Proximity Effect in E-beam Lithography

By: Araldo van de Kraats
Modified by: Raghunath Murali

Abstract

Electron beam lithography is able to provide high resolution patterning. However, the effect of electron scattering in resist and substrate leads to an undesired influence in the regions adjacent to those exposed by the electron beam. This effect is called the proximity effect. This paper presents a study on the cause of the proximity effect and methods to correct for it.

Introduction

The electron beam has a wavelength so small that diffraction no longer defines the lithographic resolution. In electron beam lithography, the resolution is limited by electron optic aberrations and, more importantly, scattering of electrons in resist and substrate. These electron scattering effects, often referred to as the proximity effect, cause exposure of areas surrounding the area where the electron beam was incident (Fig. 1a). Any pattern written can suffer significant variation from the intended size because of proximity effect.

Electron-solid interactions

When a positive resist is exposed by an electron beam, some molecular chains in the resist molecules will break, thereby reducing the average molecular weight. This is accompanied by an increase in solubility and increases the etch rate. [1-4]. For electron beam lithography it is desirable to know the three dimensional distribution of energy deposition in the resist after exposure by the e-beam [5]. Typical electron beam lithography machines nowadays use electron beams with 10-100 keV energy per electron. Therefore, the free path of an electron is 10 um or more, which is at least an order of magnitude more than the resist thickness. Thus, the electrons can easily penetrate the resist layer and reach the substrate. As the electrons penetrate the resist and the substrate, they experience many scattering events. There are two types of scattering which may take place (Fig. 1b).
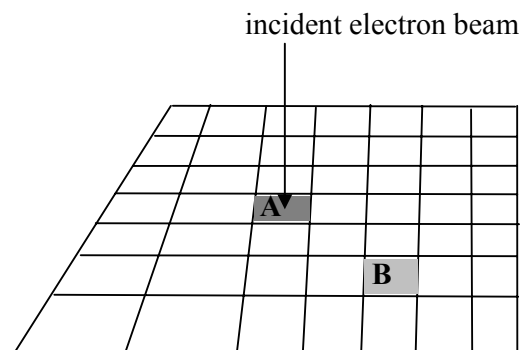
Figure 1a: Proximity effect: exposure at pixel A affects pixel B.

In forward scattering, an electron can collide with an electron from one of the atoms in the substrate/resist. The incident electron will change its direction and transfer part of its energy to the atom. Because of the extra energy, the atom will become exited (one of its electrons goes to an exited level) or ionized (one electron leaves the atom, creating a secondary atom in the material). When the target atom is part of a resist molecule, the molecular chain may break due to this excitation or ionization. The scattering angle due to inelastic scattering is, as a rule, small.

In backscattering, an electron collides with the much heavier nucleus, which results in an elastic scattering event. The electron retains (most of) its energy, but changes its direction. The scattering angle may be large in this case. After large angle scattering events in the substrate, electrons may return back through the resist at a significant distance from the incident beam, thereby cause additional resist exposure. This backscattering is what causes the proximity effect.
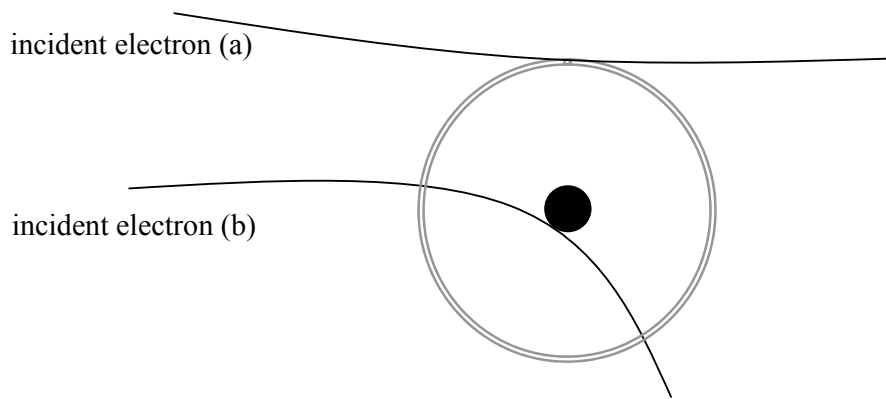

Figure 1b. Electron scattering model (a) incident electron collides with an electron from the target atom: the scattering angle is small, (b) incident electron collides with a nucleus: the scattering angle may be large.

As the primary electrons slow down, much of their energy is dissipated in the form of secondary electrons with energies in the range 2 to 50 eV. The major part of the resist exposure is due to these electrons. Since they have low energies, their range is only a few nanometers. Therefore, they contribute little to the proximity effect. However, this phenomenon, together with the forward scattering, effectively causes a widening of the exposure region. This is one of the main limiting factors in resolution of e-beam lithography machines. The distance a typical electron travels before losing all its energy depends on both the energy of the primary electrons and the type of material it is traveling in. The fraction of electrons that are backscattered, e, is roughly independent of beam energy. It does, however, have a strong relation to the substrate material. Substrates with a low atomic number give less backscattering than substrates with high atomic number.

For head-on collisions with the nucleus the transfer of energy is given by [6]:

$$E = E_0(1.02 + E_0/10^6)/(465.7A) \tag{1}$$

where E_0 is the incident beam energy and A the atom number of the target. If E exceeds some displacement energy E_d, which depends on the atomic weight, bond strength and crystal lattice, the nuclei can be displaced and the crystal structure may damage. Typical values of E_d, range from 17 eV for aluminum to 80 eV for diamond. This means, basically no damage is to
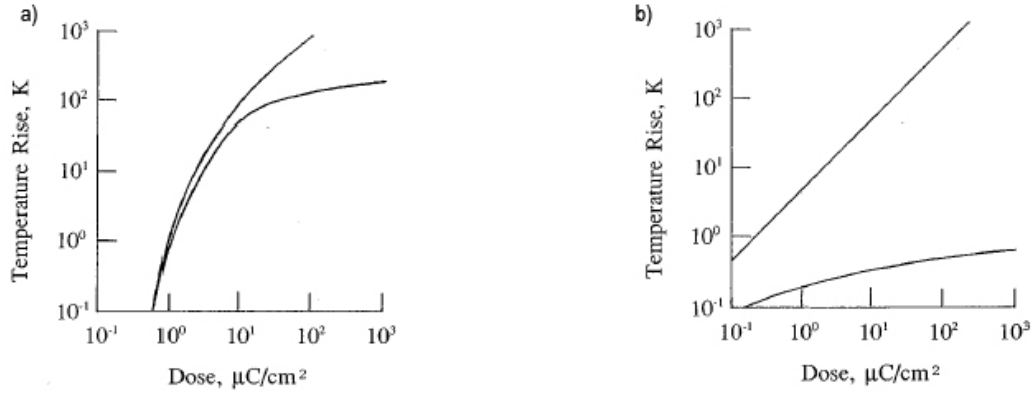
Figure 2. Substrate heating for two different types of substrates. The upper curve represents a dense pattern, while the lower is a sparse pattern (spot with an area of 0.25 um^2) (a) bulk quartz photomask, 50 kV beam voltage and 30 A/cm^2 current density (b) bulk silicon, 100 kV beam voltage and 50 A/cm^2 current density.

be expected for E_0 below 100 keV, unless the target contains hydrogen atoms. Critical values for some other materials can be found in [6]. Except for damage due to nuclei displacement, damage may be caused by substrate heating due to high exposure doses. Heating can also modify resist sensitivity, which can cause unwanted line width variation. A general analytic heating theory is given in [7], which can quantitatively describe temperature rise due to beam induced substrate heating. Results for two common substrates used in electron beam lithography are shown in Fig. 2.

Energy intensity profile

Models of the energy profile

A proximity effect correction algorithm requires an accurate knowledge of the energy density profile deposited in the electron resist layer due to a point or pixel exposure (often called point spread function). In general, this profile is a function of the system setup. An important property of these profiles is that the shape is independent of dose as well as position, assuming a planar and homogeneous substrate[8]. This profile is often approximated by the sum of two Gaussian distributions [9]:

$$f(r) = C_1 \exp(-(r/B_1)^2) + C_2 \exp(-(r/B_2)^2) \tag{2}$$

representing the forward and the backscattered electrons. C_1, C_2, B_1 and B_2 are constants and r is the distance from the point of electron incidence. More popular is to write this expression as follows [10]

$$f(r) = \frac{1}{1+\eta} \left(\frac{1}{\pi\alpha^2} \exp(-\frac{r^2}{\alpha^2}) + \frac{\eta}{\pi\beta^2} \exp(-\frac{r^2}{\beta^2}) \right) \tag{3}$$

where η is the ratio of the backscattered energy to the forward-scattered energy, α is the forward scattering range parameter and β is the backscattering range parameter. Equation (3) is normalized so that

$$\int_0^\infty f(r)2\pi r dr = 1 \tag{4}$$

Several researchers have indicated that the double Gaussian function often is insufficient for expressing the energy density profile. More complex functions are needed for certain types of substrate, multi-layer substrates and for very small feature sizes. Improved functions have been proposed, such as triple and multi Gaussian functions, to express complex phenomena which the double Gaussian function fails to express. Very accurate results have been obtained by adding an extra exponential term to the double Gaussian distribution [11].

$$f(r) = \frac{1}{1 + \eta_1 + \eta_2} \left(\frac{1}{\pi\alpha^2} \exp(-\frac{r^2}{\alpha^2}) + \frac{\eta_1}{\pi\beta^2} \exp(-\frac{r^2}{\beta^2}) + \frac{\eta_2}{24\pi\gamma^2} \exp(-\sqrt{\frac{r}{\gamma}}) \right) \quad (5)$$

The models discussed above are two dimensional versions of an essential three dimensional phenomenon. In general, the energy profile depends upon depth as well as radius. By averaging out the depth dependence, a two dimensional profile can be obtained out of a three dimensional profile. There are several reasons for using this simplification. These include a greatly reduced computation time for the exposure estimation and correction, the fact that it will be difficult to determine the three dimensional profile accurately, and that the major difference between profiles at different depths occur in the 0.00 um to 0.01 um range, which is often well below the minimum feature size[8].

For certain applications it may be necessary to use a three dimensional profile. In this case, a Monte Carlo simulation of electron scattering in the resist layer can be used. Electron scattering in resist and substrates can be modeled with reasonable accuracy. It is assumed that the electrons continuously slow down as described by the Bethe equation, while undergoing elastic scattering, as described by the screened Rutherford formula [5, 8].

Electron beam lithography process parameters

In this section, important process parameters and their effect on the proximity will be discussed. These are electron beam energy, resist type, resist thickness, exposure time (dose) and development time. Due to the many small angle scattering events, forward scattering increases the effective beam diameter. Empirically, it is given by the following formula [5]:

$$d_f = 0.9(R_t / V_b)^{1.5} \quad (10)$$

where d_f is the effective beam diameter in nanometers, R_t is the resist thickness in nanometers and V_b is the beam voltage in kilovolts [5]. A slightly different relation for the resist thickness dependence is given in [13]:

$$d_f \propto R_t^{1.75} \quad (11)$$

In Table I, typical values for the forward and backward scattering are given for a 0.5 um resist on a silicon substrate. Values shown in brackets are extrapolations. Values for α are calculated values, while β and η are experimental data.

**Table I**. Proximity parameters as a function of the beam energy [13]

Beam energy (keV)	α (um)	β (um)	η
5	1.33	[0.18]	[0.74]
10	0.39	[0.60]	[0.74]
20	0.12	2.0	0.74
50	0.024	9.5	0.74
100	0.007	31.2	0.74

A convenient method for quantitatively characterizing the proximity effect is the modulation transfer function (MTF). This function can be obtained by Fourier transforming and normalizing the energy density profile:

$$M = \frac{1}{1+\eta}\left(\exp(\frac{-\pi^2\alpha^2}{p^2}) + \eta\exp(\frac{-\pi^2\beta^2}{p^2}) \right) \tag{12}$$

where p is the spatial period. Ideally M should be 1 for all p. However, in the presence of electron scattering, M is less than 1 and is dependent on p. As put forward in [13], M is allowed to be smaller than 1, but it is crucial that it is independent of p for the proximity effect to be corrected. In figure 4, the MTF curve for several electron beam energies are given (again for a 0.5 um resist layer). For comparison, a spatial passband is drawn, in which M varies by no more than ±15%.
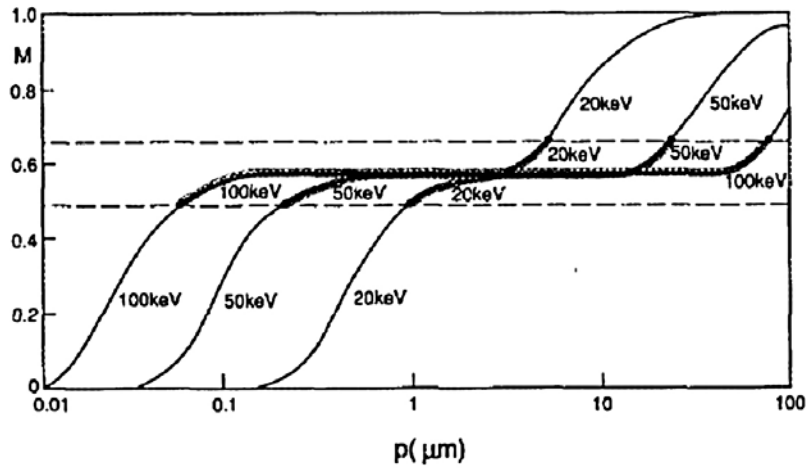

Figure 4, MTF curve for beam energies of 20, 50 and 100 keV for a silicon substrate with 0.5 um resist thickness.

Analogue to the MTF for optical lenses, the Y-axis can be thought of as the contrast while the X-axis presents the spatial period of line pairs. As can be seen from this figure, the flat part in this curve is much longer for higher beam energies. For example in 100 keV, 0.1 um features have the same contrast as 10 um features (M is independent of p in this range). Contradictory, in 20 keV, the backscattering component of the 10 um feature will swallow up the 0.1 um feature, due to the much lower contrast value of the latter. Considering only this, it makes sense to make the electron beam energy as high as possible. The drawback using high beam energies is that the sensitivity is reduced and consequently the dose must be increased. [7] The dose is proportional to the beam voltage, due to the increased transparency of resist layers at high voltage. [7, 14] Care must be taken that no damage is caused by nuclei displacement of substrate heating.

From Table I, it can be concluded that the backscattering effect becomes negligible when reducing the beam energy below 10 keV. Unfortunately, by decreasing the energy the forward scattering will increase beyond 1 um. This, however, can be countered by using smaller resist thickness (see equation 10). In Fig. 5, a MTF curve is given for a 5 keV beam with a 0.035 um resist thickness and for a 20 keV beam with 0.5 um resist. The passband at 5 keV is [0.5 um, ∞] while at 20 keV it is [1 um, 5 um]. From this we can conclude that low energy beams can be useful when using thin resist films. Unfortunately, semiconductor processes often

---
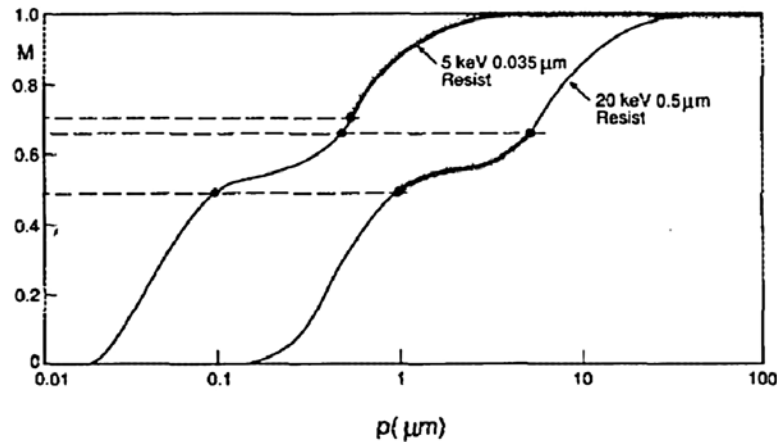
**Figure 5**. MTF curve for a 5 keV beam with 0.035 um resist thickness and a 20 keV with 20 um resist thickness.
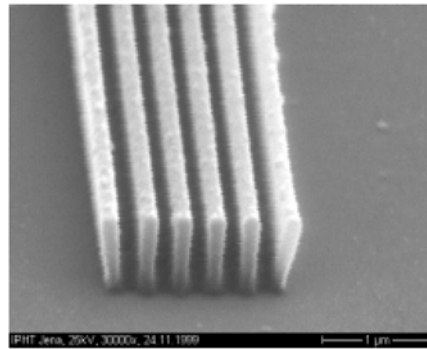
Figure 6. Distortions in 800 nm resist film with 150 nm line and space width.[14]

require a resist thickness much higher than 0.035 um, so this approach may not be practical in many cases.

Another important factor in choosing resist thickness is the aperture value, which is defined as the ratio between the resist thickness and the minimum feature size. Aperture values around 3 or 4 should be easily obtainable. In [14], aperture values of 5 and higher are reported. When the aperture becomes too high, part of the pattern may collapse or distort. For example, in figure 6, it can be seen the outer lines are distorted due to a high aspect ratio.

Multilayer resists can be used to reduce the proximity effect. Typically the upper layer is used for patterning, while the lower layer functions to reduce backscattering. This it does, since the backscatter coefficient n is lower and the backscatter range β is larger for a polymer than for silicon. In Fig. 7, an example is given of a MTF curve of a multilayer resist. The lower layer has a relatively large thickness of 2 um, while the upper layer is 0.2 um thick. As can be seen, the resolution increases considerably. The disadvantage is the increased process complexity.
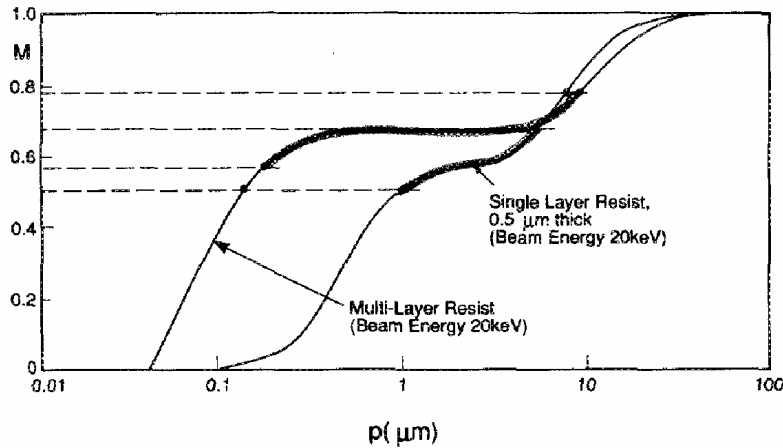
Figure 7. MTF curve comparing single and multilayer resist.

The correct exposure time (dose), as well as the development time, is strongly related to the type of resist and developer used. Negative resist will remain at the exposed area, while the unexposed parts of the resist will be etched away by the developer. In positive resist the exposed part will be etched away (Fig. 8). In negative resist, the edge profile of a line exposed is bell-shaped, caused by the electron scattering. In positive resist, on the other hand, more control over the profile is possible. By using a higher dose and/or a short development time, the edge profile will be dominated by the energy deposition profile, and will have a shape as in figure 9(a). A low dose and long development time will yield a shape as in Fig. 9(c). With medium dose and develop, steep vertical edges can be obtained (Fig. 9(b)) [5, 15-16].
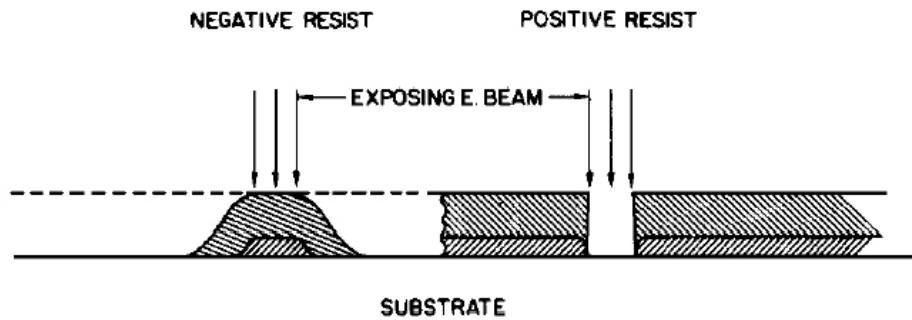
Figure 8. Negative and positive resist profiles.
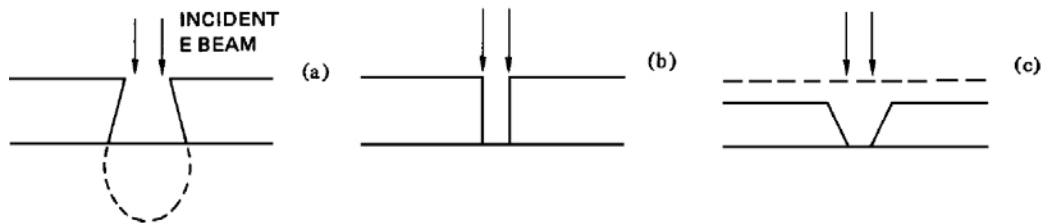
Figure 9. Edge profile in positive resist (a)high dose and short development time, (b) medium dose and development time, and (c) low dose and long development time

---

Proximity effect correction

Exposure estimation

Exposure estimation is important to simulate the effects of a proximity effect correction and it is used in many correction schemes. Since the energy deposition profile gives the response of a single point exposure, the exposure of a circuit pattern can be mathematically described by a convolution:

$$E(x, y) = f(r) * d(x, y) \qquad \text{with} \qquad r = \sqrt{x^2 + y^2} \qquad\qquad (13, 14)$$

where $E(x,y)$ is the energy deposited in the resist, $f(r)$ the point exposure profile and $d(x,y)$ the input dose as a function of position. The developed image $E'(x,y)$ can be obtained from $E(x,y)$ by

$$E'(x, y) = \begin{cases} 0 & E(x, y) < \tau \\ 1 & E(x, y) \geq \tau \end{cases} \qquad\qquad (15)$$

where τ is an experimentally determined development threshold. $E'(x,y) = 0$ and $E'(x,y) = 1$ are denoting undeveloped and developed resist respectively. An overview of this concept is given in Fig. 10 [17].
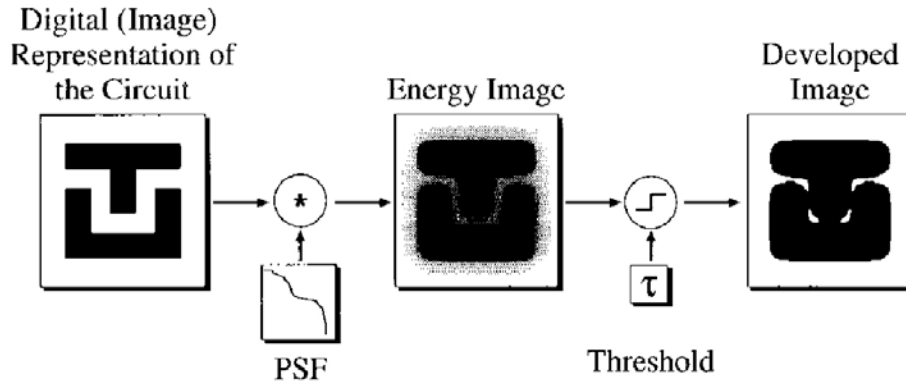
Figure 10. Exposure simulation of a circuit pattern.

Small pixel sizes are necessary to obtain an accurate image. However, convolving a large circuit using small pixels with the point exposure profile will give unacceptably long computation times. In [8], an efficient method is developed, based upon tables with cumulative distribution function of primitive shapes (e.g. rectangles). Furthermore, the memory requirements are reduced by separating the total exposure in two components, one due to the forward scattering component (local exposure), which is sharp and has a short range, and one due to the backscattering component (global exposure), which is rather flat and has a long range. The local exposure can be evaluated in a small window around the critical point, while the global exposure can be evaluated in a coarser grid without much accuracy degradation.

Exposure correction methods

There are essentially three methods of proximity effect correction. These are background correction exposure, shape modification, and dose modification. In the latter a different dose can be applied to each pixel and is therefore limited to direct writing electron beam systems.

Dose modification

Many proximity correction schemes variants have been proposed, which use some form of dose modification [19-21]. The problem is to determine the required dose for each pixel with a reasonable accuracy while being computationally practicable.

Numerous variants of the "self-consistent dose correction" have been developed. In its simplest form, it is basically the reverse of the exposure estimation discussed before. Let Q_j be the dose applied to pixel j and let N be the total amount of pixels. The total energy on pixel i will be:

$$E_i = \sum_{j=1}^{N} R_{ij} Q_j \quad \text{with} \quad R_{ij} = \frac{\overline{\Delta V_f}}{t} \left(\frac{1}{\pi \alpha^2} \exp(-\frac{r_{ij}^2}{\alpha^2}) + \frac{\eta}{\pi \beta^2} \exp(-\frac{r_{ij}^2}{\beta^2}) \right) \quad (18, 19)$$

where r_{ij} is the distance between pixel centers of i and j. This equation can be written in matrix notation for all i:

$$[E_i] = [R_{ij}][Q_j] \quad (20)$$

Solving this set of equations with matrix operations will provide a proximity effect corrected pattern. However this "self-consistent" scheme will not be a perfect correction since only the exposed pixels are considered in this equation [13]. Variants and improvements of this algorithm and their performance are discussed in [20]. The problem can be simplified, thereby reducing the calculation time, by splitting the dose modification into a problem of forward scattering and back scattering correction [20-21]. With dose modification, it is possible to achieve superior proximity effect correction. The main disadvantage is that with very large circuits, it may require large computation times.

Shape modification

In this method, a single dose is used for the entire circuit. The shapes found in the pattern image are modified in such a way that the developed image will resemble the intended image as close as possible. A good example of a shape modification method is the correction scheme in PYRAMID [8, 19]. PYRAMID takes a pattern with rectangular circuit elements. The circuit is then passed to a correction hierarchy, which adjusts each element via pre-calculated rule tables. This rule table is created using exposure estimation as described in the previous paragraph. The first step is to replace each rectangle with its inner maximal rectangle, as depicted in Fig. 12. The second step is to correct the effect of interaction among the different circuit elements. Each edge facing other circuit elements will be adjusted so that the midpoint of the edge will be equal to the experimental determined development threshold. Even better results can be obtained by bending the edge when appropriate. The final step is to modify the shapes at critical points, that is, junctions between adjacent rectangles (Fig. 13).
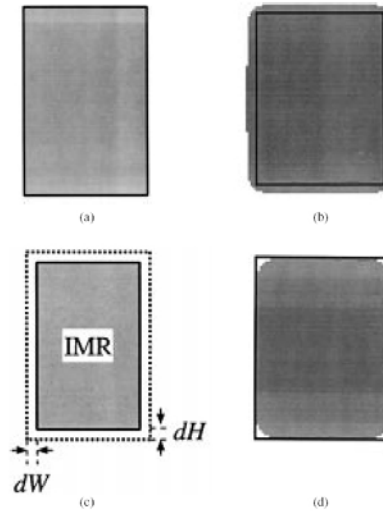
Figure 12: reducing rectangle size for exposure compensation
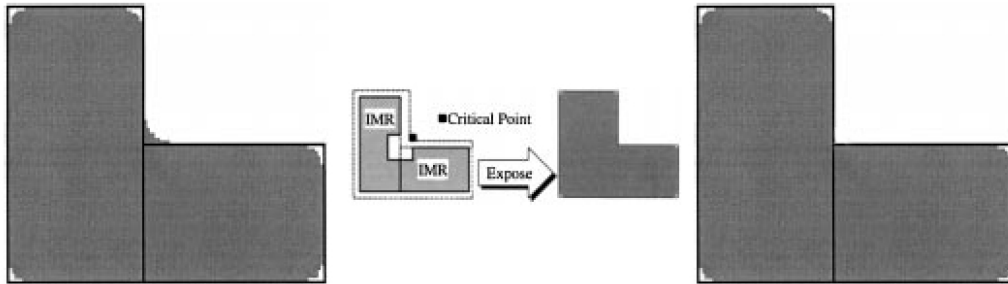
Figure 13: Shape modification of critical points.

Problems can be expected when placing for example very large rectangles very close to small ones. Experimental results in [19] showed a 0.1 um line 0.3 um next to a 11 x 11 um rectangle was missing completely, due to the high exposure in the gap. A solution for this is to remove parts of the interior of the large rectangle, in such a way that the rectangle will still develop, while backscattering is reduced substantially.

The major advantage of the shape modification method is that accurate results can be obtained without being computationlly expensive and without losing throughput. However, it may not be as flexible as the other methods and experimental data is needed to obtain the necessary rule-tables.

Background exposure correction

Background exposure correction, often referred to as GHOST, works by writing a second exposure which is the inverse of the intended image. This is done in such a way that the background dose is brought to a constant level [17-18]. The main advantage of this method is that it is one of the easiest proximity effect correction methods found in the literature and can be used with virtually all electron beam machines. However, there are several disadvantages with this method. One problem may be a contrast reduction (although this is true for many other correction types too). However, the main problem is that it only provides correction to

the backscattering component, where the forward scattering remains uncorrected [13]. There is also a loss of throughput because of the double exposure.

Conclusion

Proximity effect in electron beam lithography was examined. Electron scattering is the most challenging problem in e-beam lithography for producing very high resolution images. The physical concepts behind the electron scattering are explained and the exposure process is quantitatively described using energy density profile models. The influence of different process parameters were summarized. Often, the electron beam system's highest possible electron beam energy available should be used to obtain the highest resolution. However, care must be taken that no damage and excessive heating is caused to the substrate due to the increase dose requirements. When it is possible to use thin resist layers, low electron beam voltage may be feasible too. Exposure and development time may be tweaked to obtain vertical edge profiles, or, when negative or positive slopes, necessary for certain applications. Algorithms that can correct the proximity effect were looked at. There exists a trade-off in proximity effect correction between speed, complexity and accuracy.

References

[1]   *Introduction to electron beam lithography*, http://dot.che.gatech.edu/henderson.
[2]   U.S. Tandon and W.S. Khokle, *Patterning of material layers in submicron region*, John Wiley & Sons, 1994
[3]   C.R.K Marrian and D.M. Tennant, *Nanofabrication*, Journal of Vacuum Science Technology A, 21(5), S207-S215, 2003
[4]   *Electron beam lithography*, http://www.elettra.trieste.it/experiments/beamlines/lilit/ htdocs/people/luca/tesihtml/node37.html
[5]   P. Rai-choudhury, *Handbook of microlithography, micromachining and microfabrication, volume 1: microlithography*
[6]   R.F. Egerton, P. Li and M. Malac, *Radiation damage in the TEM and SEM*, Physics department, University of Alberta, Edmonton, Canada
[7]   T.R. Groves, *Theory of beam-induced substrate heating,* Journal of Vacuum Science Technology B, 14(6), 3839-3844, 1996
[8]   S. Lee, B. Cook, *PYRAMID – a hierarchical, rule-based approach toward proximity effect correction – part I: exposure estimation*, IEEE Transactions on Semiconductor Manufacturing, 11(1), 108-116, 1998
[9]   T.H.P. Chang, *Proximity effect in electron-beam lithography,* Journal of Vacuum Science Technology, 12(6), 1271-1275, 1975
[10]   E. Seo, B.K Choi, O. Kim, *Determination of proximity effect parameters and the shape bias parameter in electron beam lithography,* Microelectronic Engineering, 53, 305-308, 2000
[11]   S. Aya, K. Kise, H. Yabe and K. Marumoto, *Validity of double and triple gaussian functions for proximity effect correction in X-ray mask writing,* Japanese Journal of Applied Physics, 35, 1929-1936, 1996
[12]   L.I. Aparshina, S.V. Dubonos, S.V. Maksimov, A.A. Svintsov, S.I. Zaitsev, *Energy dependence of proximity parameters investigated by fitting before measurement test,* Journal of Vacuum Science Technology B, 15(6), 2298-2302, 1997
[13]   G. Owen, *Methods for proximity effect correction in electron lithography,* Journal of Vacuum Science Technology B, 8(6), 1889-1892, 1990
[14]   H. Elsner and H.G. Meyer, *Nanometer and high aspect ratio patterning by electron beam lithography using a simple DUV negative tone resist,* International Conference "Micro and Nano Engineering", Germany, 2000

[15]   D.R. Medeiros et al., *Recent progress in electron-beam resists for advanced mask-making,* IBM Journal Research and Development, 45(5), 639-650, 2001

[16]   I. Raptis, B. Nowotny, N. Glezos, M, Gentili and G. Meneghini, *Electron beam lithography simulation on homogeneous and multilayer substrates,* Japanese Journal of Applied Physics, 39, 635-644, 2000

[17]   G.P. Watson, S.D. Berger, J.A. Liddle and W.K. Waskiewicz, *A background dose proximity effect correction technique for scattering with angular projection electron lithography implemented in hardware,* Journal of Vacuum Science Technology B, 13(6), 2504-2507, 1995

[18]   G. Owen and P. Rissman, *Proximity effect correction for electron beam lithography by equalization of background dose,* Journal of Applied Physics, 54(6), 3573-3581, 1983

[19]   S. Lee, B. Cook, *PYRAMID – a hierarchical, rule-based approach toward proximity effect correction – part II: correction,* IEEE Transactions on Semiconductor Manufacturing, 11(1), 117-128, 1998

[20]   S.J. Wind, P.D. Greber, H. Rothuizen, *Accuracy and efficiency in electron beam proximity effect correction,* Journal of Vacuum Science B, 16(6), 3262-3268, 1998

[21]   E.H. Anderson, D.L. Olynick, W. Chao, B. Harteneck and E. Veklerov, *Influence of sub-100 nm scattering on high-electron beam lithography,* Journal of Vacuum Science, 19(6), 2504-2507, 2001