# Generalized Performance Optimization for Massively-Parallel Electron-beam Systems

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In a massively-parallel e-beam system (MPES), there are a large number of programmable beams of which the optimal use is critical for maximizing the efficiency of the system. In our previous study of proximity effect correction (PEC) on the MPES, the critical dimension (CD) error and line edge roughness (LER) were minimized by adjusting the feature size to be exposed and the dose given in each region of a feature. In another study, a method to reduce the exposing time while still ensuring a near-optimal PEC result was developed. The maximum dose difference between two regions of a feature was judiciously decreased after first obtaining the optimal linewidth reduction ($\Delta W$) and spatial dose distribution for the PEC. This method designed with the emphasis on the PEC and simplicity may miss the optimal result due to the fixed order of performance metrics considered and recursive effects between the metrics and between iterations, especially when multiple performance metrics are to be taken into account. Therefore, it is desired to develop an adaptive optimization method which can handle any combination of performance metrics in a cost function and the recursive effect. All the metrics in the cost function are considered in each iteration to adjust the control parameters. Also, an adjustment factor is used in each iteration to pre-compensate for the recursive effect.

The performance of the new optimization method has been analyzed, being compared to the previous method, via simulation. In the simulation, a line/space pattern of $4.5 \times 4.5\mu\text{m}^2$ is considered with varying feature size and space. The transfer function (TF) of a beam is modeled based on the 3-D point spread function generated using the Monte Carlo simulation for the substrate system of 100nm PMMA on Si and the beam energy of 50 keV where the TF mainly includes the forward scattering of electrons. The beam size is $10 \times 10\text{nm}^2$ with both sharp and broad TFs considered, i.e., the blurring factor of 1nm and 4nm.

Tables 1 and 2 provide the simulation results for the case of all the performance metrics (in a cost function) equally weighted and the case of four different cost functions, respectively. It is clear that the new optimization method achieves a significant improvement over the previous ("old") method. In this paper, a comprehensive set of optimization results will be presented with a detailed discussion.

| Method | $W$ (nm) | $\sigma_t$ (nm) | Type | $\Delta W$ (nm) | Dose ratio | CD error (nm) | LER (nm) | $t_{exp}$ (cycle) | Cost function value |
|---|---|---|---|---|---|---|---|---|---|
| Old | 50 | 1 | A | 4 | 1.1:2.7:5.1:2.7:1.1 | 0.32 | 0.16 | 902 | 1.312 |
| New | 50 | 1 | A | 4 | 1.3:2.6:5.1:2.6:1.3 | 0.31 | 0.16 | 864 | 1.243 |
| Old | 50 | 1 | M | 4 | 1.1:4.9:1.6:4.9:1.1 | 0.32 | 0.17 | 1009 | 1.350 |
| New | 50 | 1 | M | 4 | 1.2:4.9:1.4:4.9:1.2 | 0.32 | 0.17 | 911 | 1.262 |
| Old | 50 | 1 | V | 4 | 3.3:2.1:2.0:2.1:3.3 | 0.36 | 0.17 | 994 | 1.398 |
| New | 50 | 1 | V | 4 | 3.1:2.1:1.9:2.1:3.1 | 0.38 | 0.18 | 804 | 1.295 |
| Old | 50 | 4 | A | 10 | 2.9:4.4:6.5:4.4:2.9 | 0.44 | 0.24 | 1226 | 1.554 |
| New | 50 | 4 | A | 8 | 1.4:3.7:9.5:3.7:1.4 | 0.39 | 0.22 | 1095 | 1.377 |
| Old | 50 | 4 | M | 10 | 3.1:6.0:4.4:6.0:3.1 | 0.44 | 0.23 | 1283 | 1.596 |
| New | 50 | 4 | M | 8 | 1.5:7.3:3.4:7.3:1.5 | 0.40 | 0.22 | 1137 | 1.398 |
| Old | 50 | 4 | V | 10 | 4.5:3.2:1.8:3.2:4.5 | 0.37 | 0.23 | 1244 | 1.622 |
| New | 50 | 4 | V | 10 | 4.2:3.2:1.8:3.2:4.2 | 0.39 | 0.22 | 1102 | 1.587 |
| Old | 150 | 1 | A | 4 | 3.3:6.1:14.4:6.1:3.3 | 0.37 | 0.16 | 2568 | 1.701 |
| New | 150 | 1 | A | 4 | 3.2:6.1:14.1:6.1:3.2 | 0.36 | 0.16 | 2483 | 1.649 |
| Old | 150 | 1 | M | 4 | 3.3:10.2:5.4:10.2:3.3 | 0.34 | 0.18 | 2735 | 1.618 |
| New | 150 | 1 | M | 4 | 3.2:9.5:5.7:9.5:3.2 | 0.32 | 0.18 | 2605 | 1.486 |
| Old | 150 | 1 | V | 4 | 10.1:6.3:4.3:6.3:10.1 | 0.33 | 0.19 | 2812 | 1.686 |
| New | 150 | 1 | V | 4 | 10.1:6.3:4.8:6.3:10.1 | 0.30 | 0.18 | 2832 | 1.604 |
| Old | 150 | 4 | A | 10 | 3.9:7.4:8.7:7.4:3.9 | 0.44 | 0.21 | 4688 | 1.825 |
| New | 150 | 4 | A | 8 | 2.2:4.7:13.2:4.7:2.2 | 0.40 | 0.22 | 3268 | 1.611 |
| Old | 150 | 4 | M | 10 | 4.1:11.1:9.0:11.1:4.1 | 0.40 | 0.19 | 4252 | 1.738 |
| New | 150 | 4 | M | 8 | 2.2:6.9:5.6:6.9:2.2 | 0.38 | 0.23 | 3344 | 1.561 |
| Old | 150 | 4 | V | 12 | 12.9:10.2:4.8:10.2:12.9 | 0.33 | 0.21 | 4902 | 1.621 |
| New | 150 | 4 | V | 10 | 7.5:4.8:4.2:4.8:7.5 | 0.35 | 0.23 | 3823 | 1.474 |

Table 1: Th optimization results with the cost function $C = Error_{CD} + LER + t_{exp}$. $W$ is the feature width, $\sigma_t$ the blurring factor of beams, and $t_{exp}$ the exposing time. The beam interval is 200nm and the spacing between two features is 40nm. Three types of dose distributions over 5 regions cross the feature width are considered, i.e., A-type (the highest dose in the center region and monotonically decreasing toward the edge regions), M-type (the highest dose in the middle of center and edge regions) and V-type (the highest dose in the edge regions and gradually decreasing toward the center region).

| Cost function | Method | $\Delta W$ (nm) | Dose ratio | CD error (nm) | LER (nm) | $t_{exp}$ (cycle) | Cost function value |
|---|---|---|---|---|---|---|---|
| $C1$ | Old | 10 | 1.9:3.4:5.5:3.4:1.9 | 0.44 | 0.24 | 1226 | 1.554 |
| $C1$ | New | 8 | 1.4:3.7:9.5:3.7:1.4 | 0.39 | 0.22 | 1095 | 1.377 |
| $C2$ | Old | 10 | 1.9:3.7:4.7:3.7:1.9 | 0.47 | 0.24 | 1009 | 2.351 |
| $C2$ | New | 6 | 1.3:2.4:10.5:2.4:1.3 | 0.49 | 0.24 | 791 | 1.977 |
| $C3$ | Old | 10 | 1.9:4.0:4.1:4.0:1.9 | 0.52 | 0.25 | 994 | 3.397 |
| $C3$ | New | 4 | 1.2:1.9:11.1:1.9:1.2 | 0.56 | 0.26 | 714 | 2.718 |
| $C4$ | Old | 10 | 1.9:4.0:4.1:4.0:1.9 | 0.52 | 0.25 | 994 | 3.845 |
| $C4$ | New | 2 | 1.0:1.2:12.2:1.2:1.0 | 0.61 | 0.31 | 675 | 2.884 |

Table 2: The optimization results with four different cost functions, $C1 = Error_{CD} + LER + t_{exp}$, $C2 = 0.75Error_{CD} + 0.75LER + 1.5t_{exp}$, $C3 = 0.5Error_{CD} + 0.5LER + 2t_{exp}$ and $C4 = 0.25Error_{CD} + 0.25LER + 2.5t_{exp}$. The feature width is 50nm, the blurring factor of beams is 4nm, the beam interval is 200nm and the spacing between two features is 40nm. $t_{exp}$ represents the exposing time. The A-type dose distribution (the highest dose in the center region and monotonically decreasing toward the edge regions) is considered.