Curvilinear Optical Proximity Correction via Cardinal Spline

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Outline

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2. Algorithms
3. Experimental Results

Introduction

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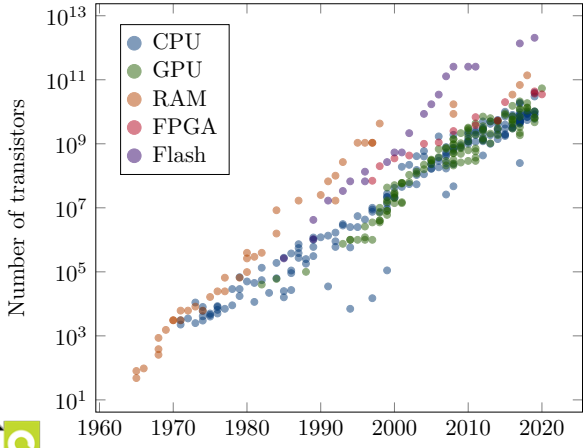
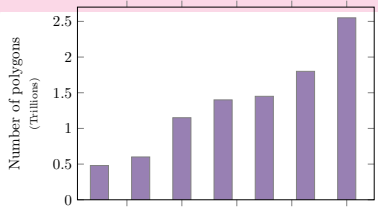
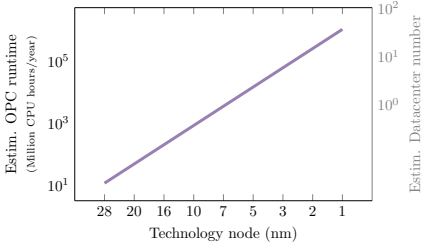
Moore's Law to Extreme Scaling

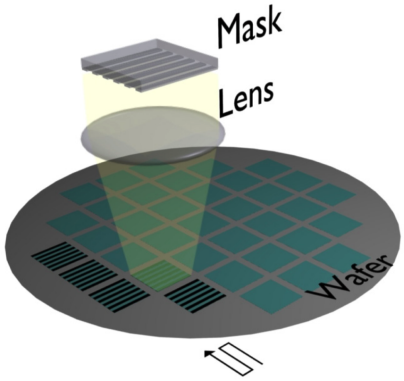
- Billions of transistors on a chip → ... Trillions of polygons



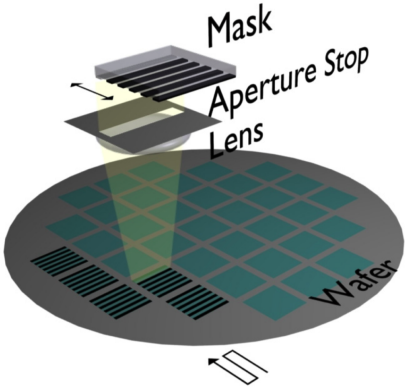




Semiconductor Manufacturing: Lithography

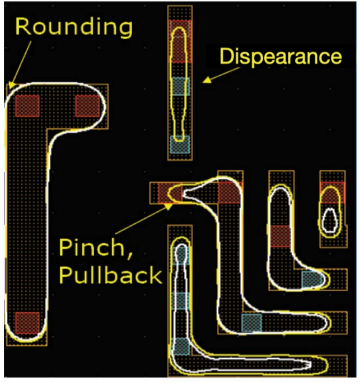


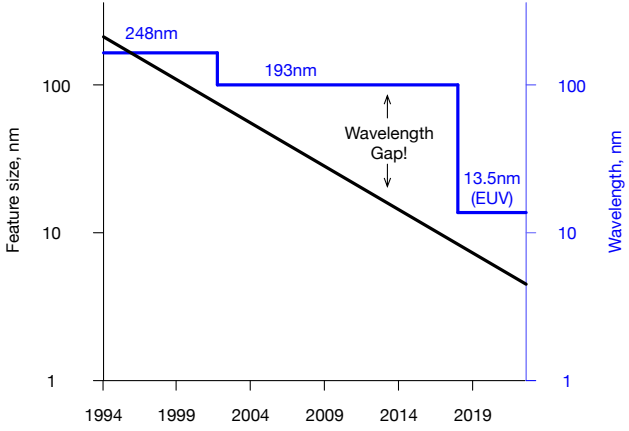
(a)



(b)

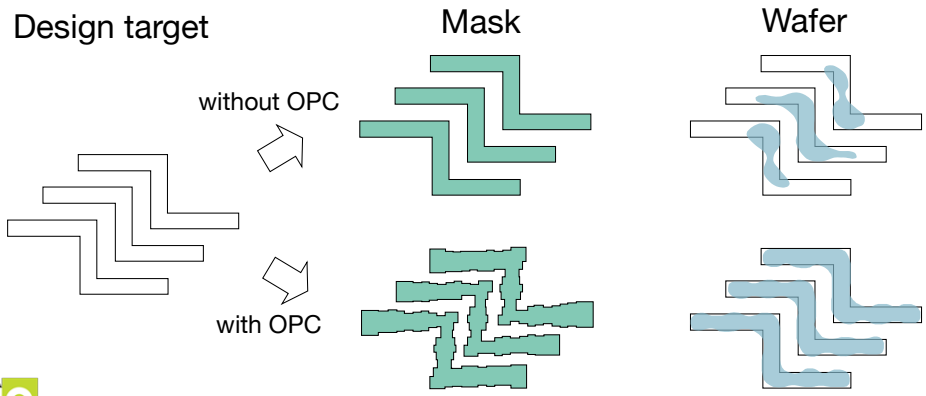
When feature is small: what you see ≠ what you want





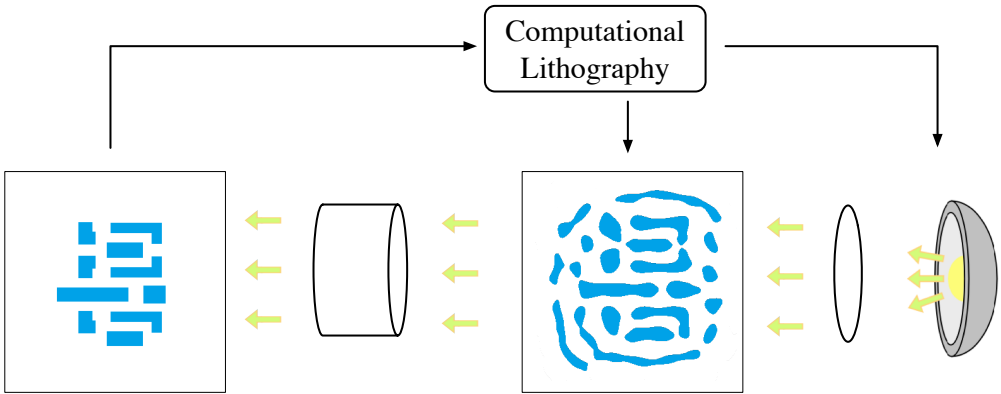
Optical proximity Correction (OPC)

- Dissect the layout patterns → Move the segments to correct errors



Inverse Lithography Techniques (ILT)

- Pixel-based representation → Solve an inverse problem



Motivation

- **Combining the advantages of OPC and ILT**
- OPC adjusts layout segments to minimize errors
  - Computationally efficient
  - Compliance with mask rules
- ILT solves an inverse problem
  - Greater flexibility and higher fidelity
  - Computationally intensive
  - Struggle with mask rule checking

Curvilinear OPC

- Curvilinear OPC enables more flexible shapes in mask optimization

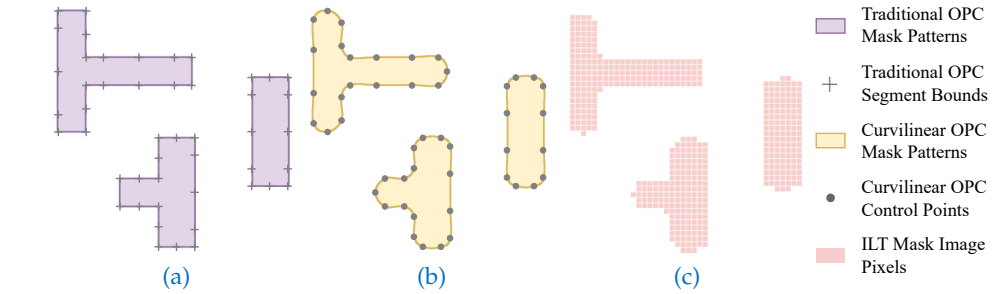


Illustration of the mask pattern representation in (a) traditional OPC; (b) curvilinear OPC; (c) ILT. Curvilinear OPC combines the reduced number of variables from traditional OPC and the flexibility of curvilinear shapes from ILT.

Algorithms

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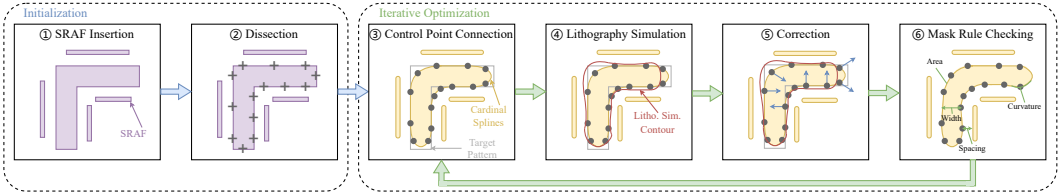
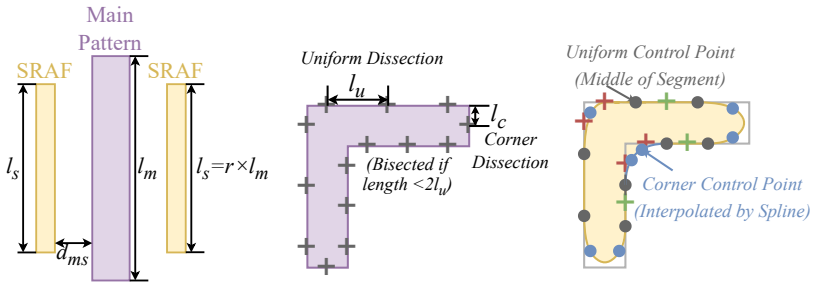
The Proposed Flow

① Insert SRAFs as traditional OPC does
② Dissect the polygons as traditional OPC does
③ Connect the control points with cardinal splines
④ Lithography simulation
⑤ Correct the distortions by moving the control points
⑥ Mask rule checking and MRC violation resolving



① ② Initialization Phase: OPC Only

- SRAFs are placed at a certain distance from the main pattern
- Dissect the layout polygons into segments
- Generate the control points for cardinal splines



① ② Initialization Phase: Initialized by ILT

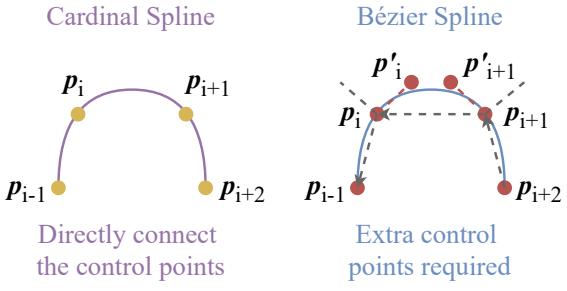
Algorithm Fitting Method for ILT-Optimized Masks

Require: ILT-optimized mask image $\boldsymbol{M}$, cardinal spline function $\boldsymbol{F}(\cdot)$, ratio r_Q and r_R, learning rate α.

//Initialization;
$\boldsymbol{Q} = \emptyset$, $\boldsymbol{R} = \emptyset$;
for each shape $\boldsymbol{S}_i$ in the mask image $\boldsymbol{M}$ **do**
    Extract the boundary points of $\boldsymbol{S}_i$, denoted by $\boldsymbol{P}_i$;
    Sample $r_Q|\boldsymbol{P}_i|$ points from $\boldsymbol{P}_i$ evenly, add them to $\boldsymbol{Q}$;
    Sample $r_R|\boldsymbol{P}_i|$ points from $\boldsymbol{P}_i$ evenly, add them to $\boldsymbol{R}$;
end for
//Optimization;
for $k \in \{1, 2, ..., K\}$ **do** //K iterations in total;
    Interpolate $\boldsymbol{Q}$ with $\boldsymbol{F}(\cdot)$ to have $|\boldsymbol{R}|$ points;
    Compute the loss $L(\boldsymbol{Q}, \boldsymbol{R}) = \|\boldsymbol{F}(\boldsymbol{Q}) - \boldsymbol{R}\|^2$;
    Optimize $\boldsymbol{Q}$ with $\boldsymbol{Q} \leftarrow \boldsymbol{Q} - \alpha \frac{\partial L(\boldsymbol{Q}, \boldsymbol{R})}{\partial \boldsymbol{Q}}$;
end for
return $\boldsymbol{Q}$;

③ Cardinal Spline v.s. Bézier spline

- Cardinal spline requires fewer control points, improving the efficiency



Comparison between cardinal splines and Bézier splines in curvilinear OPC. Using cardinal splines, the curve can pass through all the control points p_{i-1}, p_i, p_{i+1}, and p_{i+2}. However, when using Bézier splines, two extra control points p'_i and p'_{i+1} should be generated to ensure that the curve can pass through p_i and p_{i+1}. This introduces non-negligible computational overhead.

Hopkins model—the aerial image $\boldsymbol{I}$ is obtained by applying a set of optical kernels $\boldsymbol{H}$ to the mask $\boldsymbol{M}$ with:

$$\boldsymbol{I}(x,y) = \sum_{k=1}^{N_h} w_k \left| \boldsymbol{M}(x,y) \otimes \boldsymbol{h}_k(x,y) \right|^2 . \tag{1}$$

N_h is the number of optical kernels, $\boldsymbol{h}_k$ is the k-th optical kernel in $\boldsymbol{H}$, and w_k is the corresponding weight. $\boldsymbol{I}$ can be binarized using the intensity threshold I_{th} that indicates the exposure level. After the binarization, the contour $\boldsymbol{C}$ of the lithography simulation result can be extracted and utilized to guide the OPC process.

⑤ Correction

- Mathematical formulation:

$$\boldsymbol{f}_{EPE}(\boldsymbol{M}_{\tau+1}) \approx \boldsymbol{f}_{EPE}(\boldsymbol{M}_{\tau}) + \boldsymbol{f}'_{EPE}(\boldsymbol{M}_{\tau}) \times \boldsymbol{\Delta}\text{Positions}_{\tau}. \tag{2}$$

- Move control points to minimize EPE:

$$\boldsymbol{\Delta}\text{Positions}_{\tau} = -\boldsymbol{f}'_{EPE}(\boldsymbol{M}_{\tau})^{-1} \times \boldsymbol{f}_{EPE}(\boldsymbol{M}_{\tau}). \tag{3}$$

- Smooth the moving distances:

$$\overline{\Delta d_i} = \sum_{k=-W}^{W} w_k \Delta d_k. \tag{4}$$

⑥ MRC Violation Resolving

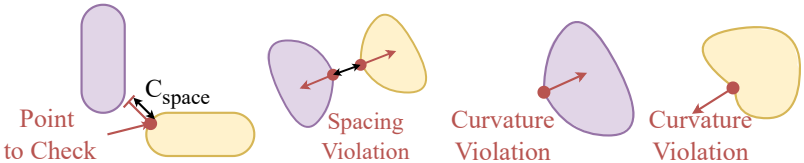


Illustration of mask rule checking and MRC violation resolving. (a) shows how to create a line segment to test the spacing rule violation. (b) moves the control points to resolve spacing rule violations. (c) and (d) resolve curvature rule violations by moving the control points in and out, respectively.

Experimental Results

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Results

Table: Via-layer OPC result comparison on EPE (nm) and PVB (nm^2)

Testcase	#Vias	DAMO		Calibre		RL-OPC		CAMO		CardOPC	
		EPE	PVB	EPE	PVB	EPE	PVB	EPE	PVB	EPE	PVB
V1	2	7	5822	8	5837	6	5730	1	5797	2	5775
V2	2	8	5836	8	5834	7	5813	5	5734	4	5772
V3	3	14	8565	11	8587	13	8594	10	8470	5	8426
V4	3	14	8621	12	8771	14	8679	10	8576	7	8550
V5	4	18	10615	15	10775	16	10772	10	10503	5	10501
V6	4	20	10739	15	10763	19	10659	15	10507	8	10499
V7	5	28	12993	23	12615	23	12485	23	12097	7	12381
V8	5	26	13047	19	12784	24	12547	19	12437	16	12270
V9	6	30	15497	24	15454	26	15414	19	15186	15	15112
V10	6	35	15088	27	15064	33	14588	26	14556	16	14287
V11	6	39	15516	27	15782	31	15538	21	15333	9	15290
V12	6	36	15424	23	15686	24	15464	23	15204	18	15073
V13	6	32	16970	23	17035	39	17440	14	16712	6	16833
Average	4.5	23.6	11902.5	18.1	11922.1	21.2	11824.8	15.1	11624.0	**9.1**	**11597.6**
Ratio	-	156.3%	102.4%	119.9%	102.6%	140.4%	101.7%	100.0%	100.0%	**60.3%**	**99.8%**

Results

Table: Metal-layer OPC result comparison on EPE (nm) and PVB (nm^2)

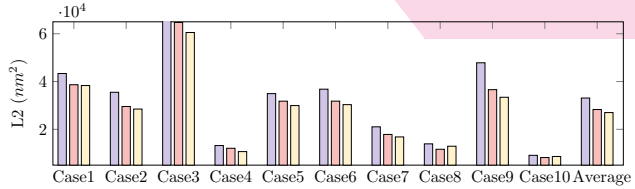
Testcase	#Points	Calibre		RL-OPC		CAMO		CardOPC	
		EPE	PVB	EPE	PVB	EPE	PVB	EPE	PVB
M1	64	49	28728	104	29390	44	27795	37	26387
M2	84	61	37386	117	39139	67	36467	49	34737
M3	88	81	39430	137	41623	59	39451	37	36491
M4	100	89	45741	252	46892	60	44961	44	40528
M5	106	66	47220	336	47041	69	46582	36	45283
M6	112	102	49887	355	51433	78	49438	23	47567
M7	116	89	52584	325	50770	83	49961	57	48794
M8	24	20	11014	32	10770	23	10928	1	10353
M9	72	50	22531	197	22360	42	22032	15	21139
M10	120	91	37546	263	36368	95	36849	11	37727
Average	88.6	69.8	37206.7	211.8	37578.6	62.0	36446.4	**31.0**	**34900.6**
Ratio	-	112.6%	102.1%	341.6%	103.1%	100.0%	100.0%	**50%**	**95.8%**

Results

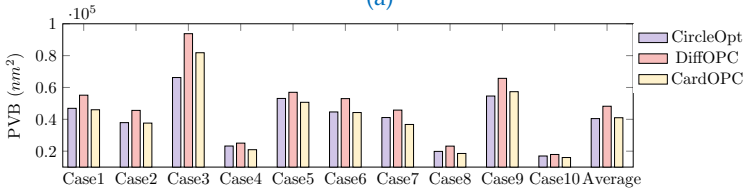
Table: Large-scale OPC result comparison on EPE violations and PVB (μm^2)

Testcase	#Tiles ($30 \times 30 \mu m^2$)	Calibre		SimpleOPC		CardOPC	
		EPE	PVB	EPE	PVB	EPE	PVB
`gcd`	1	3657	35.6651	3454	37.3002	3507	34.2606
`aes`	144	2722	27.7226	2571	29.4301	2578	27.3485
`dynamicnode`	144	2088	26.1663	1941	27.1213	1923	25.5011
Average	-	2409	26.9746	2260	28.3069	**2255**	**26.4519**
Ratio	-	100.0%	100.0%	93.8%	104.9%	**93.6%**	**98.1%**

Results



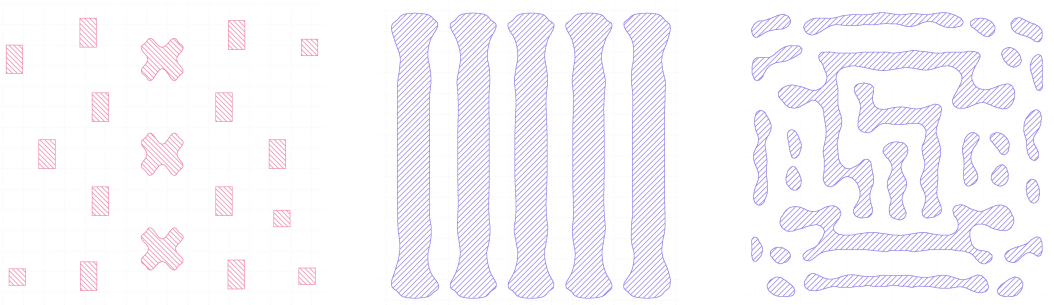
(a)



(b)

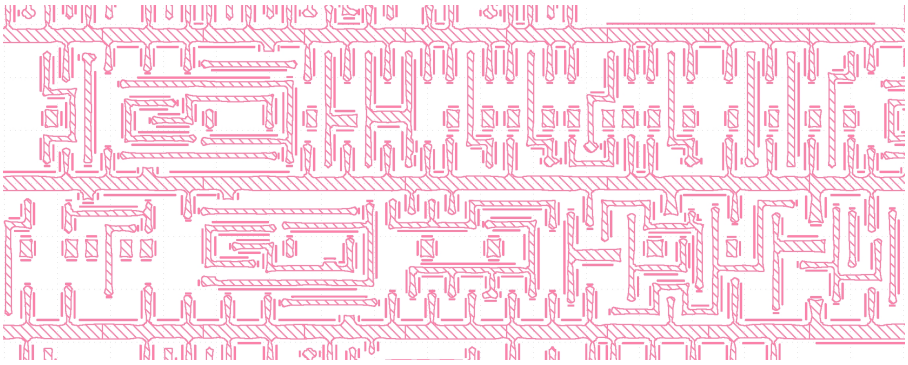
Comparison between our ILT-OPC hybrid approach and SOTA methods. Additionally, our approach achieves 1.4 EPE violations on average, outperforming CircleOpt (3.9) and DiffOPC (2.2).

Results



Examples of curvilinear OPC results: (a) via-layer OPC; (b) metal-layer OPC; (c) ILT-based OPC.

Results



Examples of large-scale curvilinear OPC results.

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