Appendix 4

Evaluation of the proximity correction effectiveness by pattern edge evaluation method

A4.1 Introduction

To evaluate quantitatively and objectively the proximity correction method the precise estimation of the written pattern width is proposed. Simulations are very useful investigative tool, but the evaluation region is restricted due to the large amount of computations required. Consequently, a quantitative evaluation of overall layout pattern characteristics cannot be obtained. Measuring patterns directly with a scanning microscope in another way to evaluate pattern width. This approach is necessary for final pattern verification, but the many experimental steps involved are time consuming and expensive. Therefore it is difficult to apply it to various VLSI patterns or when e - beam writing conditions, and consequently the proximity effect change.

In this Appendix we study the computational method for pattern width evaluation based on exposure intensity distribution function. Its application for sub *100 nm* patterning is evaluated. The strength of the proximity effect greatly depends on e - beam writing process conditions such as acceleration voltage, beam edge sharpness, resist characteristics, and the substrate structure and material.

In e - beam writing systems, the pattern to be fabricated is defined by elemental figures such as rectangles. With a vector scan e -

beam system, dose can be allocated to each elemental figure for proximity effect correction. Therefore the shape partitioning algorithm for the elemental figure affects the correction.

The information about the pattern edge location is then necessary to optimise the correction process. It should be pointed out that pattern edge location defined by e - beam writing data does not always correspond to the ideal location.

The principle of the edge evaluation was first introduced by Watanabe et al. [1]. It is shown in Fig. A4.1.

A top view of the layout pattern is shown in inlet (a). Dotted line shows the ideal pattern edge location. Small circles show sampling point positions. Those points are randomly and uniformly generated within the target region. Distance x between the point and the nearest ideal edge location is refereed to as edge distance. The effective exposure energy is calculated using the EID and data layout.

All sample points are plotted according to the edge distance and the effective exposure energy, as shown in inlet (b). Each dot corresponds to a sampling point. In the vicinity of the ideal edge, sampling point with the same edge distance can have different effective energy due to the variety of pattern allocations around the sampling point.

Next, consider a narrow slice with width dx at edge distance x, $F(x)$ can be defined as follows :

$$F(x) = n(x) / N(x) \qquad (\text{A4.1})$$

where $N(x)$ is the total number of points in the slice, and $n(x)$ is the number of points whose dose is greater than the critical dose, which is the minimum effective exposure energy sufficient for pattern resolution.

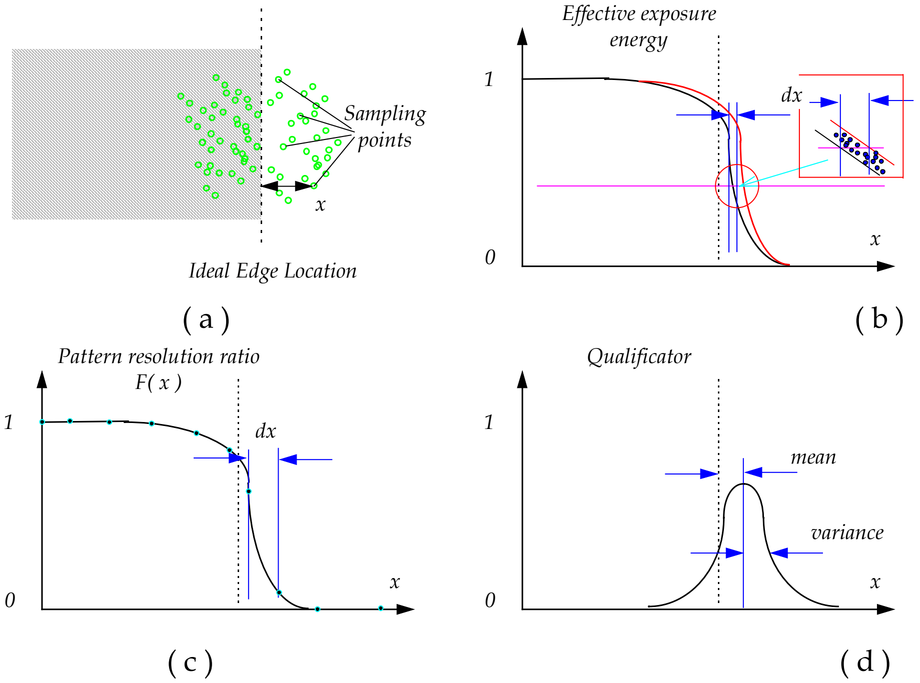

Fig. A4.1. Principle of the edge evaluation method (after [1]). (a) Layout pattern. (b) Effective exposure energy distribution. (c) Pattern resolution ratio. (d) Derivative of the pattern resolution ratio.

Function *F(x)* shows the probability that the point at edge distance x will be within the resolved pattern region depicted in inlet (c). It also shows the probability that a pattern edge will exist somewhere in the infinite distance beyond edge distance *x*. The derivative function of *F(x)*, *dF(x)/dx*, shows the probability that the pattern edge exists between *x* and *x + dx*, as shown in inlet (d). Function *F(x)* is refereed to as the pattern resolution ratio.

Function *F(x)* is assumed to have a Gaussian distribution. The probability density function *dF(x)/dx* can be expressed as

$$\frac{dF(x)}{dx} = A\exp\left[-(x-\mu)^2 / \sigma^2\right] \tag{A4.2}$$

where the parameters (μ or σ) are, respectively, the mean and standard deviation of the edge positioning error respectively. The number of sampling points in the slice with width *dx* must be large enough for statistical treatment.

A4.2 Evaluation procedure

The evaluation procedure is shown in Fig. A4.2. As an input it is assumed the proximity function parameters (in our investigation the double Gaussian model was used, but method is general and not confines itself for such representation), the critical dose for the system resist / substrate under evaluation, and data of the layout.

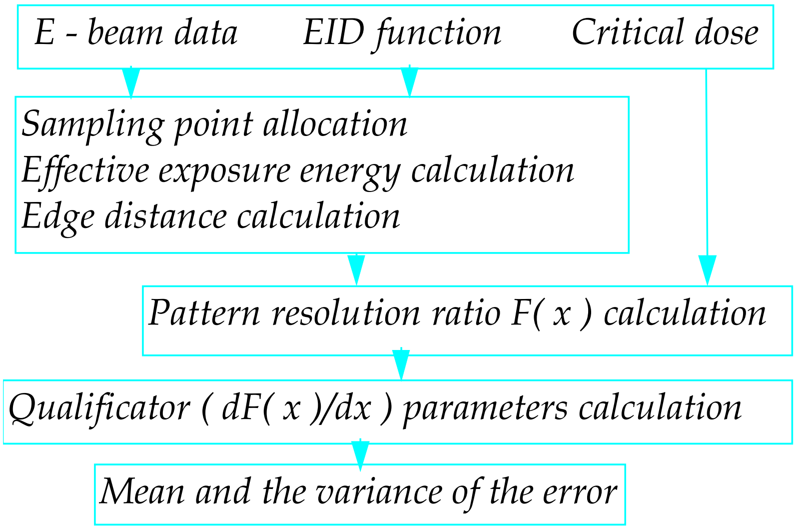

Fig. A4.2. Evaluation procedure.

Step 1 is the calculation of attributes for sampling points. Sampling point are randomly allocated within the whole target region and the effective exposure energy and edge distance *x* are calculated using the EID function and the e - beam writing data.

Step 2 is the calculation of the pattern resolution ratio *F(x)*. For every sampling point a judgement is made as to whether the point is in or out of the resolved pattern by comparing the effective exposure energy and critical dose. *F(x)* is obtained based on the result of that judgement and distance *x*.

Step 3 is the calculation of the mean and the standard deviation, which are obtained by using the regression form of the pattern resolution ratio *F(x)* as an integral form of the Gaussian curve.

In the proximity effect correction, the backward scattering energy is estimated at the pattern edge, and the dose is modulated to make it the same as the critical dose. Some results from the algorithm are shown in Fig. A4.3 (proximity parameters was $\alpha = 10\ nm$, $\beta = 3.45\ \mu m$, $\eta = 0.82$).

All sampling points are plotted according to the effective exposure energy and the edge distance *x*, as shown in Fig. A4.3 (a). The size of the evaluated region was $50\ \mu m \times 50\ \mu m$. The number of the points was chosen to be 25.000. The computation time was about one minute on Pentium PC 200, using MATLAB 4.2. The pattern resolution ratio *F(x)* is shown in Fig. A4.3 (b). Each circle is the calculated value for each slice with a width *dx*. The solid line is the regression function of *F(x)*.

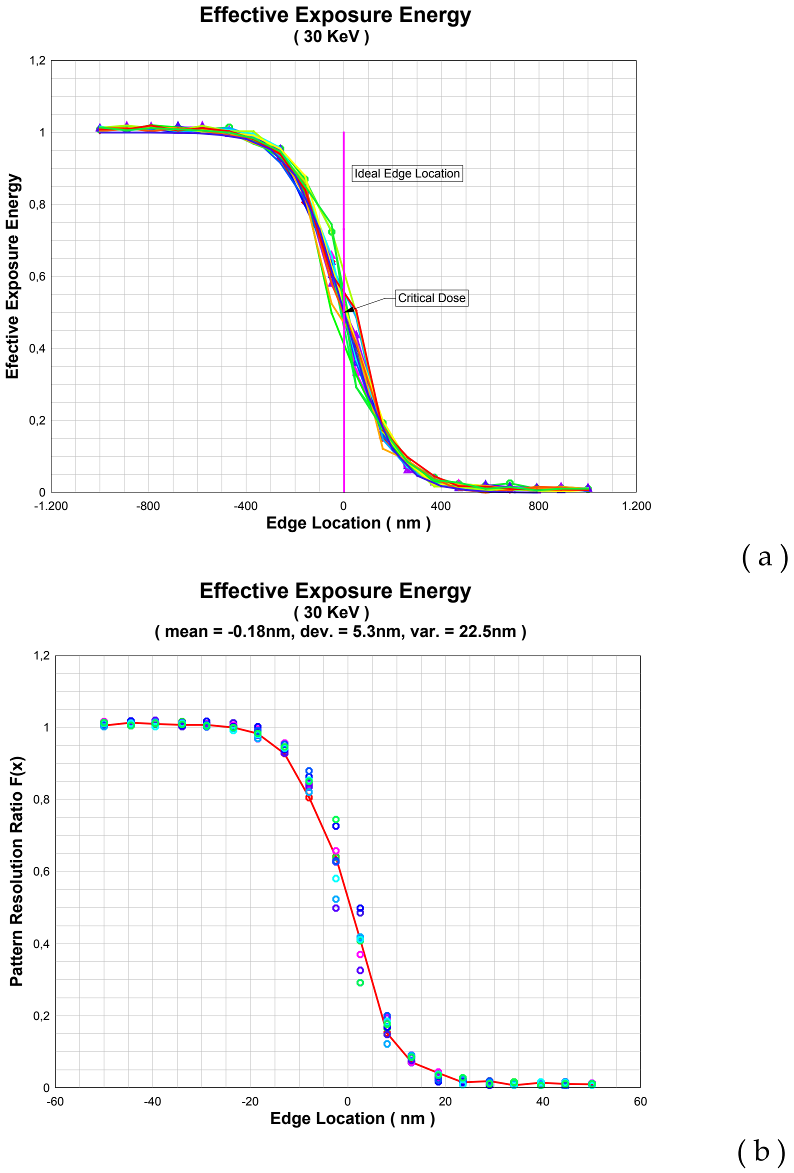

Fig. A4.3. Evaluation example : Effective exposure energy (a). Pattern resolution ratio *F(x)* (b).

For edge positioning errors the mean is *-0.18nm* (μ) and the standard deviation is *5.3 nm* (σ). If the proximity effect independently occurs on both edges of one line, the mean and standard deviation of the linewidth error can be expressed by 2μ and $\sqrt{2}\sigma$, respectively. The variance in linewidth error is usually evaluated as three times the standard deviation. If the critical dimension (*CD*) has to be controlled to less than *10 %* of the linewidth, a variance of *22.5 nm* as $3\sqrt{2}\sigma$ is larger than the allowance for sub *100 nm CD*, which should be below *10nm*. One should keep in mind that on this level of accuracy, with α = *10 nm* the resolution of the system is reached.

Proposed qualificator (derivative of the *F(x)*) can be applied for effective evaluation of the edge positioning error dependence on the beam energy. Calculations were made with proximity parameters grouped in Table. A4.2.

Energy (KeV)	α (nm)	β (μm)	η
20	43	0.48	1.01
30	35	0.26	0.81
40	32	0.85	0.72
50	31	1.1	0.56
60	28	1.3	0.45
70	28	1.5	0.43
80	28	1.81	0.41
90	28	1.94	0.32
100	28	2.43	0.26

Table A4.2. Parameters of the proximity function for different beam energies (data for writing of X-ray masks, after [2]).

Calculated qualifiacator parameters (mean and standard deviation) for different energies are shown in Fig. A4.4. As acceleration voltage increases, standard deviation decreases. The *15 nm* variance at *20 KeV* decreases to *2.3 nm* at *60KeV*. Therefore it becomes clear that the variance of *2.3 nm* (*9.76 nm* as linewidth error $3\sqrt{2}\sigma$) satisfies the *10 %* margin for sub *100 nm* fabrication.

The method presented here is feasible one for an error estimation of the proximity correction methods in the case of *70 nm* design rule chip generation.

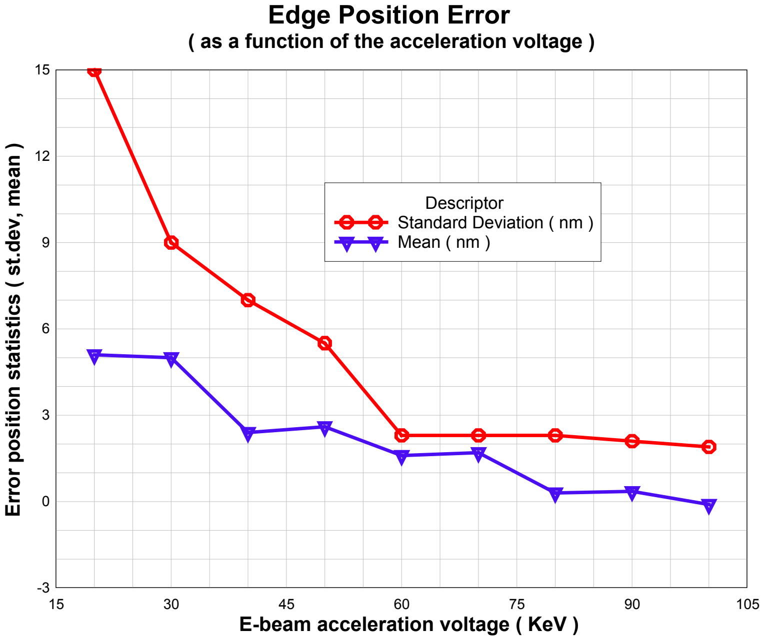

Fig. A4.4. Parameters of the qualificator as a function of the beam energy.

It is important to point out that the standard deviation of linewidth error has been simply expressed as $2^{1/2}$ times the standard deviation ($2^{1/2}\sigma$) of the edge positioning error. However, for fine patterns, the standard deviation of linewidth error should be considered to be two times the standard deviation (2σ) of the edge positioning error.

Bibliography

[1] T. Watanabe, S. Moriya, and K. Komatsu, “ J. Vac. Sci. Technol. ”, B 13, 2637, (1995).
[2] Y. Kuriyama, S. Moriya, S. Uchiyama, and N. Shimazu, “ Jpn. J. Appl. Phys. ′, 33, 6983, (1994).