A Fast Path-based Method for 3-D Resist Development Simulation in Electron-beam Lithography

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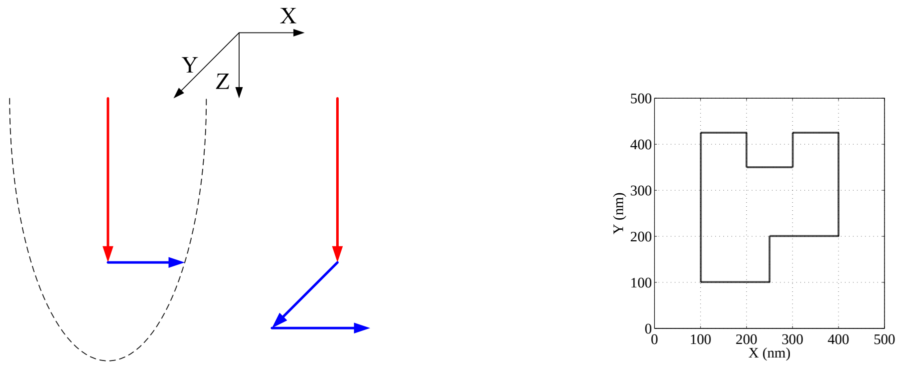
The simulation of resist development process plays an important role in applications such as estimation of remaining resist profiles and proximity effect correction. In the past, several 2-D and 3-D methods were developed, such as the the string method, the ray-tracing method, and the cell removal method. The string and ray-tracing methods usually have difficulties in the treatment of boundaries and the elimination of loops. In contrast, the cell removal method is quite stable and robust as it does not suffer from such problems. In this method, each resist layer is partitioned into cubic cells, and the resist development process is traced on a cell-by-cell basis. This kind of cell-based method is generally easy to implement which makes it widely-used. However, the main drawback of the cell removal method is a long computation time required, specially for estimating 3-D resist profiles. When an iterative proximity effect correction scheme requires the resist development simulation in each iteration, it would not be practical to employ such a time-consuming method.

In this study, a fast path-based method for 3-D resist development simulation which avoids the time-consuming computation without sacrificing the simulation accuracy is proposed. The key idea of the proposed method is that though resist is developed in all possible directions, the development process can be modeled by "development paths," i.e., paths starting from the top surface of resist toward the boundaries of the final resist profile. Given a developing time, all "possible paths" are individually followed without any iterative procedure and a set of the paths reaching the farthest points on individual layers of resist determines the resist profile. More specifically, a path consists of two orthogonal types of path segments, i.e., vertical and lateral path segments. A path makes a "turn" when it switches from one type of path segment to another. Whether and in what direction a path is to be turned at a point depends on the relative developing rates of adjacent points compared to that of the point. The more turns allowed, the more accurate the simulation result becomes, but the longer the simulation time is. It is found that in many cases, one turn is sufficient to achieve high accuracy of simulation, e.g., when one is interested only in cross-sections of resist profile for a line feature. Even for more general shapes of feature, two turns are sufficient to obtain accurate 3-D resist profiles at the expense of a longer simulation time compared to the case where only one turn is allowed. In order to minimize the simulation time, an adaptive approach is incorporated into the simulation procedure. Before the final stage of simulation, the resist profile would be usually smooth without sharp shapes such as corners and junctions. Therefore, a developing period (time) is partitioned into two phases where only one turn is allowed in the first phase and two turns in the second phase. This adaptive approach reduces the simulation time greatly without sacrificing simulation accuracy substantially.

The proposed path-based method for 3-D resist development simulation has been implemented and its performance has been compared with the cell removal method in terms of simulation accuracy and time. The substrate system assumed in this comparison is composed of 300 nm PMMA on Si. The beam energy is set to 50 KeV with the beam diameter of 5 nm. Several patterns including Pattern I shown in Fig. 1(b) are considered in the comparison. The contours of resist profiles at the top, middle and bottom layers, obtained for Pattern I, are provided in Fig. 2. It can be seen that the resist profiles by the proposed method are well matched with those by the cell removal method. The same high accuracy is observed in all of the other patterns. In Table 1, the simulation time measured on a PC with a 2.53 GHz CPU (Intel Core i5-540M) and 2 GB memory is provided for various patterns. It is clear that the proposed method takes much less time for simulation, compared to the cell removal method. The speed-up is larger for larger patterns. Therefore, the proposed path-based method has a good potential to be a practical and efficient alternative to the existing methods such as the cell removal method. In this paper, the path-based method will be described in detailed with a more comprehensive set of results.



(a) (b)

Figure 1: (a) The development paths with one and two turns where the red and blue lines are the vertical and lateral path segments, respectively, and the dashed curve represents a cross-section of resist profile. The Z-axis corresponds to the resist depth dimension. (b) A test patten of Pattern I.

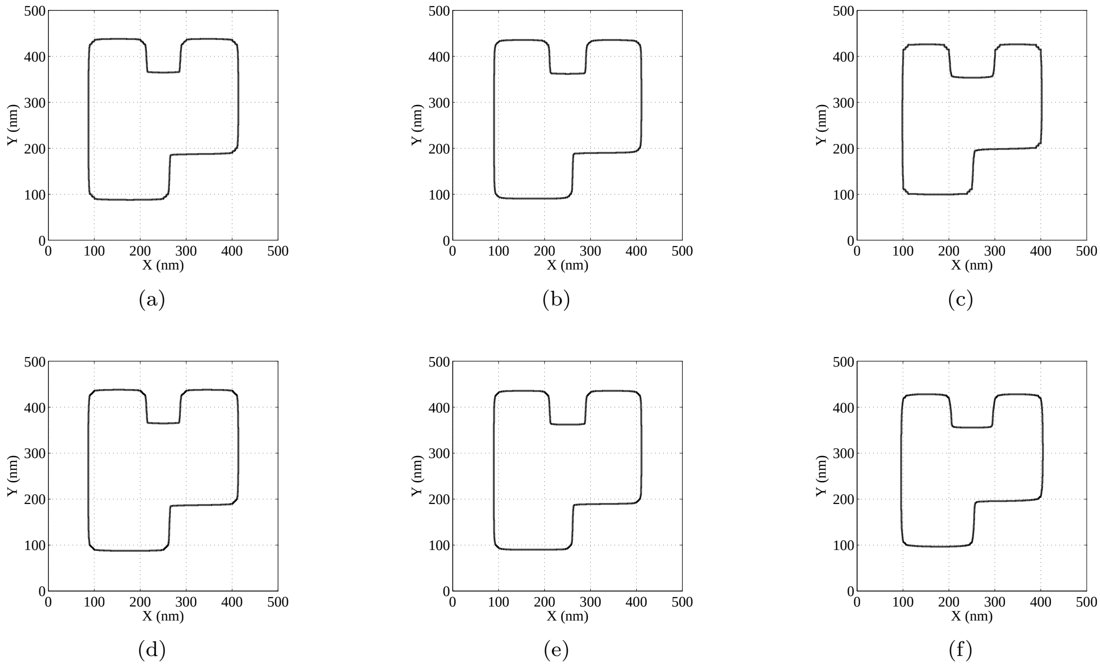


Figure 2: Contours (top view) of resist profiles for Pattern I at the (a) top, (b) middle, and (c) bottom layers of resist by the cell removal method, and at the (d) top, (e) middle, and (f) bottom layers of resist by the path-based method.

Pattern		Cell Removal	Path-based Method (sec)			Speedup		
ID	Size (nm × nm)	Method (sec)	One-Turn	Two-Turn	Adaptive	One-Turn	Two-Turn	Adaptive
I	500 × 500	403.86	6.96	32.52	18.73	58.03	12.42	21.56
II	1000 × 1000	5332.55	27.01	116.07	88.97	197.43	45.94	59.93
III	150 × 1000	160.72	4.89	19.50	12.21	32.82	8.24	13.16
IV	350 × 1000	1050.71	13.92	59.99	38.56	75.48	17.51	27.25
V	550 × 1000	2744.31	22.48	101.25	66.04	122.08	27.11	41.56

Table 1: Simulation time of the cell removal method and the path-based method, measured on a PC with a 2.53 GHz CPU (Intel Core i5-540M) and 2 GB memory.