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BEAM: Bidirectional MEEF-Driven Mask Optimization for Photonic Integrated Circuits

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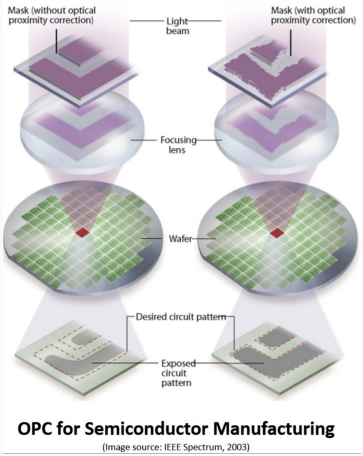
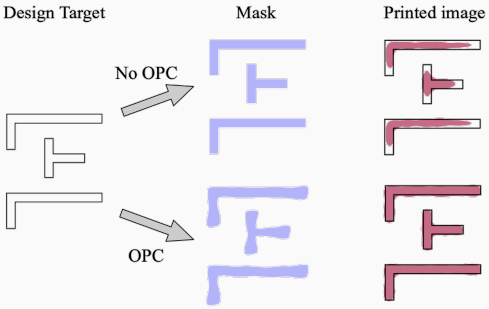
Background: Optical Proximity Correction

Optical Proximity Correction

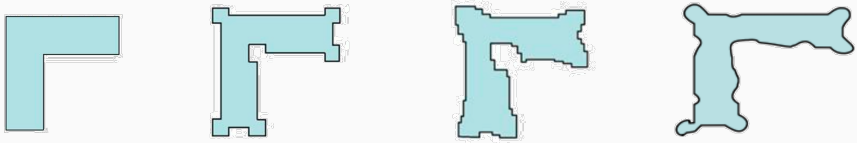
- Light proximity effect leads to image distortion.
- Conduct optical proximity correction (OPC) before lithography.

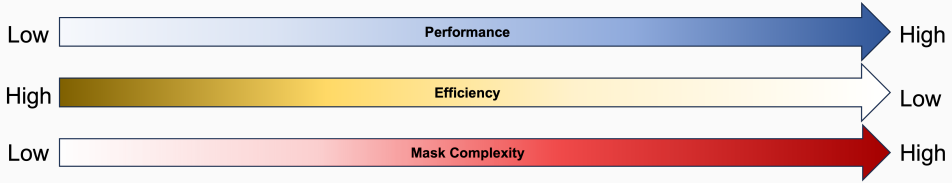




OPC Methods for Conventional Designs

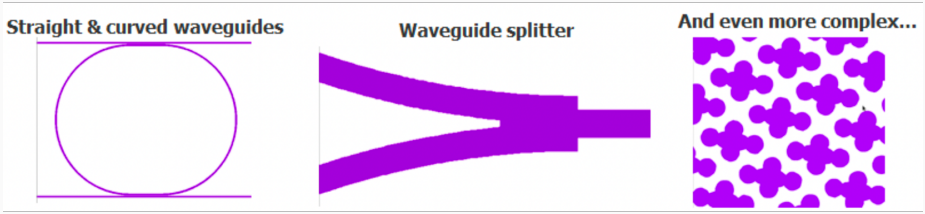
- Rule-based OPC
  - Empirical rule table
  - No litho-simulation
- Model-based OPC
  - Edge fragmentation
  - With litho-simulation
  - Segment in & out
- Inverse lithography
  - Image translation
  - With litho-simulation
  - Forward & backward

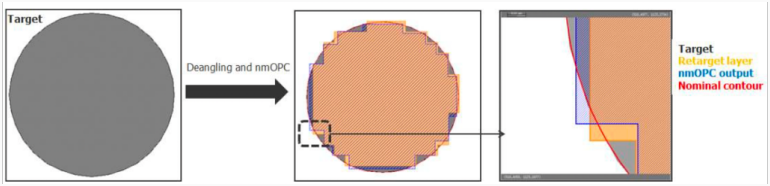




OPC for Curvilinear Designs

- A brute-force idea: Manhattanize at first





- Pros: lightweight representation, compatible with existing OPC methods
- Cons: Extra distortions to target pattern

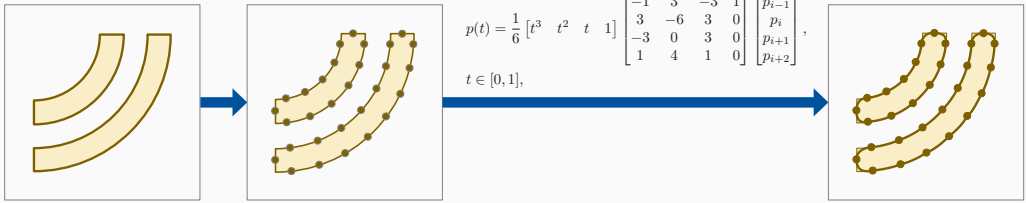
OPC for Photonic IC Designs

Problems of OPC on PIC Designs

- Problem 1: Proper representation of mask patterns
  - Conventionally: GDSII, piece-wise linear approximation with vertices
  - Pixelized matrix: storage & scalability issue
- Problem 2: Mask quality evaluation
- Problem 3: OPC solver design
  - Optimization variable composed with mask representation
  - Solve 2-D pattern displacement

Curvilinear Mask Representation

- Spline curves + control points, e.g. B-spline



- Light-weighted
- Align with target boundaries

Mask Quality Evaluation

- Two primary metrics: Edge placement error (EPE) and Process Variation band (PV band)
- Edge placement error (EPE): no explicit measuring direction on curvy edges

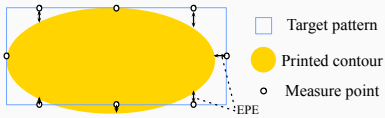


Figure 1: EPE on conventional layouts: horizontal/vertical displacement

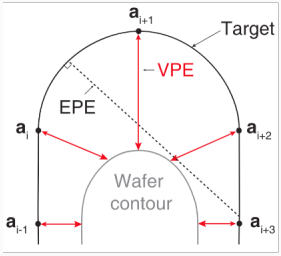


Figure 2: Curvilinear EPE measurement: minimum distance

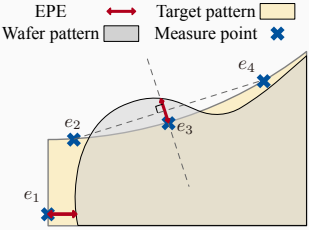
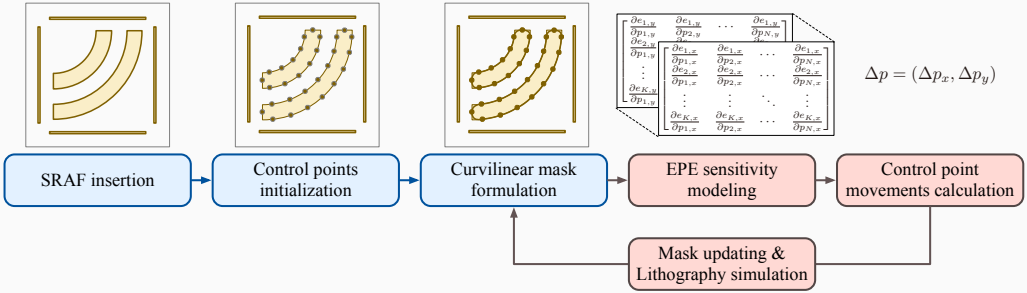


Figure 3: Ours: normal to segment between neighbors

Pipeline

- Set up: SRAF insertion, mask initialization with spline curves
- OPC solver: follow the mainstream MEEF-based OPC routine, but tailored for PIC layouts
- Design algorithm to move the control points, so that the target image can be precisely transferred to the wafer



OPC Solver: MEEF-driven

- Mask Error Enhancement Factor (MEEF)[1]
  - Describe the relation between changes in the mask pattern and the corresponding wafer pattern:

$$\text{MEEF} = \frac{\partial e}{\partial m} \tag{1}$$

- Reformulate Manhattan-style OPC: break edges into fragments, minimize EPE by assigning segment movements.
- Jacobian matrix, describes a linearized model, mapping edge movement to EPE changes by partial derivatives
- *K*: # EPE measure points; *N*: # segments

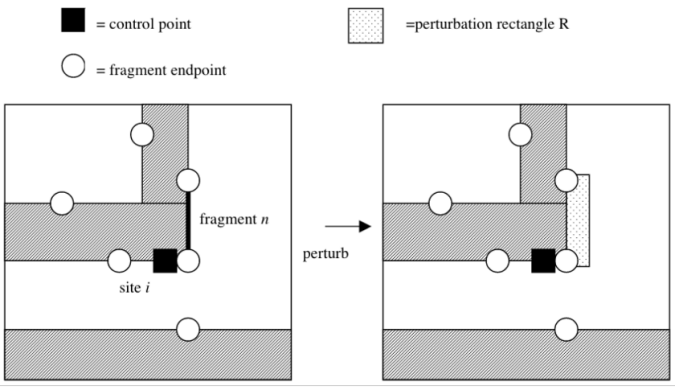
$$\text{EPE} \approx \text{EPE}_0 + \text{MEEF} \times \Delta\text{edge},$$

$$\text{MEEF} = \frac{\partial e}{\partial m} = \begin{bmatrix} \frac{\partial e_1}{\partial m_1} & \frac{\partial e_1}{\partial m_2} & \cdots & \frac{\partial e_1}{\partial m_N} \\ \frac{\partial e_2}{\partial m_1} & \frac{\partial e_2}{\partial m_2} & \cdots & \cdots \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial e_K}{\partial m_1} & \frac{\partial e_K}{\partial m_2} & \cdots & \frac{\partial e_K}{\partial m_N} \end{bmatrix}$$

[1] N. B. Cobb and Y. Granik, **"Model-based opc using the meef matrix,"** in *22nd Annual BACUS Symposium on Photomask Technology*, SPIE, vol. 4889, 2002, pp. 1281–1292.

OPC Solver: MEEF Matrix Formulation

- Step 1: build MEEF matrix by perturb-simulate-perturb cycle, each time fill a column
- Step 2: minimize EPE via numerical optimization methods



- Question: how to deal with 2-D movement of control points?

OPC Solver: Extend to PIC Designs

- Bi-directionally define control point movement as horizontal & vertical movement

$$\Delta p = (\Delta p_x, \Delta p_y), \Delta p \in \mathbb{R}^{2\times N}, \tag{2}$$

- Objective: minimize EPE via a linear surrogate encoding EPE response

$$\min_{\Delta P} \|J_x \Delta p_x + J_y \Delta p_y + \mathrm{EPE}_0\|_2^2, \tag{3}$$

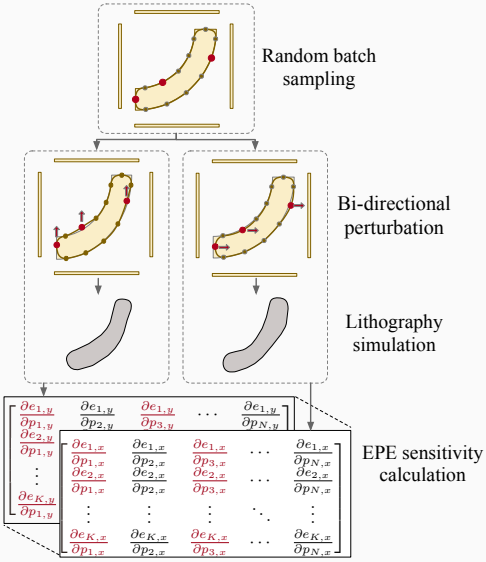
- Since solving with inverse matrix leads to ill-posed solution, we perform a gradient descent step:

$$\begin{aligned} \mathrm{grad} &= \begin{bmatrix} J_x^T \cdot (J_x \Delta P_x + J_y \Delta P_y + \mathrm{EPE}_0) \\ J_y^T \cdot (J_x \Delta P_x + J_y \Delta P_y + \mathrm{EPE}_0) \end{bmatrix}, \\ \Delta P &= \Delta P - \alpha \cdot \mathrm{grad}, \end{aligned} \tag{4}$$

and update mask with Δp, simulate for wafer image, evaluate, until a satisfying EPE is met.

MEEF Estimation

- Conventional method: perturb one point + one lithosim at a time – exhaustive
- Batch sampling over control points
- Problem:
  - Decide the perturbation properly
  - Decide sampling approach: balance EPE change vector informativeness & computational cost
  - Decompose resulted EPE vector into the contribution of each perturbed point



OPC Solver: MEEF Estimation

- Perturbation: align with control point movement, separately perturb in both directions to model J_x and J_y, rightward & upward are positive directions

$$\begin{aligned} &\Delta p_i = (\Delta p_{i,x}, 0) \text{ for horizontal perturbation, and} \\ &\Delta p_i = (0, \Delta p_{i,y}) \text{ for vertical perturbation.} \end{aligned} \tag{5}$$

- Decide the way of sampling
  - Need to match the linear independency assumption of the MEEF theory – should be **sparse**
  - Control with sampling batch size (hyper parameter n)
  - Big n : EPE change information of moving n points integrated in only one vector, hard to decompose
  - Small n: one batch needs one time lithography simulation, significant computational cost

OPC Solver: MEEF Estimation

- Assume perturbing n control points results in EPE change $\Delta e \in \mathbb{R}^{K\times 1}$
- Contribution decomposition: let w_{ij} quantifies the contribution **percentage** of perturbation p_i to measuring site e_j

$$\Delta e_j = \sum_{i=1}^{n} w_{ij} \Delta e_j, \tag{6}$$

- In deciding w_{ij}, rationale: proximity effect
  - The influence of a local mask modification on the wafer image attenuates with increasing distance
- Assume contribution is inversely related to Euclidean distance in between

$$w_{ij} = \frac{\exp(-dist_{ij})}{\sum_{k=1}^{n} \exp(-dist_{kj})} \quad \forall i = 1, 2, \cdots, n, \tag{7}$$

- Sensitivity of e_i to movement of p_j: $w_{ij} \cdot \frac{e_j}{p_i}$

Experiments

Experiment

- Benchmark: fundamental components in curvilinear design

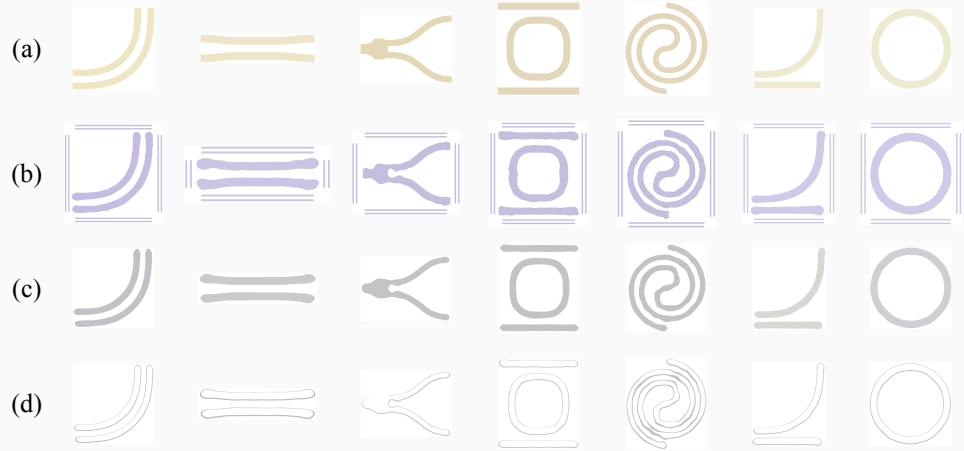


Figure 4: (a) target patterns, (b) mask image, (c) wafer image, (d) process variation band

Experiments

Design	# MP†	MOSAIC [4]				Multi-level ILT [21]				Manhattanized OPC				Rigorous BEAM				BEAM			
		MEPE	L2($\times 10^3$)	PVB($\times 10^3$)	RT	MEPE	L2($\times 10^3$)	PVB($\times 10^3$)	RT	MEPE	L2($\times 10^3$)	PVB($\times 10^3$)	RT	MEPE	L2($\times 10^3$)	PVB($\times 10^3$)	RT	MEPE	L2($\times 10^3$)	PVB($\times 10^3$)	RT
Case 1	196	15	525	1213	2.31	15	574	1266	2.33	22	753	1201	2.67	12	545	1237	32.45	15	615	1209	2.19
Case 2	126	15	285	1006	6.52	15	370	982	2.64	22	474	1126	2.78	14	341	1022	28.95	15	338	1006	4.6
Case 3	204	15	637	1827	1.83	15	680	1825	2.19	20	878	1884	4.92	15	531	1847	34.17	15	519	1842	3.77
Case 4	326	17	1124	4459	18.24	20	1366	4269	11.13	26	1547	4214	9.38	22	1402	4397	69.52	15	1018	4451	7.46
Case 5	160	15	576	1195	2.01	14	530	1171	3.48	15	514	1190	2.63	9	403	1198	5.24	7	352	1199	0.79
Case 6	102	15	262	699	2.35	14	301	736	1.38	22	442	732	2.49	12	257	687	7.25	13	288	695	0.82
Case 7	144	14	319	900	2.07	15	380	893	1.84	24	331	879	2.49	15	386	943	28.16	14	347	901	3.45
Case 8	72	15	208	574	1.91	14	242	597	1.72	19	298	576	2.47	15	235	561	7.84	13	212	578	1.07
Case 9	154	15	354	985	2.43	15	441	1042	1.91	21	542	1013	2.52	15	419	1042	17.48	15	417	1042	2.45
Case 10	106	15	272	692	2.12	15	497	719	1.28	21	414	686	2.52	13	272	670	4.88	14	282	677	0.54
Case 11	98	15	298	675	2.02	15	457	847	1.42	20	375	636	2.5	13	250	621	6.21	13	278	631	0.45
Case 12	72	14	207	562	1.81	15	239	563	2.15	18	289	595	2.61	14	214	549	4.47	11	166	562	0.95
Sum	1760	180	5067	14787	45.62	182	6077	14910	33.47	250	6857	14732	39.98	169	5255	14774	246.62	160	4832	14793	28.54
Ratio		1.11	1.05	1.00	1.60	1.13	1.26	1.01	1.17	1.56	1.42	1.00	1.40	1.06	1.09	1.00	8.64	1.00	1.00	1.00	1.00

Figure 5: Performance comparison against baselines. Mean EPE per measure point, PV band, and runtime are compared and measured in nanometers (*nm*), square nanometers (nm^2), and seconds (*s*), respectively.

Experiment

- Ablation study: # batches sampled in each iteration
- Increased # batches sampled, reliable EPE sensitivity estimation, increased computational cost

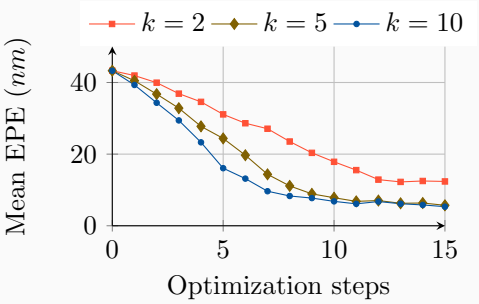


Figure 6: The EPE trajectories of Case 1 with varying number of batches.

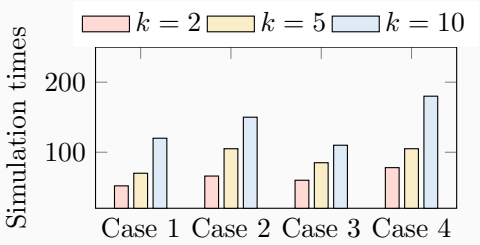


Figure 7: The number of lithography simulation times. Testcases correspond to Case 1 to Case 4.