A Staged Distance-Based Segmentation Method to Enhance Computational Efficiency and Patterning Accuracy in Curvilinear MPC

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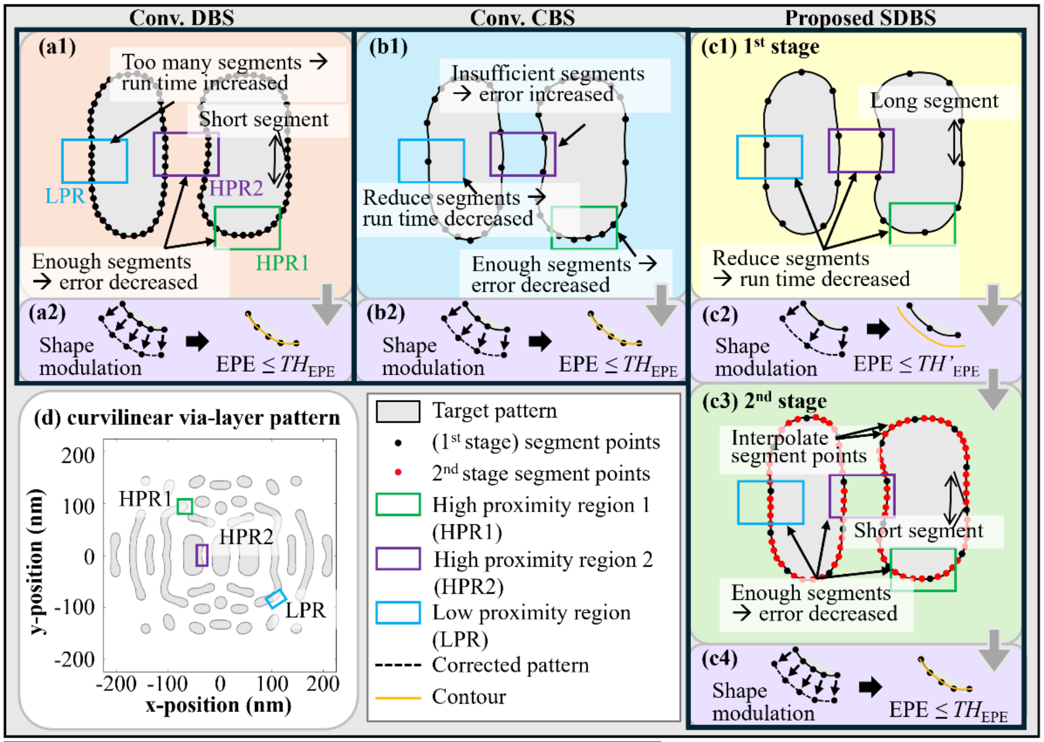
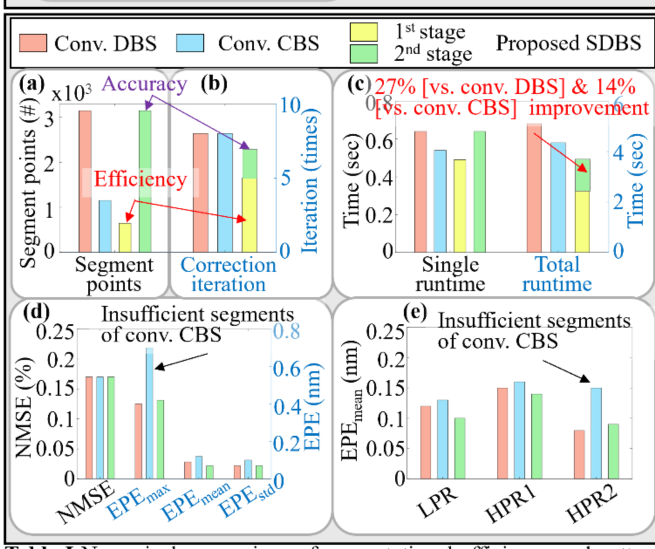
The advances in high numerical aperture (NA) extreme ultraviolet (EUV) lithography and inverse lithography technology (ILT) have driven significant progress in semiconductor manufacturing. Photomask patterns are becoming smaller and more curved, making curvilinear mask process correction (CLMPC) essential. This study introduces a staged distance-based Segmentation (SDBS) method for CLMPC, achieving the shortest correction time and highest patterning accuracy compared to two established segmentation methods. In this study, we: (1) used Monte Carlo simulations to obtain the energy absorption distribution in a 64 nm HSQ resist layer for pattern prediction on a binary high-NA EUV mask; (2) applied three segmentation methods (two conventional and one proposed): patterning-accuracy-oriented distance-based segmentation (DBS)[1], computational-efficiency-oriented curvature-based segmentation (CBS)[2], and the dual-oriented proposed SDBS method, which demonstrates improvements in both patterning accuracy and computational efficiency. Modulating the corresponding segments to achieve edge placement error (EPE) convergence, as shown in Fig. 1; and (3) evaluated each method based on segment points, correction iterations, single and total runtime, normalized mean square error (NMSE), and both overall pattern EPE and EPE in regions of interest (ROIs). In Fig. 1, (a1) the conventional DBS method segments the pattern with fixed-distance segments, and Fig. 1 (a2) shows the process of modulating the corresponding segments achieves EPE convergence at a threshold (TH_{EPE}). This approach provides a high density of segments, achieving high patterning accuracy but resulting in an excessive number of segments in low-proximity regions (LPR), thereby increasing runtime. Fig. 1 (b1) shows the conventional CBS method, which segments the pattern based on curvature, and Fig. 1 (b2) shows the process of modulating the corresponding segments achieves EPE convergence at the TH_{EPE}. This method reduces the number of segments in low-curvature regions, thereby shortening runtime, but at the expense of limited patterning accuracy in high-proximity regions (HPR) with low curvature, such as HPR2. The proposed SDBS method is demonstrated with 2 stages: Fig. 1 (c1) illustrates the 1st stage, which references conventional DBS but uses longer segments to save runtime, and Fig. 1 (c2) shows the process of modulating the corresponding segments achieves EPE convergence at a higher threshold (TH'_{EPE}). In the 2nd stage, as shown in Fig. 1 (c3), shorter segments are introduced to improve patterning accuracy, continuing from the 1st stage, and Fig. 1 (c4) shows the process of modulating the corresponding segments achieves EPE convergence at the lower threshold (TH_{EPE}). Fig. 1 (d) shows a curvilinear via-layer pattern used for correction, with LCR, HCR1, and HCR2 marked. According to simulation results, Fig. 2 compares: (a) segment points, (b) correction iterations, (c) runtime, (d) NMSE, overall pattern EPE, and (e) EPE in ROIs. Table I summarizes the numerical performance metrics. Fig. 2 (a) shows that the 1st stage of proposed SDBS [yellow bar] provides the fewest segment points, resulting in the lowest single runtime in Fig. 2 (c) and a 13% reduction in total iterations compared to conventional DBS [red bar] and conventional CBS [blue bar], as shown in Fig. 2 (b). These lead to a 27% and 14% decrease in total runtime compared to conventional DBS and conventional CBS, respectively. Additionally, Fig. 2 (a) shows that the 2nd stage of proposed SDBS [green bar] achieves a comparable number of segments to conventional DBS and more than conventional CBS, aiming to enhance patterning accuracy. As shown in Fig. 2 (d), NMSE and overall EPE achieved by proposed SDBS are close to conventional DBS values. Compared to conventional CBS, proposed SDBS improves EPE_{max}, EPE_{mean}, and EPE_{std} by 40%, 42%, and 30%, respectively. Furthermore, in ROIs, as illustrated in Fig. 2 (e), proposed SDBS improves EPE_{mean} over conventional CBS by 23% in LPR, 13% in HPR1, and 40% in HPR2. These results suggest that while conventional CBS struggles with severe proximity effects, proposed SDBS consistently maintains high correction patterning accuracy across all conditions. In conclusion, the proposed SDBS method effectively reduces CLMPC runtime while achieving consistent high patterning accuracy, making it a robust solution for CLMPC. Additionally, future work will integrate machine learning to optimize segmentation efficiency and enhance the proposed SDBS method's adaptability to different lithographic conditions.

[1] J. Wang, A. Wei, P. Verma, and W. Wilkinson, in *31st European Mask and Lithography Conference* (SPIE, 2015), pp. 79.

[2] I. Bork, P. Buck, B. Durvasula, V. Liubich, N. Rao, R. Sharma, and M. Zuo, in *Photomask Technology 2021* (SPIE, 2021), pp. 148.



🡅 Fig. 1 Schematic diagram of **(a1)** the conv. DBS method and **(b1)** the conv. CBS method. **(a2)** and **(b2)** illustrate the corresponding segments, modulation, and EPE convergency processes for conv. DBS and CBS methods, respectively. The schematic diagram of the proposed SDBS method including **(c1)** the 1st stage and **(c3)** the 2nd stage procedures. **(c2)** and **(c4)** depict the corresponding segments, modulation, and EPE convergence processes for the 1st stage and 2nd stage procedures, respectively. **(d)** shows a curvilinear via-layer pattern with various region of interests (ROIs).



🡄 Fig. 2 Performance comparison of computational efficiency and patterning accuracy among the three methods, including **(a)** segment points, **(b)** correction iteration, **(c)** single and total runtime, **(d)** NMSE and overall EPE, and **(e)** EPE in ROIs.

Table I Numerical comparison of computational efficiency and patterning accuracy indexes for the conv. DBS, conv. CBS and the proposed SDBS methods, including the relative improvements achieved by the proposed SDBS method over the conv. DBS and conv. CBS methods.

Performance index		Conv. DBS	Conv. CBS	Proposed SDBS (the 1st, 2nd stage)		
				Value	Impro. vs. DBS	Impro. vs. CBS
Segment points (#)		3148	1154	(643, 3148)	(80%, 0%)	(44%, -173%)
Iteration (times)		8	8	7 (5, 2)	13%	13%
Single runtime (sec)		0.64	0.54	(0.49, 0.64)	(23%, 0%)	(9%, -19%)
Total runtime (sec)		**5.11**	**4.35**	**3.72 (2.44, 1.28)**	**27%**	**14%**
NMSE (%)		0.17	0.17	0.17	0%	0%
EPE_{max} (nm)		0.40	0.70	0.42	-5%	40%
EPE_{mean} (nm)	Overall	0.09	0.12	0.07	22%	42%
	LPR	0.12	0.13	0.10	17%	23%
	HPR1	0.15	0.16	0.14	7%	13%
	HPR2	0.08	0.15	0.09	-13%	40%
EPE_{std} (nm)		0.07	0.10	0.07	0%	30%

Runtime improved (Segment points to Total runtime); Maintain the same level accuracy (Impro. vs. DBS, NMSE to EPE_{std}); Accuracy improved (Impro. vs. CBS, NMSE to EPE_{std})