Accelerated Curvilinear Mask Process Correction via Direct Energy-based Modulation

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As high-numerical-aperture (high-NA) extreme ultraviolet (EUV) lithography and inverse lithography technology continue to advance, mask patterns are becoming smaller and curved, making curvilinear mask process correction (CL-MPC) essential. The conventional dose-based correction[1] process requires convolution with the PSF to translate updates in the corrected dose distribution into corresponding energy corrections, this indirect process that requires more iterations and leads to long runtime. Therefore, this study introduces an direct energy-based correction method to enhance computational efficiency while maintaining pattern fidelity.

In this study, we (1) adopted a parametric point spread function (PSF) model under a 50 keV acceleration voltage to obtain the absorbed-energy distribution within a 64 nm HSQ resist layer for high-NA EUV mask pattern prediction; (2) applied both the conventional dose-based[1] and the proposed energy-based correction method, iterating until the edge-placement error (EPE) converged, as illustrated in Fig. 1; and (3) compared the two methods in terms of computational efficiency, patterning accuracy, and anti-process variation ability performance. Figure 1(a) compares the two correction workflows. Both begin with an electron beam exposure simulation and iteratively apply correction method to reduce the EPE. The conventional dose-based method (dashed line) modulates the dose and relies on convoluting with PSF to translate these changes into the energy domain; this indirect linkage often weakens the effectiveness of each update, resulting in slow EPE convergence. In contrast, the proposed energy-based method (solid line) performs the energy modulation directly in the energy domain and then applies deconvolution with PSF to obtain the corresponding dose. As shown in Fig. 1(b), the energy (purple line) in (b1) exhibits a mismatch between the edge energy and the threshold. In (b2), we shift the energy distribution according to the nearest edge (red arrows) so that the corrected edge energy aligns precisely with the threshold. As illustrated in (b3), an ideal energy distribution (green line) corresponding to EPE = 0 is formed. The adjusted energy is then deconvoluted with PSF into a corrected dose distribution, and the process iterates until EPE converges. Because the correction directly targets the desired energy and convolution/deconvolution behave nearly inversely, each update is transferred more accurately into the next simulation, allowing the energy-based method to achieve significantly faster EPE convergence.

Figure 2 compares the corrected dose distributions generated by (a1)–(a2) the conventional method and (b1)–(b2) the proposed method. The proposed method produces a smoother dose distribution without abrupt variations near the pattern edges. This is because the dose is obtained via a deconvolution process, which automatically optimizes the dose across the entire pattern rather than adjusting only the edge regions to meet the corrected energy requirement. As a result, the proposed method reduces the need for precise process control during fabrication. In Table I, the proposed method reduces the number of iterations by 65% and the total runtime (single runtime × number of iterations) by 64% compared with the conventional method, while both methods achieve similarly low normalized mean square error (NMSE) and EPE. The slightly higher process variation band (PVB) and lower energy slope observed in the proposed method can be attributed to the deconvolution step, which computes a dose distribution that satisfies the corrected energy over the entire pattern rather than adjusting only the edge regions. In conclusion, the proposed energy-based correction provides a more direct and efficient approach for CL-MPC without sacrificing accuracy.

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[1] H. Zable et al., "GPU-accelerated inline linearity correction pixel-level dose correction", *Proceeding of SPIE*, 2017, vol. 10454, pp. 76-84

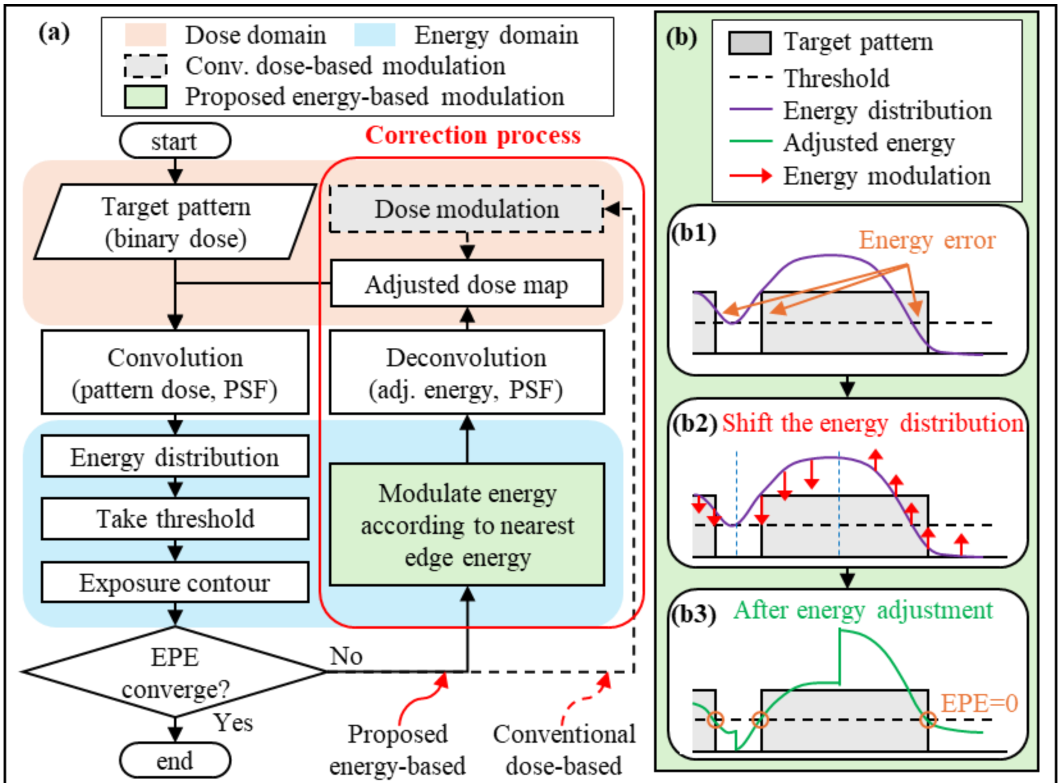

Fig. 1 (a) Flow chart of conv. dose-based and proposed energy-based correction method. (b) Detail of proposed energy modulation method, (b1) exhibits a mismatch between the edge energy and the threshold, (b2) shift the energy distribution according to the nearest edge, (b3) get a modulated energy distribution so that the corrected edge energy aligns with the threshold.

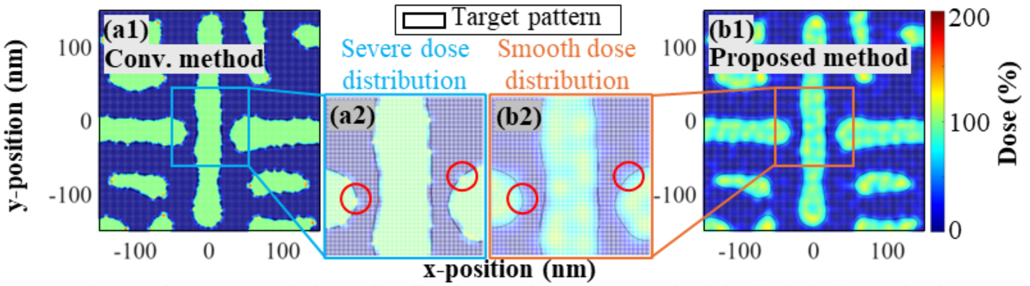

Fig. 2 Shows the corrected dose distributions. The conv. method in (a1)-(a2) results in more severe dose distribution near the pattern edges than the proposed method in (b1)-(b2).

Table I Numerical comparison of conventional and proposed correction method, including computational efficiency, patterning accuracy and anti-process variation ability.

	Conv. dose-based	Proposed energy-based	Improv.
Iteration (times)	17	6	65%
Single runtime (sec)	76.46	78.67	-3%
Total runtime (sec)	1299.82	472.02	64%
NMSE (%)	0.6	0.6	0%
EPE_{max} (nm)	0.41	0.36	12%
EPE_{mean} (nm)	0.06	0.06	0%
EPE_{std} (nm)	0.06	0.06	0%
PVB_{mean} (nm)	2.07	2.54	-23%
Energy $slope_{mean}$ (a.u. / nm)	0.05	0.04	-20%

Significantly lower runtime & iteration

Comparable low error