An Image Contrast-Based Curvilinear Mask Process Correction Method for Enhancing Computational Efficiency and Manufacturability

C.H. Liu*, Z.A. Ding, Y.L. Chung, Y.H. Tu, Y.T. Sun, S.K. Wong
Department of Electrical Engineering, National Taipei University, Taipei, Taiwan
E-mail: chliuzzh@mail.ntpu.edu.tw

Inverse lithography technology (ILT) is critical for advanced nodes, especially in extreme ultraviolet (EUV) lithography, but complex EUV mask structures and curvilinear (CL) ILT patterns cause imaging distortions. This study proposes a novel image contrast-based (CTB) CL mask process correction (MPC) method, which maintains accuracy while reducing computation time and ensuring manufacturability. Fig.1 (a1)-(a3) show dissection points distribution for conventional DB[1], conventional CB[2], and proposed CTB methods. The DB method uses a fixed distance to acquire DP. As shown in the gray-highlighted region of Fig. 1 (a2), the CB method uses cumulative local curvature to determine DP. However, in high curvature region (HCR) and high proximity region (HPR), insufficient DP results in reduced correction accuracy. Fig. 1 (a3) and (c) show the CTB method, where the contrast index (S_{idx}) of the image is first obtained, and the DP distribution is determined based on a contrast threshold (TH_{S}) and point count threshold (N_{S}). TH_{S} and N_{S} are derived through optimized iteratively, aiming to balance accuracy and point count while maintaining manufacturability. Fig. 1(b) shows an algorithm of the CTB method: the energy slope is first obtained in Eq. 1 and normalized to a 0-1 range, then a square root transformation is applied in Eq. 2 to amplify values near 1, resulting in S_{idx}. Then execute shape correction[3] until EPE converge. As simulation we performed the following: (1) calculated the absorb energy distribution for binary high numerical aperture EUV mask in 50 keV by Monte Carlo simulation; (2) compared EPE, computation time and manufacturability performance for curvilinear pattern with three methods under specific simulation conditions: A zero-width beam size, 0.1 nm grid size, and a 0.4 nm error criterion. According to the simulation results, Fig. 2 shows the DP distribution, corrected pattern, and contour after correction within a CL metal layer for the conventional DB, conventional CB, and proposed CTB methods. The DB method has a higher DP count, resulting in a corrected pattern with numerous jogs, making the pattern less smooth and reducing manufacturability; CB method lacks sufficient DP in HPR and low curvature region (LCR) [dotted red circle], causing convergence issues. In contrast, the CTB method provides more DP than the CB method but fewer than the DB method in both HPR and LCR, making it easier to achieve convergence. Table I presents numerical result, including accuracy [EPE max, mean and sigma], computation time [count of DP, iteration and runtime] and manufacturability. for DB, CB, and the proposed CTB methods, where EPE is calculated per pixel along the pattern edge. As for EPE mean and EPE sigma, CTB method improves by 33% and 29%, respectively. While DB method performs better in EPE max, it consumes significant runtime for shape correction. On the other hand, although CB method has an advantage in DP count, it fails to achieve EPE convergence during shape correction. Due to CTB's lower point count, iteration count and runtime improve by 45% and 20% over DB, respectively. Additionally, manufacturability, measured as the average distance between DPs, shows a 328% improvement for DB. In conclusion, the proposed CTB method optimizes DP distribution, improving manufacturability, reducing computation time, and addressing convergence issues in low-curvature but high-proximity regions while maintaining pattern accuracy. In future work, we will continue to explore methods to enhance manufacturability.

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[1] I. Bork et al., in *Photomask Technology 2017* (SPIE, 2017), Vol. 10451.

[2] A. Kaneko et al., in *Photomask Technology 2023* (SPIE, 2023), Vol. 12751.

[3] C. H. Liu et al., in *The 36th International Microprocesses and Nanotechnology Conference (MNC 2023)*, 17P-1-5.

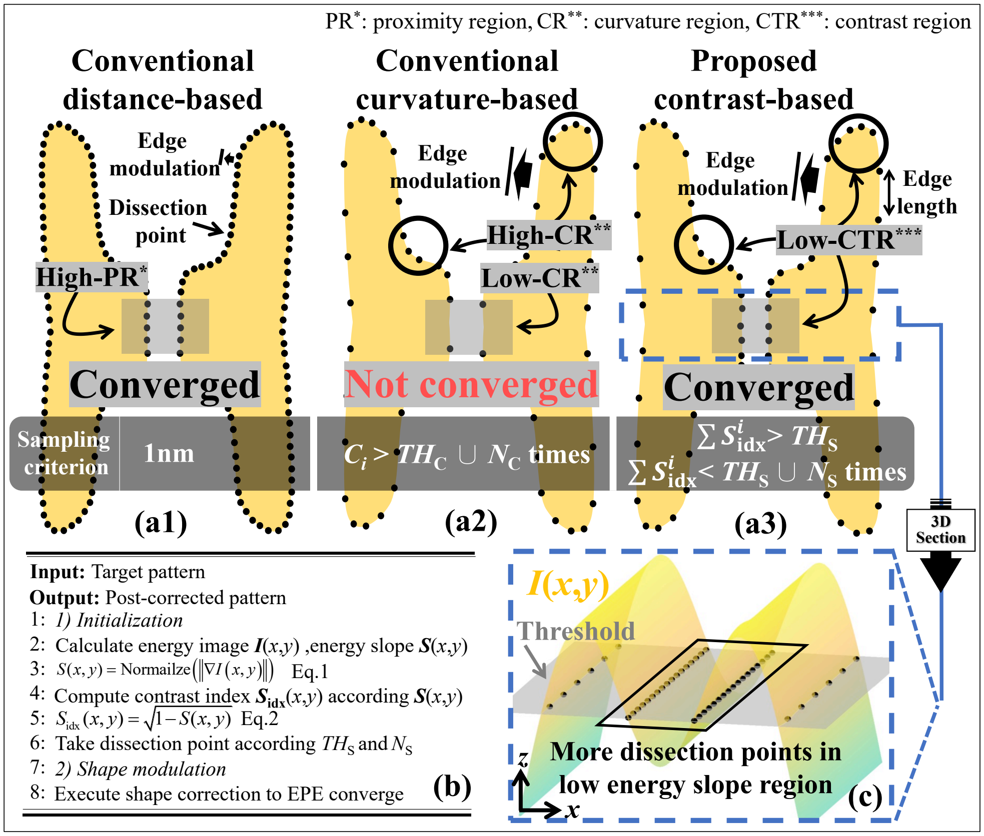

Fig. 1 Impact of dissection point (DP) density on HPR correction: (a1) conv. distance-based (DB), (a2) conv. curvature-based (CB), and (a3) the proposed contrast-based (CTB) methods. (b) Algorithm of proposed CTB method. (c) Energy image and DP distribution of the proposed CTB method.

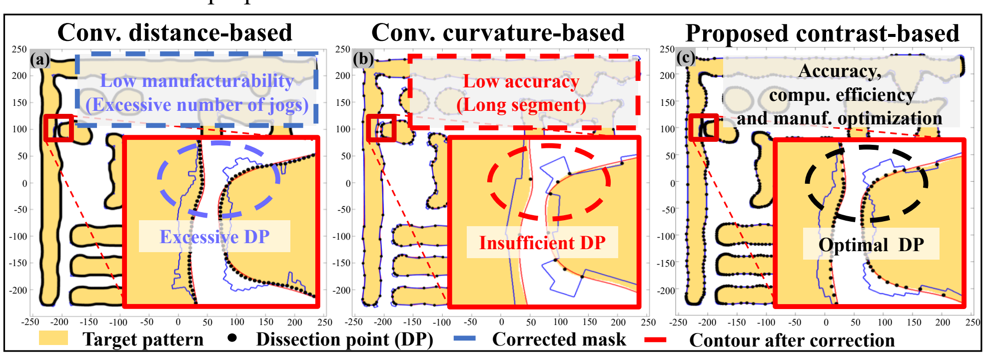

Fig. 2 Correction results in HPR using three CL-MPC methods: (a) conv. DB method (converged with excessive DP) (b) conv. CB method (not converged due to insufficient DP), and (c) the proposed CTB method (converged with optimal DP).

Table 1 Comparison of the pattern fidelity and computational efficiency improvements among the conv. DB, CB and the proposed CTB methods.

	Performance index	Conv. DB	Conv. CB	Proposed CTB	Improvement vs. Conv. DB
Accuracy	EPE max (nm)	0.40	1.30	0.50	-25%
	EPE mean (nm)	0.24	0.22	0.16	33%
	EPE sigma (nm)	0.17	0.20	0.12	29%
Compu. time	Dissection points (#)	6398	524	1263	80%
	Iteration (Times)	20	50	11	45%
	Runtime (sec/iteration)	13.14	15.75	10.53	20%
	Manufacturability (nm)	1.02	5.65	4.37	328%