absorbed dose distribution $D(r)$, $r=(x,y,z)$, in the resist depends linearly on exposure dose $T(x,y)$. For correction it is generally assumed that D is independent on resist depth z,[3] which leads to

$$D(x,y)/D^0 = \int I(x-x',y-y')T(x',y')/T^0\, dx'\, dy'. \tag{1}$$

D^0 and T^0 are absorption and exposure sensitivities of a resist, respectively. The proximity function $I(\rho)$, $\rho=(x,y)$, is written as a sum of two Gaussians (Fig. 2),

$$I(\rho) = \frac{I_1(\rho)+\eta I_2(\rho)}{(1+\eta)} = \frac{1}{\pi(1+\eta)}\left[\frac{1}{\alpha^2}\exp\left(-\frac{\rho^2}{\alpha^2}\right)+\frac{\eta}{\beta^2}\exp\left(-\frac{\rho^2}{\beta^2}\right)\right], \tag{2}$$

$$\rho^2 = x^2+y^2,$$

which are interpreted as contributions of primary beam, $I_1(\rho)$, and backscattered electrons, $I_2(\rho)$. Here I, I_1, and I_2 are normalized on unity. The primary beam is concentrated in the area of radius α and the backscattered one in the area of radius β, with $\alpha \ll \beta$. η characterizes the contribution of backscattered electrons to the exposure in a large area. α and β are the characteristic lengths of the exposure process.

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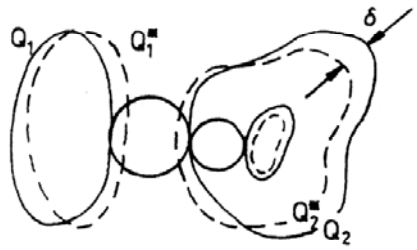

FIG. 1. Structure Q^* (dashed line) occurs on the substrate surface instead of given structure Q (solid line) with the error δ which is according definition equals to maximal value of the deviation. When determining the characteristic structure size, the circle should be first rolled along the inside element boundary and then along the outside boundary.

We use the Two Gaussian Model due to several reasons. First, two contributions have clear physical meaning (primary electrons and backscattered ones). Second, experimental measurements and simulation of absorbed dose are described by the Gaussian model very well.[4] And third, the requirement for a third Gaussian contribution in some experiments in our opinion can be addressed to an influence of the development process which usually is not taken into account in measurements of proximity function. In Ref. 5, it was shown that considering resist development the third Gaussian disappeared.

An independence of proximity function $I(\rho)$ on depth z is a good approximation due to the fact that for conventional beam energies the travel range of the electrons is much higher than the resist thickness H^0. Therefore it is possible to neglect low-angle spreading of a primary beam. In any of the cases, we assume the value of the beam size at the interface between resist and substrate to give an upper estimation of α.

Because α is normally much smaller than β and than the resist thickness H^0, it can be assumed (this will be shown) that it causes an edge effect only, and therefore the correction can be done separately just inside a small structure frame in a secondary step.

Considering first the backscattering effect only (described by β and η), it is possible (according to the arguments of Ref. 2) to substitute the first Gaussian by δ function. As a result the absorbed dose distribution Eq. (1) will take the form

$$(1+\eta)D(x,y)/D^0=T(x,y)/T^0+\eta\int I_2(x-x',y-y')\times T(x',y')/T^0\,dx'\,dy'. \qquad (1a)$$

Liquid development of positive resists is adequately described by the model of isotropic local etching[6–8] (ILE model) which assumes that the velocity of resist boundary movement is independent of the boundary form (locality of etching) and the direction of the boundary (isotropy of etching), but defined only by development rate V at the point which the boundary passes through at a given moment. Development rate V, in turn, is defined by absorbed dose distribution D and the dose characteristic of the resist written as[8]

$$V=V^0(D/D^0)^\gamma, \qquad (3)$$

where γ is the contrast of positive resist.

In the ILE model the resist surface evolution[6] is described by

$$\tau(S_0,r)=t, \qquad (4)$$

where S_0 is the initial boundary position and t is a development time. The solution of Eq. (4) with respect to point $r=\{x,y,z\}$ specifies the form and position of resist surface at time t. As shown in Ref. 6, the function $\tau(S_0,r)$ is related to rate field $V(r)$ by the expression

$$\tau(S,r)=\min_{r_0\in S_0}\left[\min_{tr}\int dl[1/V(r)]\right], \qquad (5)$$

where the integral is so-called Fermat integral. $\tau(S_0,r)$ is the time of boundary passage through point r and is defined in two steps (called in Ref. 6 as the modified Fermat construction). First, we find the trajectory connecting $r_0\in S_0$ and r on which the Fermat integral has a minimum, then the minimum value of τ is found among all the points of r_0 on initial surface S_0. The examples of the analytical and numerical solutions based on Eqs. (4) and (5) of some development problems are illustrated in Ref. 7. The problem [Eqs. (4) and (5)] allows simple 2D solution[7]

$$z(x,t)=\min_{x_0}\left[H^0-V(x_0)t+\left|\int_{x_0}^{x}\{[V(x_0)/V(\sigma)]^2-1\}^{1/2}\,d\sigma\right|\right]$$

when the rate of the development depends only on lateral direction (e.g., x axis) and is independent of depth (z axis), $V=V(x)$. An effective numerical 2D algorithm was developed[1] as application of Eq. (6).

As an example of ILE model application, we consider the development of a halfspace ($z\leqslant 0$) with step rate function[7]

$$V(r)=\begin{cases}V_1, & x\leqslant x0,\\ V_2, & x>x_00,\end{cases}\quad V_1>V_2. \qquad (7)$$

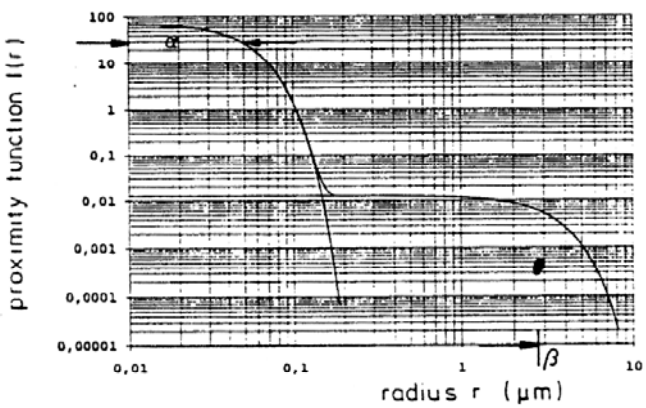

FIG. 2. Proximity function $I(r)$ consisting of two Gaussians with characteristic lengths α and β.

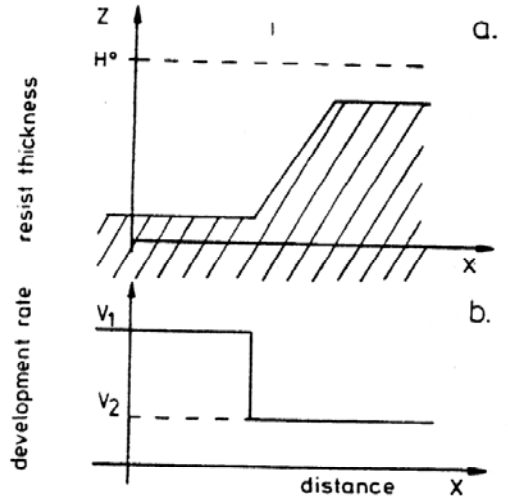

FIG. 3. The shape of resist after development for some time t (a) with step rate function V represented on (b) [see also Eq. (7)] consists of two planes jointed by inclined plane.

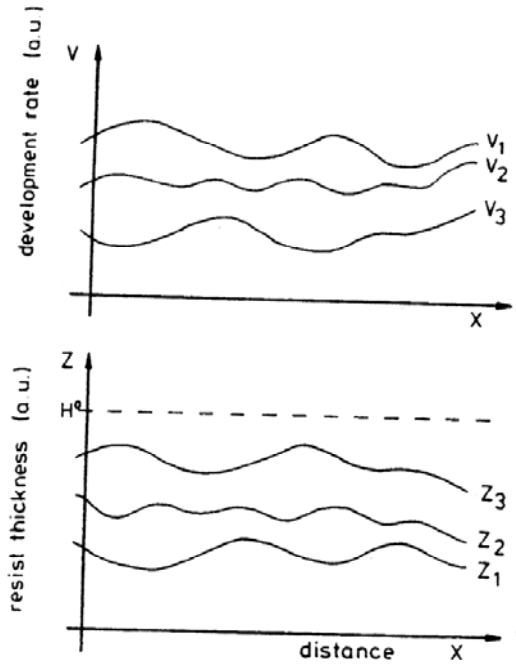

FIG. 4. Under condition $V_1(r) > V_2(r) > V_3(r)$, the profiles conserve the relation $z_3 > z_2 > z_1$ at anytime.

The surface of resist after development is shown in Fig. 3. It consists of two plane parts moving with velocities V_1 and V_2 and an inclined boundary between both regions with an angle ϕ to the planes $[\cos(\phi) = V_2/V_1]$.

A real rate distribution of course is much more complicated and the solution obtained will be explored below to estimate development errors. To use the simple distribution [Eq. (7)] and the corresponding solution it is necessary to formulate an important statement about ILE which was proved in Ref. 6.

Assuming there are three samples of identical initial shapes $z_1(x,y,0)$, $z_2(x,y,0)$, $z_3(x,y,0)$, but with different development rates,

$$V_1(r) > V_2(r) > V_3(r), \tag{8}$$

then it follows for resist surfaces

$$z_1(x,y,t) < z_2(x,y,t) < z_3(x,y,t), \tag{9}$$

e.g., the second surface lies always between the first and the third one (see Fig. 4). We intend to use (Sec. V) step functions for V_1 and V_3 to restrict real distribution (V_2) and try to get simple solutions z_1 and z_3 to estimate the deviations (z_2) in the development.

Below we will use dimensionless variables

$$D/D^0 \Rightarrow D,$$

$$T/T^0 \Rightarrow T.$$

Using the dimensionless variables one obtains that after exposure of a large rectangle with exposure dose $T=1$ the absorbed dose D is equal to 1 and in the middle of the rectangle resist is developed down to the substrate (during time $t=t_0$).

IV. 3D SIMULATION OF THE DEVELOPMENT

The development simulation is a convenient tool for research and industrial applications. For known $T(x,y)$, I_2, and dose characteristic (γ, D^0), it is principally possible to calculate the resist profile at any moment during development, but practically this 3D problem is very difficult. To provide the possibility of development simulation after proximity correction the 2D method for the 3D case $[V = V(x,y)]$ was extended. For this we use a set of cross sections of the resist. Each cross section has to contain a vector of rate gradient. In case of step function the latter means that the cross section is perpendicular to the level contour. And now it is possible to solve the development problem of reduced dimensionality in each cross section separately using 2D algorithm mentioned above.

V. DETERMINATION OF GUARANTEED ACCURACY

Due to monotonic relation of V and D [Eq. (3)] it is possible to reformulate property [Eqs. (8)–(9)] in absorbed dose terms: if

$$D_1(r) > D_2(r) > D_3(r), \tag{10}$$

then

$$z_1(x,y,t) < z_2(x,y,t) < z_3(x,y,t). \tag{11}$$

This gives us the basic idea to take into account the influence of development. It is necessary to find two dose distributions $D_{\min}(r)$ and $D_{\max}(r)$ which fit the following inequalities,

$$D_{\min}(r) < D(r) < D_{\max}(r) \tag{12}$$

for a distribution $D(r)$ generated by a correction method. $D_{\min}$ and $D_{\max}$ can be chosen in different ways. The choice of lower and upper estimations $D_{\min}(r)$, $D_{\max}(r)$ has to provide contradictory conditions. On the one hand, it is very desirable that these two functions $D_{\min}$ and $D_{\max}$ would be as simple as possible in order to calculate the

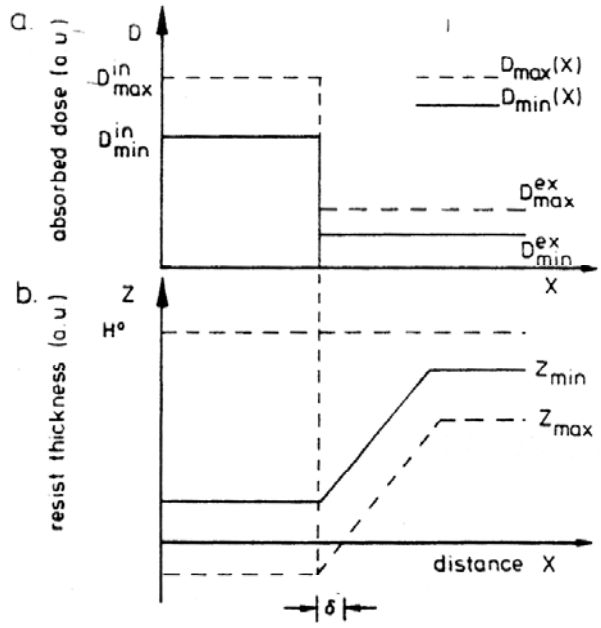

FIG. 5. The upper estimations $D_{max}(x)$ and the lower one $D_{min}(x)$ (a), result to profiles z_{max} and z_{min} (b). The quantity δ is the upper estimation of an error due to development.

development profile. On the other hand, D_{min} and D_{max} have to be as close to D as possible in order to make upper and lower estimations of profile more accurate.

With δ function instead of I_1 (approximation: $\alpha=0$) there is a discontinuity of D along the boundary of elements Q_i. The following choice of D_{min}, D_{max} for $D(r)$ is convenient

$$D_{min}(r)=\begin{cases} D^{ex}_{min}, & x,y\notin Q \quad \text{(outside } Q) \\ D^{in}_{min}, & x,y\in Q \quad \text{(inside } Q) \end{cases},$$
$$D_{max}(r)=\begin{cases} D^{ex}_{max}, & x,y\notin Q \quad \text{(outside } Q) \\ D^{in}_{max}, & x,y\in Q \quad \text{(inside } Q) \end{cases}, \tag{13}$$

where D^{in}_{min}, D^{ex}_{min}, D^{in}_{max}, D^{ex}_{max} are constants. Then distributions of development velocity are step functions and the result of development can be easily obtained (Fig. 5) using solution shown in Fig. 3. The lateral shift between two profiles δ is given by

$$\delta=\frac{(V^{in}_{max}t_0-H^0)}{[(V^{in}_{max}/V^{ex}_{max})^2-1]^{1/2}}, \tag{14}$$

and using dose characteristics [Eq. (3)] it follows,

$$\delta=\frac{(D^{in}_{max})^{\gamma}-1}{[(D^{in}_{max}/D^{ex}_{max})^{2\gamma}-1]^{1/2}}H^0, \tag{15}$$

[note that due to units definition $V^0=H^0/t_0$ in Eqs. (3) and (15)]. The quantity δ is the upper estimation of error due to development and has physical meaning if the inside development rate $V^{in}_{min}\geqslant H^0/t_0$ and the outside development rate $V^{ex}_{max}\leqslant H^0/t_0$. Now a proximity effect correction including development can be formulated in absorbed dose terms only (a) $D^{in}_{min}\geqslant 1$ (guarantees development up to the substrate surface inside of elements); and (b) $D^{ex}_{max}<1$ (to conserve resist on substrate outside of elements).

To provide minimal error δ, it is necessary that (c) D^{in}_{max} as close to unit as possible; and (d) $D^{ex}_{max}<1$ as close to zero as possible.

VI. GUARANTEED ACCURACY OF LITHOGRAPHY WITHOUT ANY CORRECTION

It would be very desirable to have a criteria for need of any correction. Each particular structure will have its own specific error, and inside each element the errors will be different. The upper estimation of such errors (guaranteed accuracy) will be given below so after comparison of this value with desirable accuracy of any particular structure it is possible to decide whether correction is necessary or not at all.

Without correction [and under conditions (a)–(d)] the exposure dose is

$$T(x,y)=1+\eta, \quad x,y\in Q,$$
$$T(x,y)=0, \quad x,y\notin Q. \tag{16}$$

Therefore, values of the absorbed dose in internal and external parts of structure lie in the intervals

$$1\leqslant D(x,y)\leqslant 1+\eta, \quad x,y\in Q,$$
$$0\leqslant D(x,y)\leqslant \eta, \quad x,y\notin Q. \tag{17}$$

The latter follows Eq. (1a) after the substitution of Eqs. (16) in Eq. (1) for simple limiting structures: isolated small circle and a similar hole in a large rectangle.

So we can use the following dose constants in Eq. (13),

$$D_{min}(r)=\begin{cases} D^{ex}_{min}=0, & x,y\notin Q \\ D^{in}_{min}=1, & x,y\in Q \end{cases},$$
$$D_{max}(r)=\begin{cases} D^{ex}_{max}=\eta, & x,y\notin Q \\ D^{in}_{max}=1+\eta, & x,y\in Q \end{cases}. \tag{18}$$

To estimate the error of development we use the estimation method of Sec. V. According to Eq. (18) $D^{in}_{max}=1+\eta$, $D^{in}_{max}/D^{ex}_{max}=(1+\eta)/\eta$, and instead of Eq. (15) we find for the overdevelopment error δ,

$$\delta=\frac{(1+\eta)^{\gamma}-1}{\sqrt{[(1+\eta)/\eta]^{2\gamma}-1}}H^0. \tag{19}$$

This is a general relation which is valid for upper estimation of development distortion for a structure exposed without any correction. It demonstrates clearly, an influence of initial thickness of resist H^0, resist contrast γ, and scattering process (parameter η) on development distortion. The correction for high-contrast resist ($\gamma=\infty$) is not necessary if the backscattering coefficient η is smaller than one, because according to Eq. (19), $\delta=0$. Actually the contrast of any resist is not infinite therefore distortions due to development are large and distinction $\Delta D=(1-\eta)$ between internal ($x,y\in Q$) and outer ($x,y\notin Q$) values of dose are not sufficient for precise lithography. For $\gamma=5$, $\eta=0.9$ Eq. (19) gives

$$\delta \simeq 0.5H^0. \tag{20}$$

We see now that even for a resist with rather high contrast, $\gamma=5$ (whereas the usual value is about 2) the development "washes out" the boundary shape and the lateral shift δ is of the order of initial thickness of the resist H^0.

VII. METHOD AND GUARANTEED ACCURACY OF SIMPLE COMPENSATION

In case of $\alpha=0$, the solution of Eq. (1a) is a solution of correction problem according to (a)–(d) conditions. The solution $T(x,y)$ of Eq. (1a), for $D(x,y)=1$, inside the structure provides an accuracy $\delta=0$. The solution exists at least in the case of $\eta<1$, it is positive and can be obtained as a result of infinite ($k \Rightarrow \infty$) iterations $T(x,y)=T^{\infty}(x,y)$,

$$T^{k+1}(x,y) = \begin{cases} 1+\eta-\eta \displaystyle\int_Q I_2(x-x',y-y')T^k(x',y')dx'\,dy', \\ \quad x,y\in Q \\ 0, \quad x,y\notin Q \end{cases}, \tag{21}$$

for any initial distribution $T^0(x,y)$. The finite number of iterations gives approximate solutions of Eq. (1a).

The method of simple compensation suggested in Ref. 2 is the first iteration of Eq. (21),

$$T(x,y) = \begin{cases} 1+\eta-\eta \displaystyle\int_Q I_2(x-x',y-y')dx'\,dy', & x,y\in Q \\ 0, & x,y\notin Q \end{cases}, \tag{22}$$

with initial distribution,

$$T^0(x,y)=\begin{cases} 1, & x,y\in Q \\ 0, & x,y\notin Q \end{cases}. \tag{23}$$

The simple compensation method considers only the part of absorbed dose corresponding to the backscattered electrons. The advantage of the method is the possibility of calculating of a guaranteed accuracy considering the development process and primary beam size α (see below). The simple compensation gives small errors comparable with α size. To prove this we will estimate at first the accuracy under condition $\alpha=0$ considering of the development. In Sec. IX, the guaranteed accuracy for $\alpha\neq 0$ will be calculated. The errors of numerical realization will be determined also.

Let us use the method of Sec. V one more time. Due to condition $\alpha=0$, $T(x,y)$ in Eq. (1a) should be substituted by distribution [Eq. (22)] to obtain absorbed dose distribution, D;

$$D(x,y)=\begin{cases} 1+\eta^2P(1,Q)/(1+\eta), & x,y\in Q \\ \eta P(\eta/(1+\eta),Q), & x,y\notin Q \end{cases}, \tag{24}$$

where

$$P(a,Q)=\int_Q dx'\,dy'\,I_2(x-x',y-y') - a\int_Q dx'\,dy'\,I_2(x-x',y-y') \times \int_Q dx''\,dy''\,I_2(x'-x'',y'-y''). \tag{25}$$

It is seen that as in Sec. V, the dose distribution $D(x,y)$ has a discontinuity along element boundaries but now the value of the step is not constant. The upper and lower estimations of $D(x,y)$ in Eq. (24) are determined by the maximum and minimum values (with respect to a structure Q) F of the functional $P(a,Q)$ which are calculated in the Appendix as function of a. The result of the Appendix leads to the following dose constants in Eq. (13) for arbitrary structure Q,

$$D_{\min}(x,y)=\begin{cases} D^{\text{ex}}_{\min}=0, & x,y\notin Q \\ D^{\text{in}}_{\min}=1, & x,y\in Q \end{cases},$$

$$D_{\max}(x,y)=\begin{cases} D^{\text{ex}}_{\max}=\dfrac{\eta}{(1+\eta)}+0.32\dfrac{\eta^3}{(1+\eta)^2}, & x,y,\notin Q \\ D^{\text{in}}_{\max}=1+0.32\dfrac{\eta}{(1+\eta)}, & x,y\in Q \end{cases} \tag{26}$$

For example, even in the case $\eta=1$, these constants are

$$D_{\min}(x,y)=\begin{cases} D^{\text{ex}}_{\min}=0, & x,y\notin Q \\ D^{\text{in}}_{\min}=1, & x,y\in Q \end{cases},$$

$$D_{\max}(x,y)=\begin{cases} D^{\text{ex}}_{\max}=0.58, & x,y\notin Q \\ D^{\text{in}}_{\max}=1.16, & x,y\in Q \end{cases}.$$

For a structure corrected by simple compensation the corresponding maximum error δ_{sc} (deviation of the achieved from the given structure) for $\gamma=2$, $\eta=0.9$ after Eq. (15) is

$$\delta_{\text{sc}}<0.073H^0. \tag{27}$$

Thus, e.g., for $H^0=0.5$ μm the error cannot exceed guaranteed accuracy $\delta_{\text{sc}}=0.036$ μm still assuming $\alpha=0$.

VIII. REALIZATION OF THE SIMPLE COMPENSATION

The realization requires a division of structures in substructures q_i with constant exposure dose values T_i. A preliminary dividing structure in parts q_i (for example, performed manually) and the calculation of T_i as average values of $T(x,y)$, Eq. (22) can be used. But in this case additional error of numerical realization in absorbed dose is proportional to l_q/β, where l_q is the characteristic size of substructure elements after dividing. We suggest to use natural dividing by isolines.

The method of simple compensation is realized as a package of routines and can be applied to any structure which can be represented by set of polygons.

The numerical procedure consists of following steps. (1) Calculation of $T(x,y)$ using Eq. (22). (2) Determina-

tion of the isolines of the exposure dose $T(x,y)=T_i$ with equal step ΔT. These isolines divide the structure Q into substructures (zones) q_i with exposure times being equal to the maximal value of $T(x,y)$ in the corresponding zone to prevent "underdevelopment" inside of the structure Q. (3) Approximation of isodoses with polygons. (4) Displaying of the dose distribution using color coding. (5) Preparation of calculated data in format suitable for a lithographic machine.

The package includes algorithms for simulation of 3D development and presentation of development data on display. All this is implemented in the software package PROXY[9,10] which runs on a PC.

The total error δ_{tot} after the correction is a sum of error of the simple compensation method Eq. (22), the error of approximation $T(x,y)$ by T_i with step ΔT and the accuracy of approximation of the smooth isoline by polygon, δT. For estimation of the total error using Eq. (15) it should be used

$$D_{\min}(\rho)=\begin{cases} D^{ex}_{\min}=0, & x,y\notin Q \\ D^{in}_{\min}=1-\delta T, & x,y\in Q \end{cases}, \tag{28}$$

$$D_{\max}(\rho)$$

$$=\begin{cases} D^{ex}_{\max}=\dfrac{\eta}{(1+\eta)}+0.32\,\dfrac{\eta^3}{(1+\eta)^2}+\eta\,\dfrac{(\Delta T+\delta T)}{(1+\eta)}, \\ \quad x,y\notin Q \\ \\ D^{in}_{\max}=1+0.32\,\dfrac{\eta}{(1+\eta)}+(\Delta T+\delta T), \\ \quad x,y\in Q \end{cases} \tag{29}$$

In comparison to Eq. (24), the last equation contains additional terms which are related to the numerical approach. For example if $\gamma=2$, $\eta=0.9$, $\Delta T=0.1$, $\delta T=0$, and $\alpha=0$, the substitution of the values from Eq. (29) into Eq. (15) leads to the guaranteed accuracy of the realized method

$$\delta_{tot}=0.127H^0. \tag{30}$$

The increase of δ_{tot} in comparison with δ_{sc} Eq. (27), demonstrates the influence of numerical errors which can be reduced by usage of smaller values of ΔT and δT.

Comparing with established methods after Parikh,[3] the method of simple compensation gives direct solution of correction problem and prevents a large system of linear equations to be solved. It eliminates an ambiguity of dividing of the initial structure into small rectangles and a guaranteed accuracy is available.

The simple compensation is the first iteration of Eq. (21) only. PROXY can also be used for further iterations [Eq. (21)], where each step considers the previous calculated exposure dose distribution, leading finally to a stable, self-consistent exposure dose map. This iteration method can be applied either for the calculating zones for a given set of exposure levels T_i or for given zone shapes (like rectangles, for example), which are considered as fixed substructures for calculating the required exposure dose. But the guaranteed accuracy is not available for this procedure and the errors of the approximations ΔT and δT restrict the positive effect of the further iterations.

IX. INFLUENCE OF THE PRIMARY BEAM SIZE

To consider the case $\alpha\neq 0$ a reformulation of the initial Eq. (1) is needed. It is possible to rewrite it in the equivalent form

$$D(x,y)=\frac{1}{(1+\eta)}\int I_1(x-x',y-y')\Big[T(x',y') +\eta\int I_3(x'-x'',y'-y'') \times T(x'',y'')dx''\,dy''\Big]dx'\,dy', \tag{31}$$

where

$$I_3(\rho)=\frac{1}{\pi(\beta^2-\alpha^2)}\exp\left(-\frac{\rho^2}{\beta^2-\alpha^2}\right).$$

After expansion in parameter α^2/β^2 and neglecting with terms of the order of α^2/β^2 one obtains $I_3=I_2$ and instead of Eq. (31)

$$D(x,y)=\frac{1}{(1+\eta)}\int I_1(x-x',y-y')\Big[T(x',y') +\eta\int I_2(x'-x'',y'-y'') \times T(x'',y'')dx''\,dy''\Big]dx'\,dy'. \tag{32}$$

The content of square brackets is ideal ($\alpha=0$) dose distribution [see Eq. (22)]. Therefore a real distribution D^α (with $\alpha\neq 0$) is related with distribution in case $\alpha=0$ by a convolution with α-Gaussian;

$$D^\alpha=I_1D.$$

After convolution the sharp step in ideal dose distribution D is washed out into a smooth step with transition length of the order of α.

The analytical solution [Eq. (15)] is not valid now, and therefore, we use more complicated procedures using the limiting elements A, B, and the characteristic size of structure L to calculate the guaranteed accuracy like it was done in Ref. 2 for the calculation of the guaranteed accuracy without any correction.

According to Ref. 2 the characteristic size L of a structure Q is the maximum diameter of a circle (Fig. 1), which can be rolled twice along the boundary of each structure element and tangent to each boundary point. During the first rolling, the whole circle lies inside elements of Q, and it has to lie outside elements of Q during another rolling. The characteristic size of structure characterizes the narrowest places of a structure by one size and is the universal characteristic of a structure. The limiting elements are a couple of simple structures with well-defined characteristic sizes, Fig. 6. In Ref. 2, Aristov *et al.* considered a circle of radius R (element A) and a circle hole of the same radius

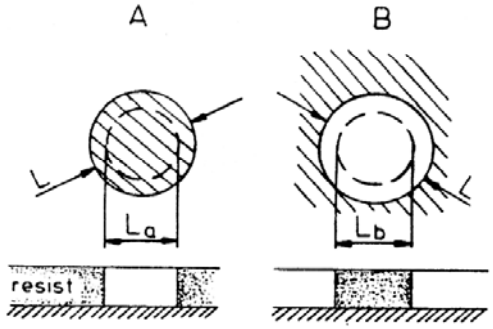

FIG. 6. Limiting elements A and B for general type structures of characteristic size L. The crosshatched regions are those to be exposed in lithography. The dashed line shows resist projection on the substrate surface after lithography.

(element B). The characteristic sizes L of both elements are equal to $2R$. For a rectangular structure, it is more convenient to use another couple, a square and a square hole of L size, for linear structures, a strip and a slot are more convenient.[2]

The upper estimations $D^{\alpha}_{\max}$ (the structure Q) and $D^{\alpha B}_{\max}$ (the element B) of real corrected dose distributions D^{α} and $D^{\alpha B}$ are given by convolution obtained by simple compensation at $\alpha=0$ $D_{\max}$, $D^{B}_{\max}$ with α-Gaussian I_1,

$$D^{\alpha}_{\max}(\rho)=\int_Q d^2\rho' I_1(\rho-\rho')D_{\max}(\rho'),$$
$$D^{\alpha B}_{\max}(\rho)=\int_B d^2\rho' I_1(\rho-\rho')D^{B}_{\max}(\rho'). \tag{33}$$

Here and below, we use reduced notation

$$d^2\rho=dx\,dy,\quad (\rho-\rho')=(x-x',y-y').$$

According to definition of the limiting elements, the element B covers any structure with the same characteristic size L (e.g., $Q\subseteq B$), providing the circle is adjacent to a point of the element boundary and lies outside the structure, therefore,

$$D^{\alpha}_{\max}(\rho)\leqslant D^{\alpha B}_{\max}(\rho)$$

for any point of the structure Q. Similar to Eq. (33), we find

$$D^{\alpha}_{\min}(\rho)=\int_Q d^2\rho' I_1(\rho-\rho')D^{Q}_{\min}(\rho'),$$
$$D^{\alpha A}_{\min}(\rho)=\int_A d^2\rho' I_1(\rho-\rho')D^{A}_{\min}(\rho'), \tag{34}$$

and for any point of the structure

$$D^{\alpha}_{\min}(\rho)\geqslant D^{\alpha A}_{\min}(\rho).$$

Finally,

$$D^{\alpha A}_{\min}(\rho)\leqslant D^{\alpha}_{\min}(\rho)\leqslant D^{\alpha}(\rho)\leqslant D^{\alpha}_{\max}(\rho)\leqslant D^{\alpha B}_{\max}(\rho), \tag{35}$$

after development of B and A with exposure dose distributions $D^{\alpha A}_{\min}(\rho)$, $D^{\alpha B}_{\max}(\rho)$ for time t the exposed substrate will comprise (Fig. 6): A^* is the whole plane with a cut out circle of diameter L_A, B^* is a circle of diameter L_B. Generally speaking, L_A and L_B are not equal to L because of the proximity effect and development. Varying development time t, it is possible to choose such limiting parameter t^* that the "underetching" and "overetching" errors are equal and

$$|L-L_A|=|L-L_B|=2\delta.$$

After exposure of the structure Q of characteristic size L with exposure dose D^{α} after the simple compensation and development under limiting condition t^*, the errors of the lithography will be smaller than in case of elements A and B due to Eq. (35) and arguments of Sec. V. Therefore, A and B were called limiting elements and the error of their reproduction is guaranteed accuracy of the simple compensation method with influence of α and development, $\delta_{SC}(\alpha)$.

To calculate $\delta_{sc}(\alpha)$ exposure doses [after Eqs. (21), (34), and (35)], absorbed doses $D^{\alpha A}_{\min}$, $D^{\alpha B}_{\max}$ and the corresponding development rates $V(x)$ should be determined in the cross sections of the elements A and B passing through the center. Then, 2D development problems [Eq. (6)] should be solved, two profiles, namely, $z_A(x,t)$ and $z_B(x,t)$ should be found, and development time t^* should be determined at which the value of underetching of element A is equal to overetching of element B,

$$z_A(L/2-\delta_{sc},t)=z_B(L/2-\delta_{sc},t)=z_{\text{substr}},$$

z_{substr} is a coordinate of an interface of resist–substrate. These two equations are sufficient to find the values δ_{SC} and t^*. Considering that $\alpha\neq 0$ results in smoothing of discontinuities in dose distributions the analytical method of Sec. V is not valid now, therefore a numerical procedure was used to calculate δ_{sc}. The guaranteed accuracy is a function of many parameters like L, α, H^0, γ, and η. According to the Appendix, the dose distribution and consequently development [Eq. (6)] does not contain the β value, therefore it is possible to reduce numerical calculations using dimensionless variables δ_{sc}/α and L/α. The L dependence of δ_{sc} is shown in Figs. 7–9 for a set of resist thicknesses, H^0, resist contrast, γ, and parameter η, respectively. The calculations show weak dependence of δ_{sc} on resist contrast. A variation does not exceed 0.2α, for $\alpha=0.1$ μm the variation is less than 20 nm and the dependence may be practically ignored. In Fig. 9, a strong dependence of δ_{sc} on parameter η is seen as well.

The L dependencies of Figs. 7–9 demonstrate a similar behavior, $\delta_{sc}(L)$ is constant for $L\geqslant 4\alpha$ and elevates rapidly with decreasing L. The constant value of δ_{sc} for $\alpha=0.1$ μm, $H^0=0.5$ μm, $\gamma=2$, and $\eta=0.9$ is equal to 0.062, where as for the same set of parameters the accuracy for case $\alpha=0$ is equal to 0.036 μm [see Eq. (27)]. The difference characterizes the influence of beam size. The comparison of the analytical method of the accuracy estimation [Eq. (19)], with results of more complex ones (Figs. 7–9), shows that the difference is about one to two tenth of α only and for the structures with L greater than 4α relation [Eq. (19)] can be recommended for the fast estimation of the accuracy.

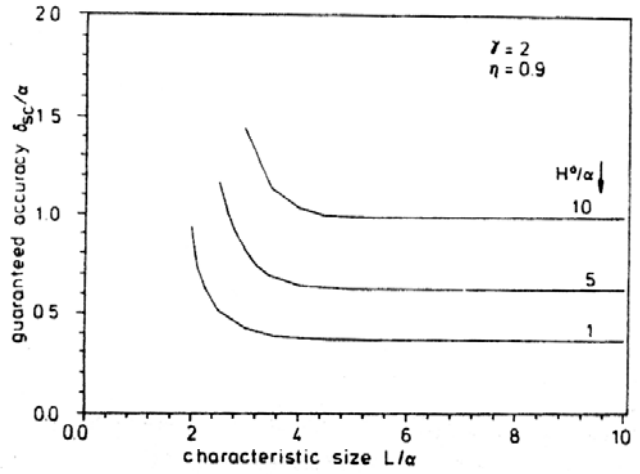

FIG. 7. Guaranteed accuracy δ_{sc} of simple compensation as a function of characteristic size L and initial resist thickness, $\gamma=2$ and $\eta=0.9$.

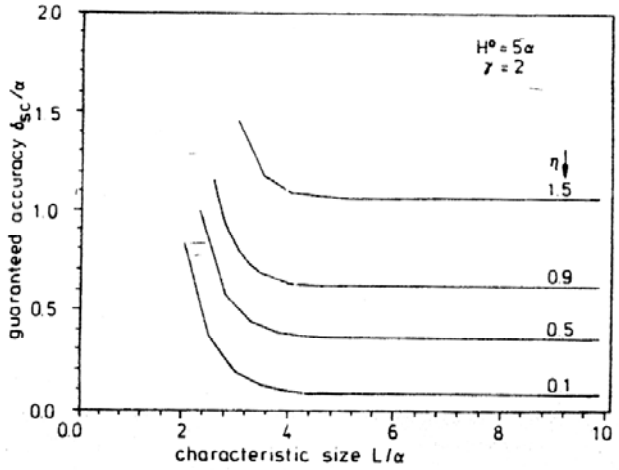

FIG. 9. Guaranteed accuracy δ_{sc} of simple compensation as a function of characteristic size L and parameter η, $H^0=.5\ \mu$, $\gamma=2$.

The independence of δ_{sc} on β shows clearly that the exact shape of wide ranges of proximity function I_2 is not important for estimation of accuracy δ_{sc} since $\alpha^2/\beta^2 \ll 1$, [the area exposed by primary electrons (α^2) is much less than the area exposed by backscattered ones (β^2)].

Note that it is impossible to obtain a structure consisting of two elements lying in a circle of diameter less than α. In the interval $\alpha < L < 4\alpha$ where the error becomes too high, the effect of spot size and forward scattering, characterized by α, can be corrected in a second procedure for example by calculating the necessary dose in a small frame with a width of α along all structure edges by trial and error method using the simulation.

X. CONCLUSION

Using the presented correction approach the accuracy of the electron lithography is determined by the forward scattering characterized by α. For the proximity correction method of simple compensation, a maximum error could be calculated which may appear after development. Whereas the mentioned correction method considers the backscattered electrons (β and η) only, the estimation of guaranteed accuracy considers also the beam size and forward scattering (α) and the development process of positive resist as well. It results in the value of the accuracy equal to a fraction of α.

Proximity correction below this guaranteed accuracy is possible by using the simple compensation in iterations for calculated zones and by correction for α inside a small structure frame according to simulated results. It allows to calculate suitable zone shapes of different doses for proximity correction, and it considers α and the full development process in simulation. Finally, the results of simulation can be used for achieving ideal dose distributions for experimental structures. These features make our proximity correction approach a powerful instrument for physical studies of proximity effects in experimental lithography as well as for reliable semiprofessional or professional e-beam mask or wafer writing of smallest linewidth structures.

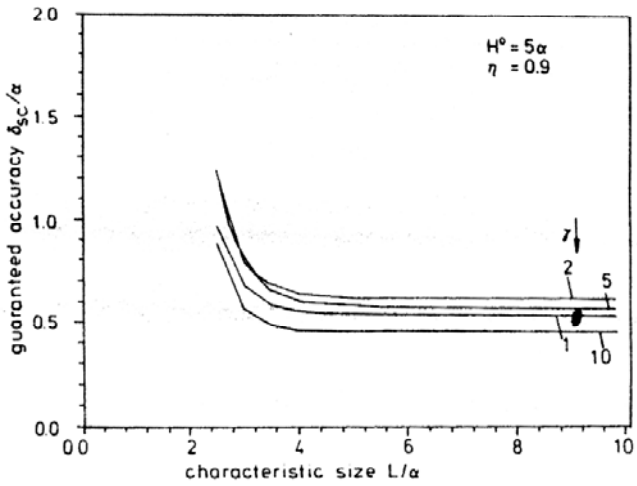

FIG. 8. Guaranteed accuracy δ_{sc} of simple compensation as a function of characteristic size L and resist contrast γ, $H^0=0.5\ \mu$ and $\eta=0.9$.

APPENDIX

Estimations of $P(a,Q)$

Let us find the lower $P_{\min}(a)$ and the upper $P_{\max}(a)$ boundaries of

$$P(a,Q)=\int_Q dx'\,dy'\,I_2(x-x',y-y')$$
$$-a\int_Q dx'\,dy'\,I_2(x-x',y-y')$$
$$\times\int_Q dx''\,dy''\,I_2(x'-x'',y'-y''),$$
$$I_2(x,y)=\frac{1}{\pi\beta^2}\exp\left(-\frac{\rho^2}{\beta^2}\right),\quad \rho=(x^2+y^2)^{1/2},$$

for arbitrary Q and fixed parameter $a\geqslant 0$. Because the extreme of P does not depend on β and point (x,y), we assume $\beta=1$, $x=0$, and $y=0$. Minimum of P is found very easy. Rewrite P

$$P(a,Q)=(1-a)\int_Q dx'\,dy'\,I_2(x-x',y-y')$$
$$+a\int_Q dx'\,dy'\,I_2(x-x',y-y')$$
$$\times\int_{Q^c} dx''\,dy''\,I_2(x'-x'',y'-y''),$$

Q^c is a complement of origin Q. The second term in the right part of the equation is positive, the first depend from sign of Eq. (1a). The minimum of P is achieved

$$P_{\min}(a)=\begin{cases}0, & a\leqslant 1 \quad (Q=0)\\ 1-a, & a>1 \quad (Q^c=0)\end{cases}$$

Let us now find $P_{\max}(a)$. It is clear that

$$P_{\max}(a)\leqslant \max_f G[f],$$

where

$$G[f]=\int dx'\,dy'\,I_2(x-x',y-y')f(x',y')$$
$$\times\int dx''\,dy''\,I_2(x'-x'',y'-y'')$$
$$\times[1-af(x'',y'')],$$

and function $0\leqslant f(x,y)\leqslant 1$. In cylinder coordinates

$$G[f]=\frac{1}{\pi^2}\int_0^\infty\int_0^\infty dr\,d\rho\,r\rho\exp(-2r^2-\rho^2)$$
$$\times\int_0^{2\pi}\int_0^{2\pi} d\phi\,d\psi\exp[2r\rho\cos(\phi-\psi)]$$
$$\times f(r,\phi)[1-af(\rho,\psi)].$$

The extremes of the $G[f]$ are achieved on functions f which does not depend on angle ϕ. Let us show this. Find the extremes of functional

$$\int_0^{2\pi}\int_0^{2\pi} d\phi\,d\psi\exp[b\cos(\phi-\psi)]f(\phi)g(\psi),$$

under conditions

$$\int_0^{2\pi} d\phi\,f(\phi)=A,\qquad \int_0^{2\pi} d\phi\,g(\phi)=B.$$

For any b the extreme is achieved and $f(\phi)=A/2\pi$, $g(\phi)=B/2\pi$. Really, find variations of the functional

$$\int_0^{2\pi} d\psi\exp[b\cos(\phi-\psi)]g(\psi)=\lambda,$$

$$\int_0^{2\pi} d\phi\exp[b\cos(\phi-\psi)]f(\phi)=\beta,$$

(λ,β-Lagrange's factors). Statement is proved. So, we can write functional G

$$G[f]=2\int_0^\infty dr\,r\exp(-r^2)$$
$$-4a\int_0^\infty\int_0^\infty dr\,d\rho\,r\rho I_0(2r\rho)f(r)f(\rho),$$

I_0 is a modified Bessel function. This task can be numerically solved by method of the square programming. The results of calculations $P_{\max}(a)$ for different values of "a" are as follows. (Error of the calculation less than 0.005.)

a	0	0.2	0.4	0.6	0.8	1
$P_{\max}$	1	0.810	0.645	0.507	0.397	0.321

The calculated data may be approximated by

$$P_{\max}(a)=1-a+0.32a^2,$$

which is valid for $a\leqslant 1$ (i.e., for any η) with accuracy less than 0.01. The substitution $a=1$ and $a=\eta/(1+\eta)$ leads to Eq. (26).

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