Estimation of Resist Profile using Layer-based Exposure Modeling

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The electron-beam (e-beam) lithographic process consists of exposing resist by e-beam and subsequently developing the resist for pattern transfer. For applications such as estimating the (remaining) resist profile and e-beam dose control for proximity effect correction, both steps are often simulated. In the first step, the *exposure* (energy deposited in the resist) distribution is computed by convolution between a circuit pattern and a point spread function (PSF) which depicts the exposure distribution when a single point is exposed. In the second step, the developing rate at each point in the resist is derived from the respective exposure and an iterative procedure is employed to estimate the resist profile based on the developing rate distribution. While such simulations are widely used, they have some practical limitations: PSF's may not be accurate; PSF’s may not be easily obtained for certain substrate systems; parameters involved in the developing process are often not considered in the simulation, leading to a significant error; such simulations are normally very time-consuming especially for large circuit patterns.

In order to avoid the above-mentioned limitations, one may estimate the resist profile of a given pattern based on the experimental results of *base patterns*. Assuming that a pattern does not vary along the *Y*-dimension, only the cross-section of resist perpendicular to the *Y*-axis is considered. Let $e(x,z)$ and $r(x,z)$ denote the exposure and developing rate distributions in the cross-section, respectively, where z represents the resist depth (layer) dimension. The resist profile is depicted by $d(x)$ which is the depth at x. Previously, a method (to be referred to as “*2-D Mod*”) using the average developing rate, i.e., $r(x)$, derived from $d(x)$ of a base pattern, $r(x)=d(x)/T$ where T is the developing time, was shown to lead to a substantial estimation error due to the fact that $e(x,z)$ varies with z. In this study, a new method which adopts layer-based exposure modeling has been developed in order to improve estimation accuracy. The new method exploits the fact that $e(x_i,z)$ is *similar in shape* to $e(x_j,z)$ or equivalently $r(x_i,z)$ is similar to $r(x_j,z)$ where x_i and x_j are any two points within the exposed area (refer to Figure 1-(a)). Given a substrate system, a typical shape of $r(x,z)$ is modeled for a certain point x_c, e.g., the center of a feature. Then, $r(x,z)$ for any other point x within the feature is estimated as $r(x,z) = s\ r(x_c,z)$ where s is a scaling factor which is derived from $d(x)$. The same approach to modeling $r(x,z)$ is taken for the points in the unexposed area, i.e., outside features. Their $r(x,z)$’s are different from those in the exposed area, but similar among themselves (Figure 1-(b)). This layer-based modeling is essential to the proposed estimation method, briefly described with a simple example in the following.

Let the function f relate exposure to developing rate, i.e., $r(x,z) = f(e(x,z))$. Consider a target pattern consisting of two lines sufficiently long in the *Y*-dimension and separated by L in the *X*-dimension. In this case, the base pattern is a single line of which resist profile, obtained through experiment, is referred to as $d_1(x)$. The resist profile of the target pattern, which is to be estimated, is denoted by $d_2(x)$. The developing rate distributions of the base and target patterns are denoted by $r_1(x,z)$ and $r_2(x,z)$, respectively. The layer-based modeling derives $r_1(x,z)$ from $d_1(x)$. Then, $r_2(x,z) = f(f^{1}(r_1(x,z)) + f^{1}(r_1(x-L,z)))$. Finally, $d_2(x)$ can be obtained from $r_2(x,z)$. This estimation procedure is valid for the flat portions of $d_2(x)$ where the development process is mostly vertical. However, it can lead to a substantial error where the development process includes a significant lateral component. In order to minimize this error, the lateral component of $d_1(x)$ is modeled and subtracted from $d_1(x)$ before the above estimation procedure is followed. Then, it is added back to $d_2(x)$ through up-scaling. The proposed method has a good potential to achieve high estimation accuracy, reducing computation time by orders of magnitude.

Feasibility and effectiveness of the proposed estimation method have been analyzed first through an extensive simulation. The *2-D Mod* and proposed estimation methods are compared to the conventional method (“*Exp-Dev*”) which requires exposure computation and resist development simulation. Test patterns consist of lines and spaces where the widths of line and space, and the number of lines are varied. Three different thicknesses of resist are considered to test the methods for varying degree of exposure variation along the depth dimension. In Table 1, the percent depth error, defined as the depth difference between each of the 2-D Mod and proposed methods and the Exp-Dev method, is provided. It can be seen that the proposed method achieves higher accuracy than the *2-D Mod* method and the accuracy improvement is larger for a thicker resist within which the vertical exposure variation is larger. In Figure 2, the typical resist profiles estimated by the three methods are compared where it can be seen that the proposed method can achieve resist profiles very close to those by the *Exp-Dev* method. In this paper, the detailed description of the proposed method will be presented along with simulation and experimental results.

Substrate system	Line Width	Space	Number of lines	2-D modeling method		Proposed method	
				Mean error	Max error	Mean error	Max error
100 nm/50-layer PMMA on Si	50 nm	50 nm	8	1.627	5.453	0.139	1.168
			16	1.774	5.326	0.143	0.972
			32	1.835	5.145	0.175	0.898
	100 nm	50 nm	8	2.067	5.350	0.216	1.911
			16	2.303	5.306	0.236	2.041
			32	2.413	5.236	0.308	2.133
500 nm/50-layer PMMA on Si	50 nm	50 nm	8	1.992	6.106	0.497	3.150
			16	2.278	5.985	0.626	3.512
			32	2.284	5.578	0.723	3.530
	100 nm	50 nm	8	2.843	6.250	0.359	3.400
			16	3.109	6.375	0.418	3.180
			32	3.123	6.149	0.504	3.139
1000 nm/50-layer PMMA on Si	50 nm	50 nm	8	4.795	36.630	1.145	11.360
			16	5.217	35.364	1.340	11.287
			32	5.224	34.512	1.431	11.184
	100 nm	50 nm	8	6.023	39.057	0.764	10.409
			16	7.184	38.463	1.385	9.490
			32	7.671	41.752	1.897	10.321

Table 1. Percent depth error (compared to depth by Exp_Dev)

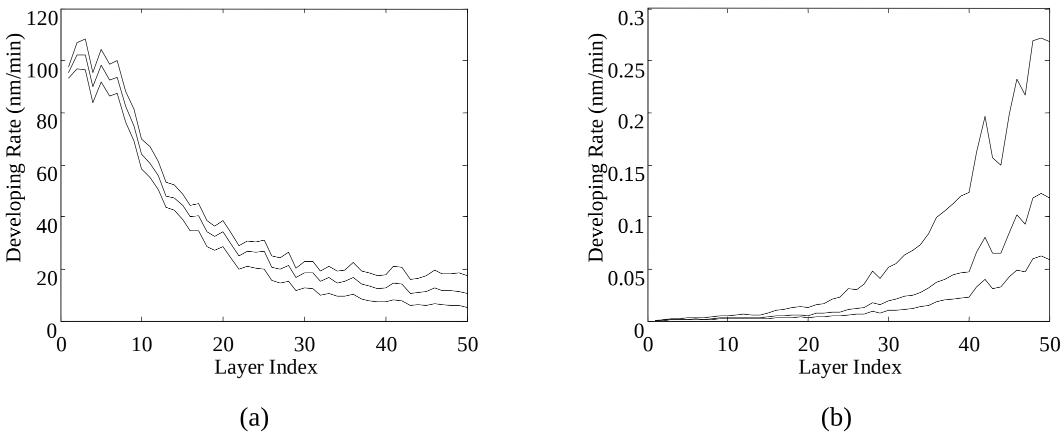

Figure 1: Distribution of developing rate at three arbitrary points: substrate of 500 nm PMMA on Si (50-layer).

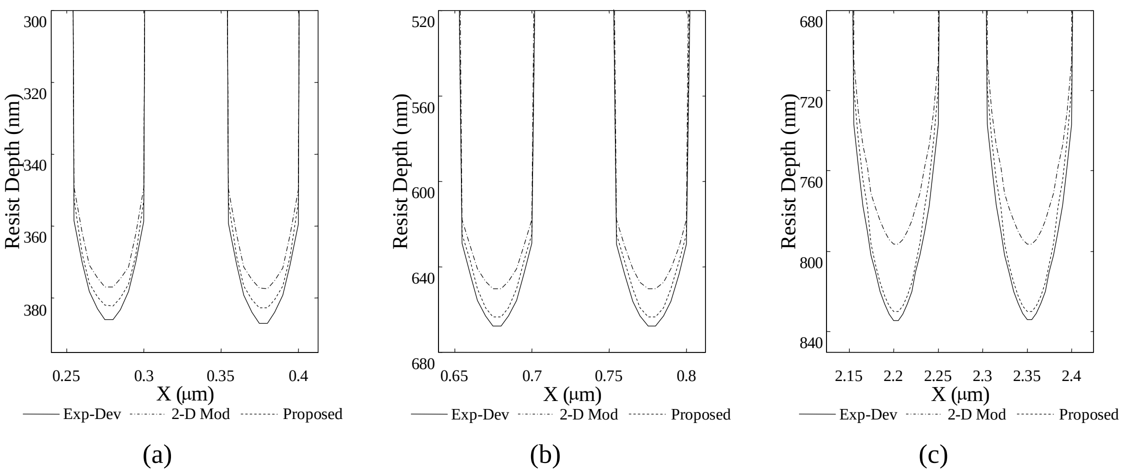

Figure 2: Resist profiles of a 32-line pattern (only a part is shown): (a) line width of 50 nm on the substrate of 500 nm PMMA on Si (50-layer), and (b) line width of 50 nm and (c) line width of 100 nm on the substrate of 1000 nm PMMA on Si (50-layer).