Impact of Model-Based Fracturing on E-beam Proximity Effect Correction Methodology

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ABSTRACT

The current e-beam proximity effect correction equations are reviewed in the context of model-based fracturing where shots can overlap and the dose of each shot can be set individually. A new set of equations is proposed and verified. The formulation is shown to lift some restrictions imposed by the older formulation such as the minimum shot size dimension and the type of model used to describe forward scattering effects. The new model does not require the function to be Gaussian or the operation with the dose map to be a convolution.

We also demonstrate that using current mask writing equipment, the correction of overlapping shots can be performed accurately if the correction of each shot is performed taking into account all the shots.

Verification is done using two different approaches. The first solution consists of using directly the modified proximity effect equations to calculate the dose for each shot. The second solution makes the correction a part of the model-based fracturing process. The results obtained for both approaches are identical showing that the theory and the implementations are correct.

Keywords: Photo mask, e-beam, proximity effect correction, shaped-beam, model-based fracturing

1. INTRODUCTION

Extending 193nm immersion lithography using single exposure is forcing the industry to move to more and more complex resolution enhancement techniques such as inverse lithography and source mask optimization. These techniques require extremely complicated mask shapes that could lead to mask write times exceeding 24 hours for advanced nodes. Inverse lithography solutions generally yield curvilinear mask shapes that have been approximated by "Manhattan" layouts in order to reduce the mask write time. Such approximation tends to preserve the overall process latitude, but reduces accuracy as the MEEF is increased as the perimeter of the features is increased [1]. Model-based fracturing [2,3] has been proposed as a way to better replicate the curvilinear shapes on the mask while reducing the number of shots and thus reducing the overall write time. To achieve low shot count and accurate mask image, more degrees of freedom are available if the shots can be overlapped and further if the dose can be assigned for each shot individually. Unfortunately, this departure from current VSB tool writing strategy breaks some of the assumptions made for proximity effect correction. For example shots generated during the model-based fracturing step do not necessarily represent the target mask image anymore.

In this paper two solutions to this problem are reviewed. The first solution consists of modifying the proximity effect equations and using the new equations to calculate the dose for each shot. The second solution makes the correction a part of the model-based fracturing process.

2. THEORY

2.1 Standard Proximity Effect Correction Approach

In this paragraph we will review briefly the results obtained by other authors [4].

The energy deposited by an electron beam inside the resist at a position **x** is given by the following formula:

$$E(\mathbf{x}) = K\left[\int_{pattern} D(\mathbf{x}')g_f(\mathbf{x}-\mathbf{x}')d\mathbf{x}' + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}'\right] \quad (1)$$

Where **x** = (x,y) in order to simplify the notation, *K* is the conversion coefficient from the irradiated dose amount to the energy deposited in the resist, η is the ratio between the deposited energy produced by forward scattering to that produced by backscattering, *D* is the dose. The first term of this equation represents the contribution of the electron forward scattering in the resist while the second term represents the contribution of the electron backscattering. The effect of electron forward scattering and backscattering are described respectively by the functions g_f and g convoluted to the dose map created by the shots $D(\mathbf{x}')$.

The functions g_f and g are normalized and therefore verify the following equations:

$$\int g_f(\mathbf{x})d\mathbf{x} = 1 \qquad \int g(\mathbf{x})d\mathbf{x} = 1$$

For the rest of this paragraph we will assume that both functions are Gaussian functions defined using the following equations:

$$g_f(\mathbf{x}) = \left(\frac{1}{\pi\sigma_f}\right)\exp\left[-\mathbf{x}^2/\sigma_f{}^2\right] \qquad g(\mathbf{x}) = \left(\frac{1}{\pi\sigma}\right)\exp\left[-\mathbf{x}^2/\sigma_f{}^2\right]$$

It should be noted that back scattering effects could be described by more than one Gaussian function.

The first term of equation (1) related to forward scattering can be computed in the case of a single exposed line, infinite in the y direction and of edge position p and q as shown in Figure 1 below.

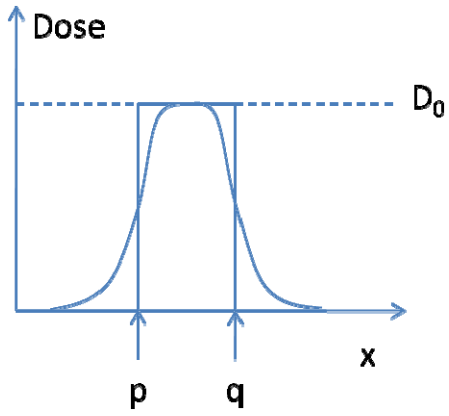

Figure 1. Forward scattering profile corresponding to a line exposed between location p and location q at a dose equal to D_0. The line is assumed to be infinite in the y direction.

Assuming now that we use the *x*, *y* coordinate system, the energy deposited at the edge p of the shot due to forward scattering is given by the following formula:

$$E_f(p) = K\left(\frac{D_0}{\pi\sigma_f{}^2}\right)\int_p^q\int_{-\infty}^{+\infty}\exp\left[-(p-x')^2/\sigma_f{}^2\right]\exp\left[-(y-y')^2/\sigma_f{}^2\right]dx'\,dy'$$

The integration is limited from p to q in the *x'* direction since p and q are aligned with the shot profile defining the term D in equation (1). This equation can be further simplified since we have (for any value of *y*):

$$\int_{-\infty}^{+\infty}\exp\left[-(y-y')^2/\sigma_f{}^2\right]dy' = \sqrt{\pi}\sigma_f$$

We obtain:

$$E_f(p) = K\left(\frac{D_0}{\sqrt{\pi}\sigma_f}\right)\int_p^q \exp\left[-(p-x')^2/{\sigma_f}^2\right]dx'$$

We can substitute the variable *x'* by: $z = x' - p$ and obtain:

$$E_f(p) = K\left(\frac{D_0}{\sqrt{\pi}\sigma_f}\right)\int_0^{q-p} \exp\left[-z^2/{\sigma_f}^2\right]dz$$

If the shot dimension is large compared to the forward scattering range (i.e.: $q - p >> \sigma_f$), the equation simplifies to:

$$E_f(p) = K\frac{D_0}{2}$$

Therefore at the edge of the pattern and using again **x** = (x,y), the following equation is satisfied:

$$E(\mathbf{x}) = K\left[\frac{D(\mathbf{x})}{2} + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}'\right]$$

This condition can be further extended to any point **x** = (x,y) within the exposed pattern. The proximity effect equation is obtained when the energy received at the edge of the pattern is constant (equal to *C* in the following equation).

$$K\left[\frac{D(\mathbf{x})}{2} + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}'\right] = C \qquad (2)$$

As done in reference 4, we can set $D_{100\%}$ as the dose for a completely exposed large pattern with dimensions much larger than the backscattering range. For a dose equal to $D_{100\%}$ the backscattering term in equation (2) is equal to $\eta\, D_{100\%}$. Therefore we have:

$$D_{100\%}\left[\frac{1}{2} + \eta\right] = \frac{C}{K}$$

The dose can be normalized by $D_{100\%}$ using this equation:

$$D(x) = D_{100\%}D^*(x)$$

Finally we get the following equation to solve:

$$\frac{1}{\frac{1}{2}+\eta}\left[\frac{D^*(\mathbf{x})}{2} + \eta \int_{pattern} D^*(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}'\right] = 1 \qquad (3)$$

A method to solve equation (3) was proposed in reference 4 and will not be described in this paper.

Another way to reformulate equation (2) would be to define the threshold dose D_t. Assuming a threshold model, a positive tone resist exposed at a dose larger than D_t is developed and is not developed if the dose is lower than D_t.

$$\frac{D(\mathbf{x})}{2} + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}' = D_t$$

Therefore we have:

$$D_t = D_{100\%}\left[\frac{1}{2}+\eta\right]$$

In this paragraph the following assumptions were made. The effect of electron forward scattering was described by a Gaussian function convoluted to the dose map created by the shots. The shot dimension was assumed to be large compared to the forward scattering range. The feature size was assumed to be infinite in the y direction so that the end shots in the y direction do not impact the profile obtained along the x direction. By forcing the dose to be constant at the edge of the pattern as a condition to correct proximity effects, we are also assuming that the pattern formed on the mask should have the same dimension as the shots, i.e. the mask pattern edges are aligned with the shot edges. In other words the data sent to the mask writer represents the target mask pattern. It should also be noted that the dose $D_0 = 2.D_t$ represents the dose necessary to print the pattern on size (pattern size equals shot size) when back-scattering is not taken into account. In the following paragraph we will discuss the case where the printed mask edges are not aligned with the mask data (pattern size differs from shot size).

2.2 Mask Target Pattern not Aligned with Shot Edge

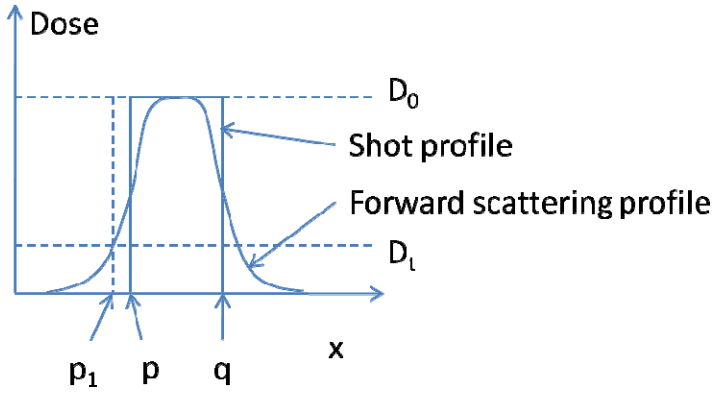

Figure 2. Forward scattering profile corresponding to a line exposed between location p and location q at a dose equal to D_0. The line is assumed to be infinite in the y direction. A dose threshold D_t is set to define the desired position of the mask edge p_1.

Figure 2 illustrates the case where a dose threshold D_t is assumed for defining the position of the mask edge p_1 based on the exposure of the shot with a shot edge p. In this case the mask data can be fractured with the information of the dose D_0 and the threshold D_t and the assumption that without backscattering when the shot is exposed at a dose D_0 and the resist reacts to a threshold D_t, the mask edge will be located at a position p_1. In this paragraph we will compute the dose D to apply to the shot in order to preserve the mask edge position p_1 when backscattering is taken into account.

First we will compute the dose received at the edge p_1 when only forward scattering is taken into account. We have:

$$E_f(p_1) = K\left(\frac{D_0}{\pi{\sigma_f}^2}\right)\int_{p}^{q}\int_{-\infty}^{+\infty}\exp\left[-(p_1-x')^2/{\sigma_f}^2\right]\exp\left[-(y-y')^2/{\sigma_f}^2\right]dx'\,dy'$$

We can simplify this equation by replacing the integral in the direction *y'* by its value, we use the same method as in the previous paragraph. We obtain:

$$E_f(p_1) = K\left(\frac{D_0}{\sqrt{\pi}\sigma_f}\right)\int_{p}^{q}\exp\left[-(p_1-x')^2/{\sigma_f}^2\right]dx'$$

The variable *x'* can now be changed to z with: $z = x' - p_1$ and we obtain:

$$E_f(p_1) = K\left(\frac{D_0}{\sqrt{\pi}\sigma_f}\right)\int_{p-p_1}^{q-p_1}\exp\left[-z^2/{\sigma_f}^2\right]dz$$

This equation can be further re-arranged to:

$$E_f(p_1) = K\left(\frac{D_0}{\sqrt{\pi}\sigma_f}\right)\int_{0}^{q-p_1}\exp\left[-z^2/{\sigma_f}^2\right]dz - K\left(\frac{D_0}{\sqrt{\pi}\sigma_f}\right)\int_{0}^{p-p_1}\exp\left[-z^2/{\sigma_f}^2\right]dz \qquad (4)$$

As shown in the previous paragraph, if $q - p_1 >> \sigma_f$ the first term of this equation can be replaced by $K\frac{D_0}{2}$

By definition of D_t and D_0 we have:

$$E_f(p_1) = KD_t \qquad (5)$$

If a dose D is applied instead of D_0, we have:

$$E_f(p_1) = K\left(\frac{D}{2}\right) - K\left(\frac{D}{\sqrt{\pi}\sigma_f}\right)\int_{0}^{p-p_1}\exp\left[-z^2/{\sigma_f}^2\right]dz$$

Using equations (4) and (5) in the previous equation, we obtain:

$$E_f(p_1) = K\left(\frac{DD_t}{D_0}\right) \qquad (6)$$

Using equations (1) and (6), the new equation becomes:

$$\frac{D(\mathbf{x})D_t}{D_0} + \eta\int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}' = D_t \qquad (7)$$

The dose can be normalized by $D_{100\%}$ to modify equation (7) and obtain:

$$\frac{1}{\frac{1}{2}+\eta}\left[\frac{D^*(\mathbf{x})D_t}{D_0} + \eta\int_{pattern} D^*(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}'\right] = 1 \qquad (7b)$$

In this paragraph the following assumptions were made. The effect of electron forward scattering was described by a Gaussian function convoluted to the dose map created by the shots. The shot dimension was assumed to be large compared to the forward scattering range. The feature size was assumed to be infinite in the y direction so that the end shots in the y direction do not impact the profile obtained along the x direction. The next step is to remove these last restrictions and derive a more general equation.

2.3 General Equation – Mask Target Edge not Aligned with Shot

In equation 1, we have made the assumption that the forward and backward scattering of the electrons is described by a convolution of the dose map created by the shots with Gaussian functions. Equation 1 can be re-written without such an assumption, the only assumption is that the energy deposited inside the resist is the sum of the energy from forward scattered electrons $K.f(x)$ and the energy from back-scattered electrons $K.b(x)$ as shown below:

$$E(\mathbf{x}) = K\left[f(\mathbf{x}) + b(\mathbf{x})\right] \qquad (8)$$

We will first calculate the energy received at the mask edge location due only to forward scattering. Referring to Figure 2, if the pattern is exposed at a dose D_0, for a dose threshold of D_t, the mask edge is printed at a location p_1, therefore we have:

$$f(p_1) = D_t$$

If the dose is changed to D to correct for proximity effects from back-scattered electrons then the dose received at the location p_1 from forward scattering only will be scaled accordingly:

$$f(p_1) = D\frac{D_t}{D_0}$$

The total energy can be computed using Equation 8 by adding the forward scattering (equation above) and the backscattering contributions:

$$E(\mathbf{x}) = K\left[D(\mathbf{x})\frac{D_t}{D_0} + b(\mathbf{x})\right]$$

To compute the dose $D(x)$ to correct for proximity effect, we need to solve the following equation:

$$D(\mathbf{x})\frac{D_t}{D_0} + b(\mathbf{x}) = D_t \qquad (9)$$

Equation 8 is very general as no assumptions were made regarding the functions $f(x)$ and $b(x)$. If we assume that $b(x)$ is obtained by convoluting the dose map created by the shots with a Gaussian function, we obtain:

$$\frac{D(\mathbf{x})D_t}{D_0} + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}' = D_t$$

This equation is exactly the same as equation 7 showing that equation 7 is more general than the restrictions applied to it when it was derived.

2.4 Exposure of Partially Overlapping Shots

In this paragraph we investigate the general case where two shots are partially overlapped. Each shot is assigned a dose before correction and as shown in Figure 4 when the shots are combined the mask edge is created at a location p_1 which is the target position that we need to achieve after proximity effect correction.

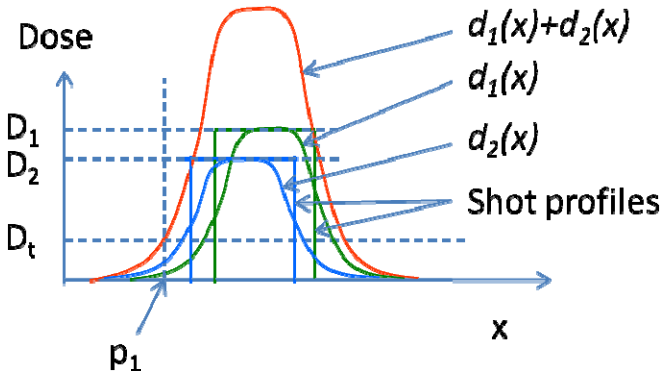

Figure 4. Forward scattering profiles for one exposure ($d_1(x)$ and $d_2(x)$) and for double exposure ($d_1(x) + d_2(x)$) corresponding to an isolated line pattern. The line is assumed to be infinite in the y direction. The dose threshold D_t is set to define the desired position of the mask edge p_1 for the combined exposure of the two shots.

We name D_1 and D_2 the doses assigned to the first and second shots respectively before correction and $d_1(x)$ and $d_2(x)$ the corresponding forward scattering dose profiles. The sum of the forward scattering dose profiles $d_1(x) + d_2(x)$ defines the target edge p_1 to be printed on the mask therefore we have:

$$d_1(p_1) + d_2(p_1) = D_t$$

D'_1 and D'_2 are the doses corrected for proximity effect assigned to the first and second shots respectively and $d'_1(x)$ and $d'_2(x)$ are the corresponding forward scattering dose profiles.

When back-scattering is taken into account and when the corrected doses D'_1 and D'_2 are applied to the shots, the total dose at the edge p_1 is given by the sum of the dose at p_1 from the first shot, the dose at p_1 from the second shot and the back-scattering:

$$d'(p_1) = d'_1(p_1) + d'_2(p_1) + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}' \qquad (12)$$

D'_1 and D'_2 verify equation 7, therefore we have:

$$\frac{D'_1 D_t}{D_1} + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}' = D_t$$

$$\frac{D'_2 D_t}{D_2} + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}' = D_t$$

The backscattering term is assumed to be the same for both shots since the two shots are in close proximity. Using the two previous equations we have:

$$\frac{D'_1}{D_1} = \frac{D'_2}{D_2} \qquad (13)$$

Moreover $d'_1(p_1)$ and $d'_2(p_1)$ can be computed using $d_1(p_1)$ and $d_2(p_1)$ as follows since the dose is scaled by the dose ratio applied to each shot:

$$d'_1(p_1) = d_1(p_1)\frac{D'_1}{D_1} \qquad (14)$$

$$d'_2(p_1) = d_2(p_1)\frac{D'_2}{D_2} \qquad (15)$$

Finally using equations 12, 13, 14, and 15 we have:

$$d'(p_1) = d'_1(p_1) + d'_2(p_1) + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}' = d_1(p_1)\frac{D'_1}{D_1} + d_2(p_1)\frac{D'_2}{D_2} + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}'$$

$$d'(p_1) = \frac{D'_1}{D_1}\left(d_1(p_1) + d_2(p_1)\right) + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}' = \frac{D'_1}{D_1}D_t + \eta \int_{pattern} D(\mathbf{x}')g(\mathbf{x}-\mathbf{x}')d\mathbf{x}' = D_t$$

Since $d'(p_1) = D_t$ we have proven that the printed mask edge after proximity effect correction is at the right location.

It should be noted that in this demonstration no assumption was made regarding D_1, D_2, D_t, and the amount of overlap between the two shots. The only restriction is that the two shots should be close enough so that the back-scattering at their location is approximately the same. For a back-scattering range of 10 micron and a maximum shot size of 500nm this condition should be satisfied.

In the case where $D_1=D_2=2.D_t$ the standard proximity effect correction can be applied. The implication of this result is that standard proximity effect correction can be used for overlapping or partially overlapping shots as long as the shots are treated individually and as long as the desired mask image for each shot individually was aligned with the shot edges.

3. VERIFICATION

3.1 Experimental Conditions

The experimental verification of this theory was accomplished using two different approaches. In one approach the doses are computed as part of an optimization step during model-based fracturing. In the other approach the doses are computed using the equations described in this paper. The advantage of running such comparison is that both the theory and the actual implementations will be verified at once.

All the experimental data were obtained with the assumption that forward and back-scattering effects can be described by Gaussian functions convoluted with the dose map. The forward scattering was set to 30nm which is a value closer to today's advanced mask making but of course taking into account effects beyond forward scattering such as resist diffusion effects. The back-scattering range was set to σ=10 microns. η was set to 0.5.

3.2 Test Pattern with Uniform Back-Scattering

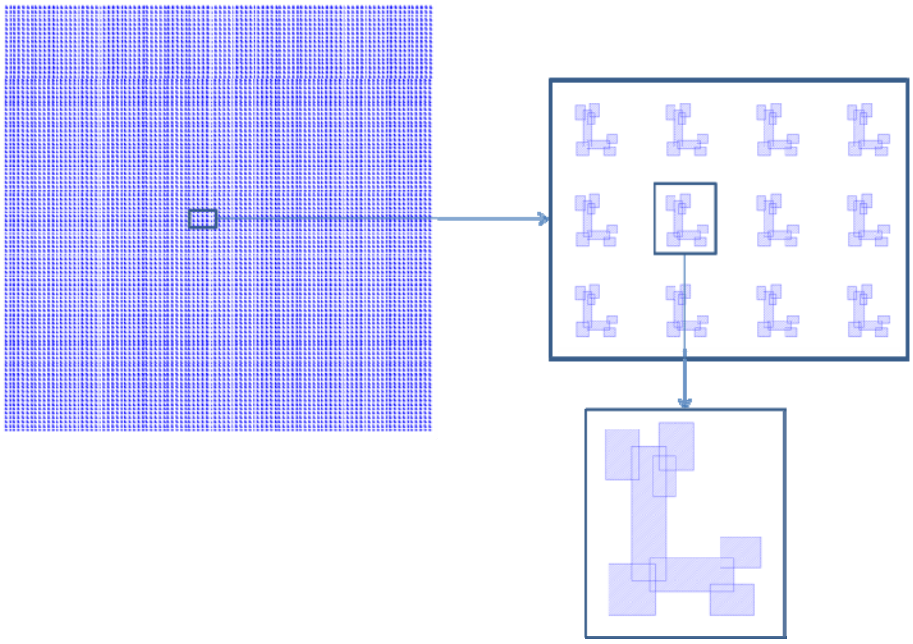

Figure 5.Test pattern comprising an array of "Ls". The picture on the left shows the entire layout. The pictures on the right show magnified views of the pattern. The pitch of the pattern in the x and y directions is 1 micron. The size of the entire pattern is 100 microns by 100 microns.

Figure 5 describes one of the patterns used in this study. Figure 6 offers a more detailed view of the shots constituting the patterns as well as the dose map and a simulation of the pattern. The simulation reveals the target layout as given using a black contour for a threshold of 0.5. It is to be noted that the contour does not necessarily follow the outside edges of the shots. The assumption of this experiment is that this pattern went through a model-based fracturing step and that the black contour represents the mask image target.

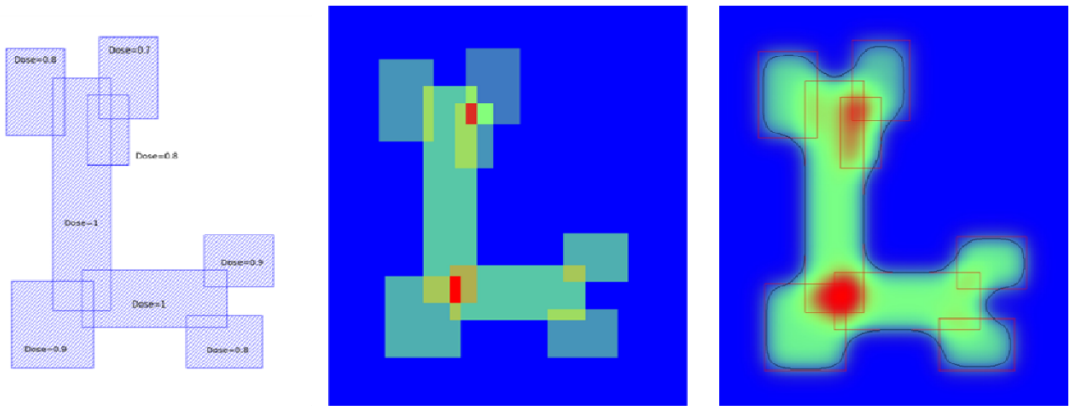

Figure 6. On the left, the pattern with the shots and the dose assigned to each shot. In the center is a dose map of shots. On the right is a simulation of the pattern taken into account only forward scattering. A contour at threshold 0.5 was overlapped in black.

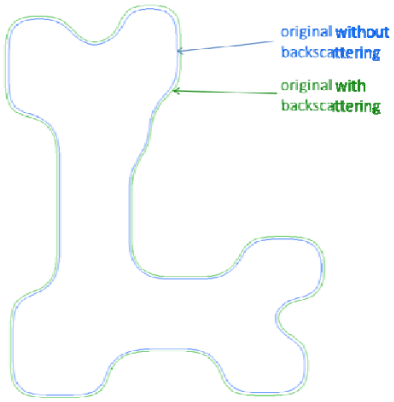

Figure 7. Contour without back-scattering taken into account and contour with back-scattering taken into account. No correction was applied to the shots.

In Figure 7 we compare the contours with and without back-scattering taken into account. We see a noticeable difference between the two contours showing that proximity effect correction is needed in order to have the two contours match. After computing the dose using the equations derived in the previous paragraph we can compare the contours after correction as given in Figure 8. We can see that after correction the contour computed taking into account forward and back scattering perfectly matches the original contour. This shows that the computation succeeded in correcting the proximity effects.

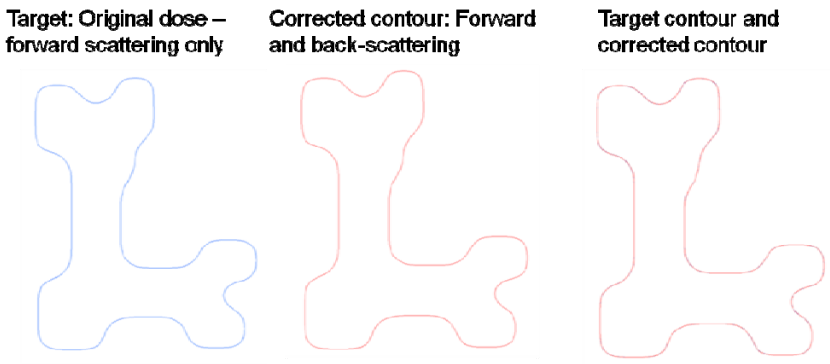

Figure 8. Left: contour with original dose and no back-scattering taken into account. Center: contour for the layout with corrected doses with forward and back-scattering taken into account. Right: Overlap of the contour in the center and the contour on the left.

The same pattern was run using model-based fracturing and the results obtained are described in Table 1 and compared to the direct implementation of the equations.

Shot Number	Model-based fracturing	Calculation using PEC equations
shot1	0.885	0.884
shot2	0.795	0.795
shot3	0.707	0.707
shot4	0.618	0.619
shot5	0.706	0.707
shot6	0.883	0.884
shot7	0.707	0.707
shot8	0.795	0.795

Table 1.Comparison between the shot doses computed using model-based fracturing and the equations.

Table 1 shows that the results obtained with model-based fracturing and the equations are virtually identical thus proving that both implementations and the theory proposed earlier are verified.

3.3 Test Pattern with Non-uniform Back-scattering

Another test pattern consisting of a large exposed area (100 micron by 100 micron) was used to test the theory. The pattern is divided in 1 micron by 1 micron shots and the dose of the shots is computed in order to make sure that the edge between the exposed and the unexposed area is placed at the initial location after correction. Figure 9 shows the dose profile at the transition between unexposed and exposed areas. The dose profile is calculated taking into account both forward and backscattering. The edge position error is given in Figure 10. After the first iteration the error is reduced to 2nm and can be brought below 1nm after the second iteration.

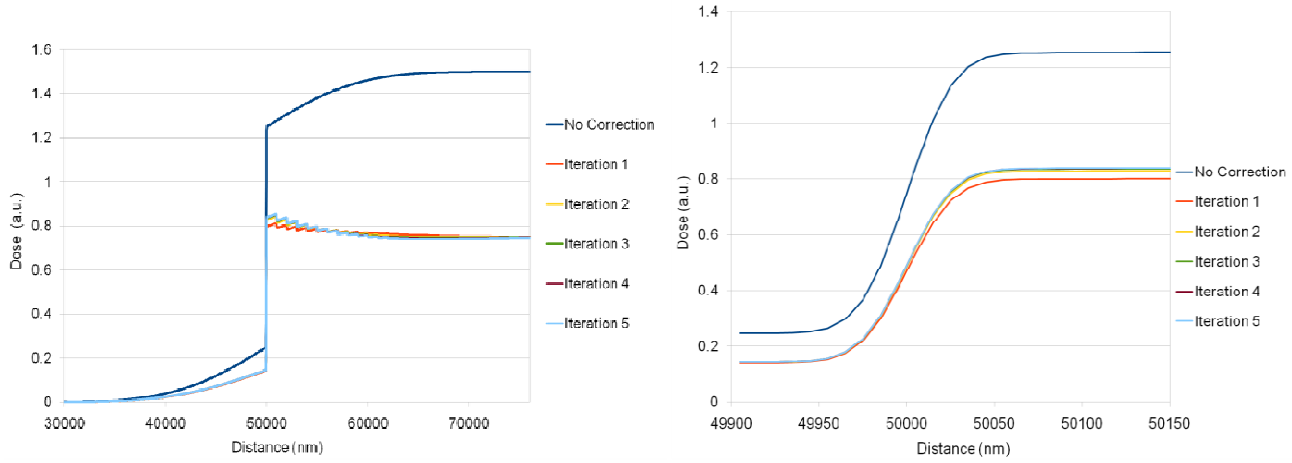

Figure 9. Dose versus distance for a 100 micron by 100 micron pattern on the right: before correction and after each iteration (from iteration number 1 to 5). The dose profile is computed taking into account forward and backscattering. The left plot gives an overview of the dose profiles; the right plot gives a closer look at the transition between the exposed and unexposed areas.

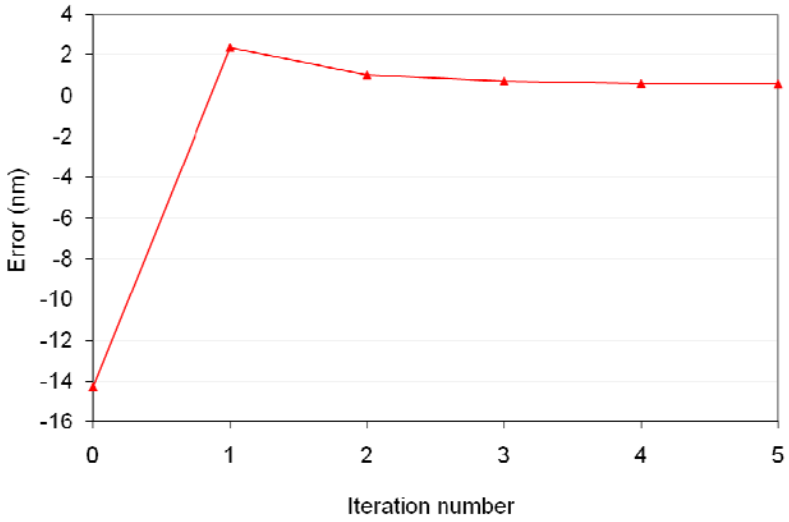

Figure 10. Proximity effect correction of large exposed pattern. This plot shows the edge position error in nanometer versus the iteration number.

4. SUMMARY

The current proximity effect correction equations were reviewed in the context of model-based fracturing where shots can overlap and the dose of each shot can be set individually. A new formulation was proposed and verified. The formulation is shown to lift some restrictions imposed by the older formulation such as minimum shot size dimension, the type of function and the model used to describe forward scattering effects.

We have also demonstrated that using current mask writing equipment, the correction of overlapping shots can be performed accurately if the correction of each shot is performed taking into account all the shots.

Verification was done using two different approaches. The first solution consists of using directly the modified proximity effect equations to calculate the dose for each shot. The second solution makes the correction a part of the model-based fracturing process. The results obtained for both approaches are virtually identical showing that the theory and the implementations are correct.

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