## A Non-Delta-Chrome OPC Methodology for Nonlinear Process Models

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Delta-chrome optical proximity correction (OPC) has been widely adopted in lithographic patterning for semiconductor manufacturing.<sup>1-6</sup> During each OPC iteration, a predetermined amount of chrome is added or subtracted from the mask pattern. The exposure intensity signal error (ISE) change or the edge placement error (EPE) change of printed contour is then calculated based on process models with Kirchhoff or thin mask transmission. Linear approximation is used to predict the proper chrome change to remove the correction error. This approximation can be very fast and effective, but must be performed iteratively to capture interactions between feature changes. As integrated circuit (IC) design shrinks to the deep sub-wavelength regime, previously ignored nonlinear process effects, especially three-dimensional (3D) or thick mask effects, become significant for accurate prediction and correction of proximity effects.<sup>8</sup> These nonlinearities challenge the delta-chrome OPC methodology. The model responses to the mask geometry perturbation by linear approximation are inaccurate, as shown in Fig. 1. A non-delta-chrome OPC methodology with ISE-based feedback compensation is proposed. It determines the proper chrome change based on ISE without intensive computation of mask perturbation response. Its effectiveness in improving patterning fidelity and runtime with the presence and absence of nonlinear effects is examined with a practical 50-nm circuit layout comprising of seven critical layers with a minimum pitch size of 125 nm. Despite the presence and the absence of nonlinear effects, our results show the proposed non-delta-chrome OPC outperforms the delta-chrome one in terms of patterning fidelity and runtime, as summarized in Table 1. The results also demonstrate that nonlinear process models limit the delta-chrome OPC methodology.

<sup>1</sup> N. Cobb et al., Proc. SPIE **2621**, 534–545 (1995).

<sup>2</sup> N. Cobb et al., Proc. SPIE **4889**, 1281–1292 (2002).

<sup>3</sup> B. Painter et al., Proc. SPIE **5377**, 1198–1206 (2004).

<sup>4</sup> N. Cobb et al., Proc. SPIE **5853**, 693–702 (2005).

<sup>5</sup> S. Choi et al., Proc. SPIE **6154**, 61540P (2006).

<sup>6</sup> Y. Chen et al., Proc. SPIE **6520**, 65204C (2007).

<sup>7</sup> Y. Su et al., Proc. SPIE 6924, 69243Z (2008).

<sup>8</sup> L. Melvin et al., Proc. SPIE 6792, 6792D7 (2008).



Fig. 1. Linear properties of delta-chrome OPC methodology for the cases of thin mask transmission:  $\bigcirc = (\triangle + (B))$ , and thick mask transmission:  $\bigcirc \neq (\triangle + (B))$ . This implies that mask perturbation responses by linear approximation such as MEEF =  $\triangle EPE / \triangle chrome or Slope = \triangle ISE / \triangle chrome are inaccurate, where MEEF is the mask error enhancement factor, EPE is the edge placement error, and ISE is the intensity signal error.$ 

Table 1. OPC methodology comparison for 45-nm process model with thin mask transmission and 32-nm process model with thick mask transmission. "# Seg" columns denote the total number of segments assigned to each layer, " $\mu_{|\text{EPE}|}$ " columns denote the mean of absolute EPEs, " $\sigma_{|\text{EPE}|}$ " columns denote the standard deviation of absolute EPEs, "# OTS" columns denote the number of out-of-tolerance segments (|EPE| > 2 nm), "RT" columns denote the runtime, "# OTS Reduc" columns denote the reduction of out-of-tolerance segment numbers, and "RT Reduc" columns denotes the runtime reduction.

52-nm half-pitch-equivalent process model with thin mask transmission											
		Delta-chrome OPC				Non-delta-chrome OPC				# OTS	RT
Layer #	# Seg	$\mu_{ \text{EPE} }$	$\sigma_{ \text{EPE} }$	# OTS	RT	$\mu_{ \text{EPE} }$	$\sigma_{ \text{EPE} }$	# OTS	RT	Reduc	Reduc
		(nm)	(nm)		(s)	(nm)	(nm)	_	(s)	(70)	(%)
1:0	30702	0.32	0.35	8	36	0.32	0.34	7	31	0.00	13.89
2:0	59255	0.43	0.67	1559	58	0.42	0.70	997	52	0.95	10.34
3:0	14436	0.13	0.11	0	88	0.28	0.19	0	22	0.00	75.00
4:0	69894	0.57	0.80	2592	69	0.53	0.65	3235	55	-0.92	20.29
5:0	3448	0.12	0.11	0	33	0.24	0.17	0	16	0.00	51.52
6:0	26317	0.36	0.39	1	33	0.36	0.38	1	28	0.00	15.15
8:0	22641	0.43	0.41	1	31	0.45	0.38	4	28	-0.01	9.68
Average		0.34	0.41			0.37	0.40			0.00	27.98
	0			$\sim$					$\sim$		
	<u> </u>	40-nm	n half-pitch	n-equivale	nt process	model wit	h thick ma	isk transmi	ission		
		40-nm	half-pitch Delta-chr	n-equivale ome OPC	nt process	model wit	h thick ma lon-delta-c	isk transmi hrome OP	ission C	# OTS	RT
Layer #	# Seg	40-nm μ <sub>[EPE]</sub>	n half-pitch Delta-chr <sub> </sub>	n-equivale ome OPC	nt process RT	model with $N$	h thick ma on-delta-c	sk transmi	ission C RT	# OTS Reduc	RT Reduc
Layer #	# Seg	40-nm $\mu_{\rm [EPE]}$ (nm)	n half-pitch Delta-chr <i>O</i> <sub>[EPE]</sub> (nm)	n-equivale ome OPC # OTS	nt process RT (s)	model with $\frac{N}{\mu_{ \text{EPE} }}$ (nm)	h thick matching $\sigma_{\rm EPE }$ (nm)	sk transmi hrome OP # OTS	ission C RT (s)	# OTS Reduc (%)	RT Reduc (%)
Layer #	# Seg 31096	$40-nm$ $\mu_{ \text{EPE} }$ (nm) 26.0	half-pitch Delta-chr $\sigma_{ EPE }$ (nm) 81.8	n-equivale ome OPC # OTS 31087	RT (s) 100	model with $\mu_{ \text{EPE} }$ (nm) 0.20	h thick ma on-delta-c $\sigma_{ EPE }$ (nm) 0.25	sk transmi hrome OP # OTS 8	C RT (s) 88	# OTS Reduc (%) 99.95	RT Reduc (%) 12.00
Layer #	# Seg 31096 58866	40-nm $\mu_{ EPE }$ (nm) 26.0 1434.7	half-pitch Delta-chr $\sigma_{EPE }$ (nm) 81.8 863.1	n-equivale ome OPC # OTS 31087 58524	RT (s) 100 132	model witt $ \frac{\mu_{\text{EPE} }}{(\text{nm})} $ 0.20 0.20	h thick ma fon-delta-c $\sigma_{ EPE }$ (nm) 0.25 0.24	sk transmi hrome OP # OTS 8 5	C RT (s) 88 103	# OTS Reduc (%) 99.95 99.41	RT Reduc (%) 12.00 21.97
Layer # 1:0 2:0 3:0	# Seg 31096 58866 14436	40-nm μ <sub>EPE</sub> (nm) 26.0 1434.7 1964		n-equivale ome OPC # OTS 31087 58524 14436	RT (s) 100 132 55	$\frac{M}{\mu_{\rm [EPE]}} \frac{M}{(\rm nm)} = 0.20$	h thick ma fon-delta-c $\sigma_{\text{[EPE]}}$ (nm) 0.25 0.24 0.06	sk transmi hrome OP # OTS 8 5 0	RT         (s)           88         103           43         43	# OTS Reduc (%) 99.95 99.41 100.00	RT Reduc (%) 12.00 21.97 21.82
Layer # 1:0 2:0 3:0 4:0	# Seg 31096 58866 14436 68938	40-nm μ <sub>EPE</sub> (nm) 26.0 1434.7 1964 16.4	half-pitch Delta-chr $\sigma_{\text{[EPE]}}$ (nm) 81.8 863.1 0.0 72.7	n-equivale ome OPC # OTS 31087 58524 14436 64826	RT (s) 100 132 55 137	model with $\mu_{\rm [EPE]}$ (nm) 0.20 0.20 0.07 0.26	h thick mathematical formula for the second	sk transmi hrome OP # OTS 8 5 0 359	C RT (s) 88 103 43 83	# OTS Reduc (%) 99.95 99.41 100.00 93.51	RT Reduc (%) 12.00 21.97 21.82 39.42
Layer # 1:0 2:0 3:0 4:0 5:0	# Seg 31096 58866 14436 68938 3448	40-nm <sup>µ</sup> <sub>EPE </sub> (nm) 26.0 1434.7 1964 16.4 1964	half-pitch Delta-chr $\sigma_{EPE }$ (nm) 81.8 863.1 0.0 72.7 0.0	n-equivale ome OPC # OTS 31087 58524 14436 64826 3448	RT (s) 100 132 55 137 36	$\frac{\mu_{\rm [EPE]}}{(\rm nm)}$ 0.20 0.20 0.07 0.26 0.07	h thick mathematical formula for the second	sk transmi hrome OP # OTS 8 5 0 359 0	C RT (s) 88 103 43 83 33	# OTS Reduc (%) 99.95 99.41 100.00 93.51 100.00	RT Reduc (%) 12.00 21.97 21.82 39.42 8.33
Layer # 1:0 2:0 3:0 4:0 5:0 6:0	# Seg 31096 58866 14436 68938 3448 26292	40-nm <u>µ<sub>EPE </sub> (nm) 26.0 1434.7 1964 16.4 1964 28.5</u>		n-equivale ome OPC # OTS 31087 58524 14436 64826 3448 25781	RT (s) 100 132 55 137 36 61	$\begin{array}{c} \text{model wit} \\ \hline \\ \\ \hline \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ $	h thick ma fon-delta-c $\sigma_{EPE }$ (nm) 0.25 0.24 0.06 0.32 0.05 0.17	sk transmi hrome OP # OTS 8 5 0 359 0 0 0	C RT (s) 88 103 43 83 33 54	# OTS Reduc (%) 99.95 99.41 100.00 93.51 100.00 98.06	RT Reduc (%) 12.00 21.97 21.82 39.42 8.33 11.48
Layer # 1:0 2:0 3:0 4:0 5:0 6:0 8:0	# Seg 31096 58866 14436 68938 3448 26292 22856	$\begin{array}{c} 40\text{-nm} \\ \mu_{\text{[EPE]}} \\ (\text{nm}) \\ 26.0 \\ 1434.7 \\ 1964 \\ 16.4 \\ 1964 \\ 28.5 \\ 26.1 \end{array}$		n-equivale ome OPC # OTS 31087 58524 14436 64826 3448 25781 22841	RT (s) 100 132 55 137 36 61 86	$\begin{array}{c} \text{model wit} \\ \hline \\ \\ \hline \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ $	h thick ma fon-delta-c $\sigma_{EPE }$ (nm) 0.25 0.24 0.06 0.32 0.05 0.17 0.19	sk transmi hrome OP # OTS 8 5 0 359 0 0 15	C RT (s) 88 103 43 83 33 54 75	# OTS Reduc (%) 99.95 99.41 100.00 93.51 100.00 98.06 99.87	RT Reduc (%) 12.00 21.97 21.82 39.42 8.33 11.48 12.79