Determination and Analysis of Minimal Dose for Achieving Vertical Sidewall in Electron-beam Lithography

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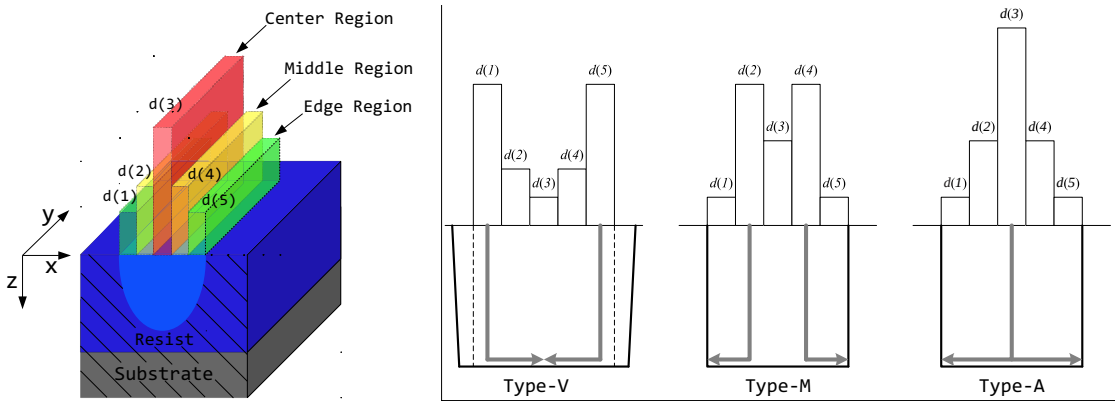
One of the major limiting factors in electron-beam (e-beam) lithography is the geometric distortion of written features due to electron scattering, i.e., proximity effect, which puts a fundamental limit on the minimum feature size and maximum pattern density that can be realized. A typical method of proximity effect correction (PEC) is to optimize the spatial dose distribution within a feature such that the proximity effect is minimized. An important practical issue is how to determine the minimum total (or equivalently average) dose required for the correction. Note that a lower total dose is desired to shorten the e-beam exposing time and reduce the charging effect. One may take a trial-and-error approach, trying a number of different total doses in PEC or even experiment and then selecting the lowest dose achieving the acceptable CD (critical dimension) error. However, such an approach is unnecessarily costly and wasteful.

In our previous work, it was shown that the dose distribution of shape-V (Fig. 1b), usually obtained in a conventional PEC scheme, is not optimal in realizing a vertical sidewall of resist profile with the total dose minimized, especially for nanoscale features. The dose distributions of shape-M and shape-A (Fig. 1b) were shown to perform better in most cases, achieving a resist profile closer to the target profile with a smaller CD error and a lower total dose. In this study, a systematic method for determining the minimal total dose for each type of dose distribution has been developed. It utilizes the concept of "critical path" (Fig. 1b) to avoid any PEC effort in dose determination. The behaviors of the minimal total dose and optimal dose distribution type are also investigated.

Given a substrate system and a developing time (T), the minimum total dose may be determined through an iterative procedure for each type of dose distribution. The total dose is set to an initial value (D_0) sufficiently lower than the dose level commonly used for the substrate system. In each iteration, the exposure (energy deposited in the resist) distribution is computed with a typical dose distribution and converted into the developing rate through a mapping function which is nonlinear and experimentally derived. The developing time is estimated along the critical path, i.e., $t = \sum_{i=1}^{N} \frac{c(i)}{r(i)}$ where $c(i)$ and $r(i)$ are the size and developing rate of the ith cell, and N is the number of cells on the critical path. Also, $r(i) = F[e(i)]$ where $e(i)$ is the exposure in the ith cell and $F[\,]$ is the mapping function. If $t > T$, the total dose is incremented by a small amount and the iteration continues. Otherwise, the current dose is the minimum total dose for the dose distribution type.

This iterative procedure can be time-consuming depending on the difference between the initial total dose and the minimal total dose and dose increment per iteration. Also, the accuracy of result varies with the initial total dose and dose increment. In order to reduce the computational requirement and improve the result accuracy, a non-iterative procedure consisting of two steps is designed. In the first step, the total dose is estimated comparing the developing rate derived as $\frac{L_{cp}}{T}$ and the average developing rate along the critical path for an arbitrarily-chosen total dose D, where L_{cp} is the length of the critical path. Noting that the exposure (developing rate) varies along the critical path, the estimated total dose is refined, in the second step, finding a correction factor p satisfying $T = \sum_{i=1}^{N} \frac{c(i)}{F[p \cdot e(i)]}$ where $e(i)$ is the exposure computed with the total dose of D' estimated in the first step. In order to solve the equation for p, $F[\,]$ is approximated to be piece-wise linear. The minimum total dose is computed to be pD'.

In Table 1, the minimum total doses estimated by the iterative and non-iterative procedures for various cases are provided where the optimal type is the type of dose distribution for which the lowest minimum total dose is obtained, and in Table 2, the computation times of the two procedures, measured using Intel Core i7-3615QM with core clock of 2.3 GHz, are compared. In this paper, the complete description of the proposed method will be presented with detailed discussion on a comprehensive set of results. Also, the behaviors of the optimal dose-distribution type and optimal dose distribution will be analyzed in detail.



(a) (b)

Figure 1: (a) 3-D model, and (b) critical paths for different dose-distribution types.

Feature Size (nm)	PMMA Thickness (nm)	Beam Energy (KeV)	Minimal Total Dose ($\mu C/cm^2$)						Optimal Type
			Iterative			Non-iterative			
			Type-V	Type-M	Type-A	Type-V	Type-M	Type-A	
50	100	50	127	106	100	138	110	104	Type-A
50	300	50	282	248	205	275	203	191	Type-A
50	500	50	523	453	352	546	444	397	Type-A
100	100	50	141	122	147	149	120	153	Type-M
100	300	50	261	232	227	257	225	217	Type-A
100	500	50	437	369	318	427	359	309	Type-A
100	500	20	241	199	169	219	175	159	Type-A
100	500	50	437	369	318	427	343	309	Type-A
100	500	100	697	582	715	690	554	700	Type-M

Table 1: The minimum total dose and optimal type of dose distribution.

Dose Type	Feature Size (nm)	PMMA Thickness (nm)	Beam Energy (KeV)	Computation Time		Speed-up
				Iterative (sec)	Non-iterative (sec)	
Type-V	100	100	50	3.59	0.01	359
Type-M	100	100	50	3.14	0.01	314
Type-A	100	100	50	3.71	0.01	371
Type-V	100	300	50	7.25	0.01	725
Type-M	100	300	50	6.32	0.01	632
Type-A	100	300	50	6.12	0.01	612
Type-V	50	300	50	7.52	0.007	1074
Type-M	50	300	50	6.59	0.007	941
Type-A	50	300	50	5.26	0.007	751

Table 2: Computation times of the iterative and non-iterative methods with the speed-up achieved by the non-iterative method over the iterative method.