NEURAL INFORMATION PROCESSING SYSTEMS
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LithoBench: Benchmarking AI Computational Lithography for Semiconductor Manufacturing

Su Zheng[1], Haoyu Yang[2], Binwu Zhu[1], Bei Yu[1], Martin Wong[1]

[1] The Chinese University of Hong Kong
[2] nVIDIA

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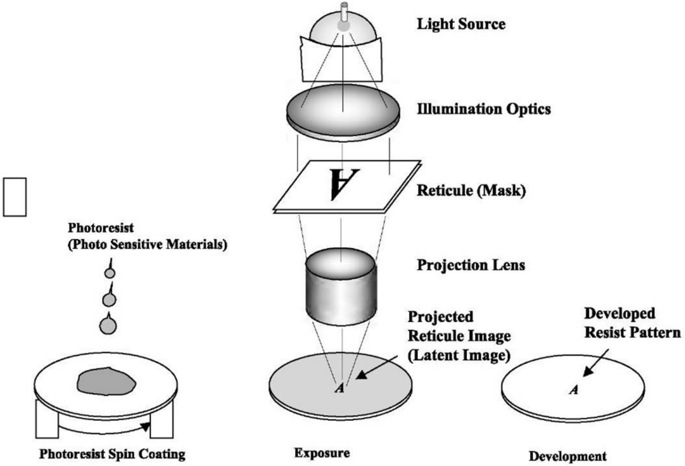
Outline

Introduction

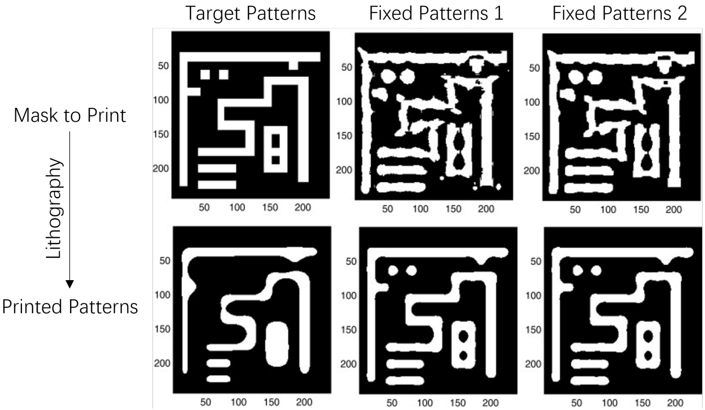
Semiconductor Lithography

- Lithography prints the mask patterns to the wafer



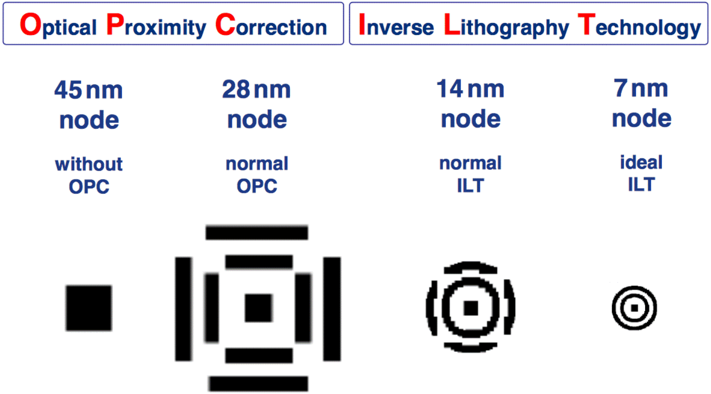
Semiconductor Lithography

- Fail to get target patterns due to distortion
  $\rightarrow$ Fix it by distoring the mask!



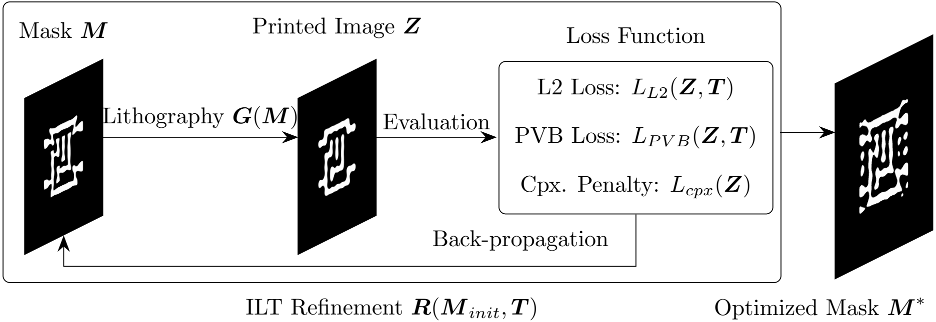
Mask Optimization

- OPC vs. ILT



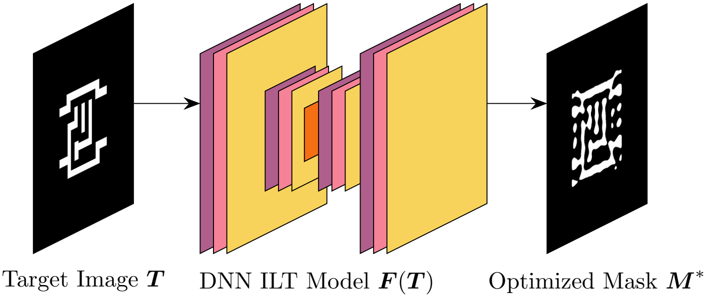
Mask Optimization

- Inverse Lithography Technology (ILT) → Iterative Optimization



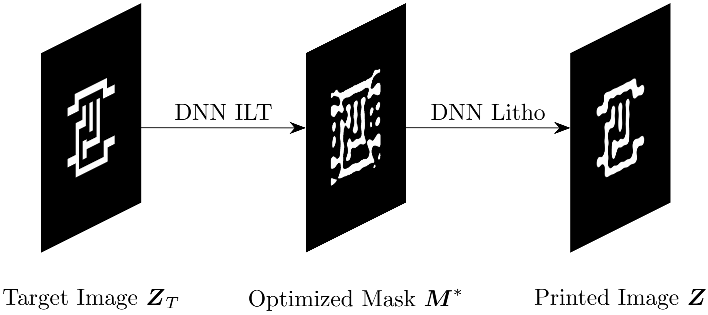
Mask Optimization

- DNN-based ILT $\rightarrow$ End-to-end, Faster



LithoBench Tasks

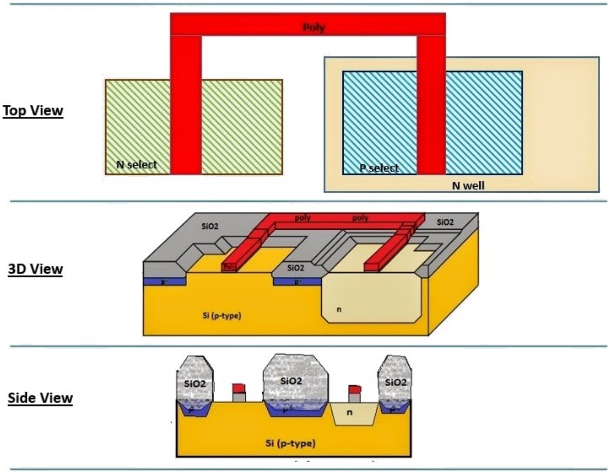
- **Lithography simulation**: mask → printed image (DNN Litho)
- **Mask optimization**: target image → optimized mask (DNN ILT)



Dataset

Layered Circuit Layout

- A circuit layout consists of multiple layers
  $\rightarrow$ Each one can be modeled by an image



LithoBench Subsets

- **MetalSet**: train DNN-based models for metal layers, compatible with the famous ICCAD-13 benchmark[1]
- **ViaSet**: train DNN-based models for via layers, compatible with the setting of related works
- **StdMetal**: test the generalization ability of the model trained on MetalSet, which is a challenging task
- **StdContact**: test the generalization ability of the model trained on ViaSet, which is very challenging

[1] Shayak Banerjee, Zhuo Li, and Sani R Nassif (2013). "ICCAD-2013 CAD contest in mask optimization and benchmark suite". In: *IEEE/ACM International Conference on Computer-Aided Design (ICCAD)*, pp. 271–274.

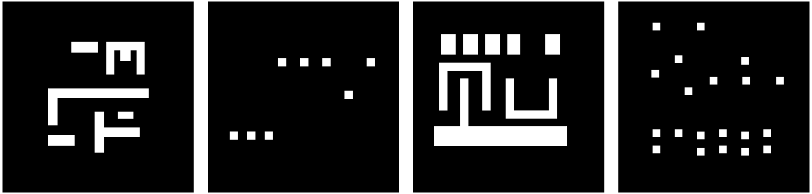
Data Collection

- Data collection
  - **MetalSet**: randomly generation following the design rules of ICCAD-13 benchmark → 16,472 tiles
    - Size: 2048 × 2048
    - Much more than ICCAD-13 (10 tiles)
  - **ViaSet**: cropped from the layouts `gcd` and `aes` from OpenROAD, the IC design tool → 116,415 tiles
  - **StdMetal**: cropped from the metal layer of the Nangate 45nm standard cells → 271 tiles
  - **StdContact**: cropped from the contact layer of the Nangate 45nm standard cells → 328 tiles

Task	Lithography Simulation				Mask Optimization			
Subsets	MetalSet	ViaSet	StdMetal	StdContact	MetalSet	ViaSet	StdMetal	StdContact
Training Tiles	14,824	104,733	0	163	14,824	104,733	0	163
Testing Tiles	1,648	11,642	271	165	10	10	271	165

Data Collection

- Examples: (a) MetalSet; (b) ViaSet; (c) StdMetal; (e) StdContact.



Data Preparation

- Lithography Simulation: Hopkins' Model
  → Different $\boldsymbol{H}$ for different process conditions

$$\boldsymbol{I} = \boldsymbol{H}(\boldsymbol{M}) = \sum_{k=1}^{K} \mu_k |\boldsymbol{h}_k \otimes \boldsymbol{M}|^2 \tag{1}$$

- Mask Optimization: Multi-level ILT[2]
  → Optimize the following loss function

$$L_f(\boldsymbol{Z}_{nom}, \boldsymbol{Z}_{max}, \boldsymbol{Z}_{max}, \boldsymbol{T}) = \|\boldsymbol{Z}_{max} - \boldsymbol{T}\|_2^2 + \|\boldsymbol{Z}_{max} - \boldsymbol{Z}_{min}\|_2^2 + L_{curv}(\boldsymbol{Z}_{nom}) \tag{2}$$

$$\boldsymbol{Z} = \boldsymbol{\sigma}_Z(\boldsymbol{H}(\boldsymbol{\sigma}_M(AvgPool(\boldsymbol{P})))) \tag{3}$$

[2] Shuyuan Sun et al. (2023). "Efficient ILT via Multi-level Lithography Simulation". In: *ACM/IEEE Design Automation Conference (DAC)*.

Metrics

- Lithography Simulation ($\boldsymbol{Z}_1 = \{\boldsymbol{Z} = 1\}$)

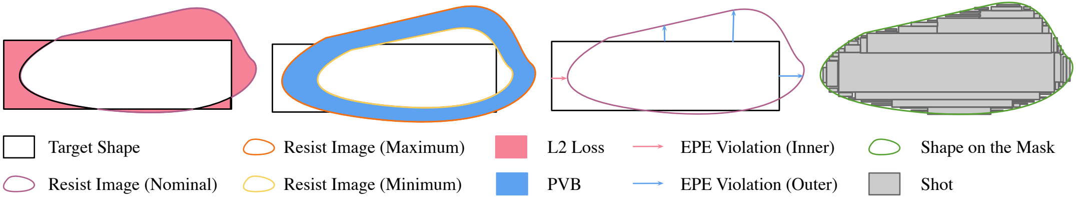
$$\text{MSE}(\boldsymbol{Z}, \boldsymbol{T}) = \|\mathbf{Z} - \mathbf{T}\|_2^2 \tag{4}$$

$$\text{IOU}(\boldsymbol{Z}, \boldsymbol{T}) = \frac{\boldsymbol{Z}_1 \cap \boldsymbol{T}_1}{\boldsymbol{Z}_1 \cup \boldsymbol{T}_1} \tag{5}$$

$$\text{PA}(\boldsymbol{Z}, \boldsymbol{T}) = \frac{\boldsymbol{Z}_1 \cap \boldsymbol{T}_1}{\boldsymbol{T}_1} \tag{6}$$

Metrics

- Mask Optimization
  (a) *L2*; (b) *PVB*; (c) *EPE*; (d) *#Shots*



Experiments

Lithography Simulation Models

- **LithoGAN**[3]: A conditional GAN with a FCN generator and a CNN discriminator, 256×256 input/output
- **DAMO**[4]: A conditional GAN with a UNet++ generator and a pix2pixHD discriminator, 1024×1024 input/output
- **DOINN**[5]: A novel reduced Fourier neural operator (RFNO) architecture, 1024×1024 input/output
- **CFNO**[6]: Combining vision transformer (ViT) and Fourier neural operator (FNO), 1024×1024 input/output

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[3] Wei Ye et al. (2019). "LithoGAN: End-to-end lithography modeling with generative adversarial networks". In: *ACM/IEEE Design Automation Conference (DAC)*.

[4] Guojin Chen et al. (2020). "DAMO: Deep agile mask optimization for full chip scale". In: *IEEE/ACM International Conference on Computer-Aided Design (ICCAD)*.

[5] Haoyu Yang, Zongyi Li, et al. (2022). "Generic lithography modeling with dual-band optics-inspired neural networks". In: *ACM/IEEE Design Automation Conference (DAC)*, pp. 973–978.

[6] Haoyu Yang and Haoxing Ren (2023). "Enabling Scalable AI Computational Lithography with Physics-Inspired Models". In: *IEEE/ACM Asia and South Pacific Design Automation Conference (ASPDAC)*, pp. 715–720.

Mask Optimization Models

- **GAN-OPC**[7]: A conditional GAN with the novel ILT-guided pretraining, 256×256 input/output
- **Neural-ILT**[8]: A UNet generator with complexity reduction mechanism, 512×512 input/output
- **DAMO**: A conditional GAN with a UNet++ generator and a pix2pixHD discriminator, 1024×1024 input/output
- **CFNO**: Combining vision transformer (ViT) and Fourier neural operator (FNO), 1024×1024 input/output

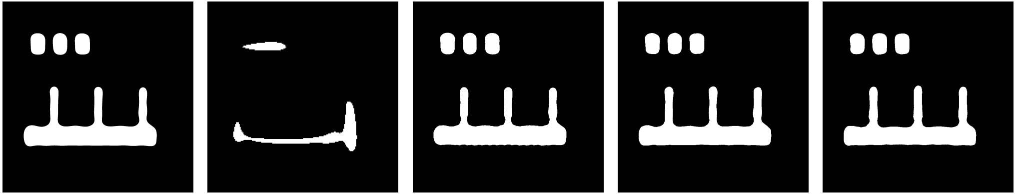
[7] Haoyu Yang, Shuhe Li, et al. (2018). "GAN-OPC: Mask optimization with lithography-guided generative adversarial nets". In: *ACM/IEEE Design Automation Conference (DAC)*.

[8] Bentian Jiang et al. (2020). "Neural-ILT: Migrating ILT to neural networks for mask printability and complexity co-optimization". In: *IEEE/ACM International Conference on Computer-Aided Design (ICCAD)*.

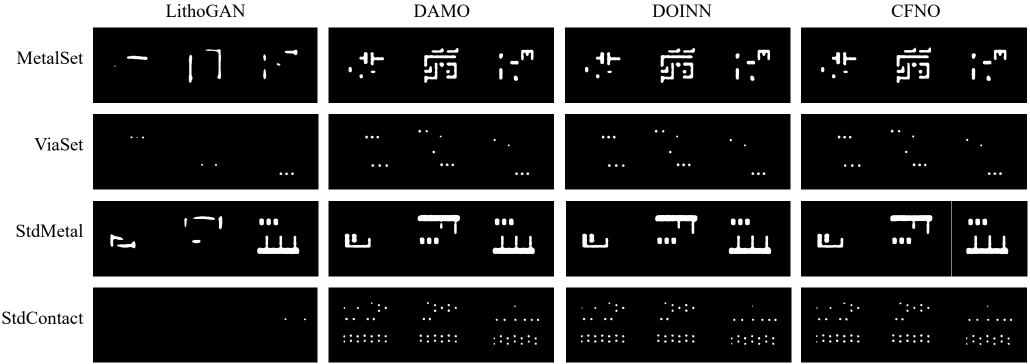
Lithography Simulation Results

Subtask	LithoGAN				DAMO				DOINN				CFNO			
	MSE_A	MSE_P	IOU	PA	MSE_A	MSE_P	IOU	PA	MSE_A	MSE_P	IOU	PA	MSE_A	MSE_P	IOU	PA
1	$9.8 \cdot 10^{-4}$	$1.7 \cdot 10^{-2}$	0.38	0.43	**$8.4 \cdot 10^{-6}$**	$7.5 \cdot 10^{-4}$	**0.97**	**0.98**	$8.5 \cdot 10^{-6}$	**$6.6 \cdot 10^{-4}$**	**0.97**	**0.98**	$1.9 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	0.94	0.97
2	$2.6 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	0.47	0.53	$3.0 \cdot 10^{-6}$	$1.5 \cdot 10^{-4}$	0.94	0.96	**$1.9 \cdot 10^{-6}$**	**$1.0 \cdot 10^{-4}$**	**0.96**	**0.98**	$3.8 \cdot 10^{-6}$	$2.1 \cdot 10^{-4}$	0.92	0.96
3	$1.4 \cdot 10^{-3}$	$2.6 \cdot 10^{-2}$	0.30	0.34	$2.5 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	0.95	0.97	**$1.8 \cdot 10^{-5}$**	**$1.2 \cdot 10^{-3}$**	**0.96**	**0.98**	$2.6 \cdot 10^{-5}$	$2.3 \cdot 10^{-3}$	0.93	0.96
4	$2.7 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	0.01	0.01	$4.6 \cdot 10^{-5}$	$1.6 \cdot 10^{-3}$	0.87	0.93	$2.4 \cdot 10^{-5}$	**$1.3 \cdot 10^{-3}$**	**0.90**	**0.94**	**$2.1 \cdot 10^{-5}$**	$2.2 \cdot 10^{-3}$	0.83	0.90
Average	$1.3 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	0.29	0.33	$2.1 \cdot 10^{-5}$	$1.0 \cdot 10^{-3}$	0.93	0.96	**$1.3 \cdot 10^{-5}$**	**$8.2 \cdot 10^{-4}$**	**0.95**	**0.97**	$1.7 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	0.91	0.95
Runtime	**0.013** s / image				0.030 s / image				0.017 s / image				0.035 s / image			

- Examples: (a)Label; (b)LithoGAN; (c)DAMO; (d)DOINN; (e)CFNO



Lithography Simulation Results

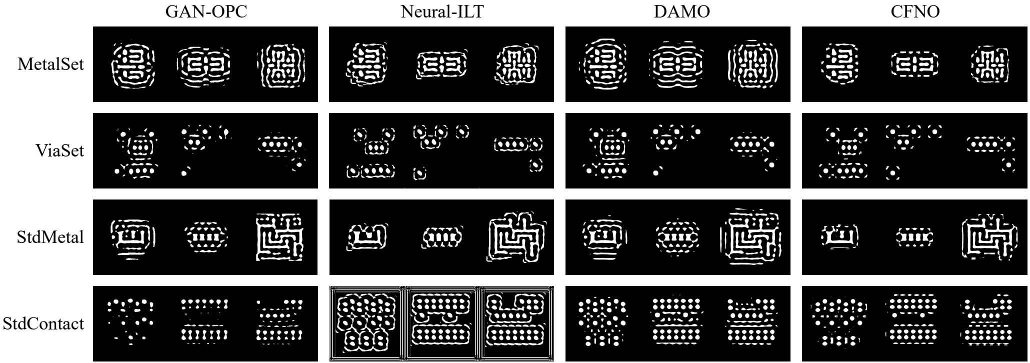


Mask Optimization Results

	GAN-OPC				Neural-ILT				DAMOILT				CFNO			
Subtask	L_2	PVB	EPE	Shots	L_2	PVB	EPE	Shots	L_2	PVB	EPE	Shots	L_2	PVB	EPE	Shots
1	43414	41290	8.7	574	36670	42666	7.3	476	**32579**	**41173**	**5.4**	523	47814	46131	12.5	**302**
2	14767	**6686**	8.3	**166**	12723	8537	6.2	263	**5081**	9962	**0.0**	176	8949	9890	0.1	184
3	25929	23715	4.6	457	20045	**23548**	2.4	373	**16120**	23796	**0.2**	418	26809	26814	4.2	**232**
4	81378	**4931**	73.2	276	**25422**	41537	**3.2**	**265**	50445	35673	26.7	458	70740	17950	55.1	396
Average	41372	**19156**	23.7	368	**23715**	29072	**4.8**	344	26056	27651	8.0	394	38578	25196	18.0	**279**
Runtime	**0.010** s / image				0.025 s / image				0.028 s / image				0.040 s / image			

- Examples: (a)Label; (b)GAN-OPC; (c)NeuralILT; (d)DAMO; (e)CFNO

Mask Optimization Results



THANK YOU!