Inverse Lithography

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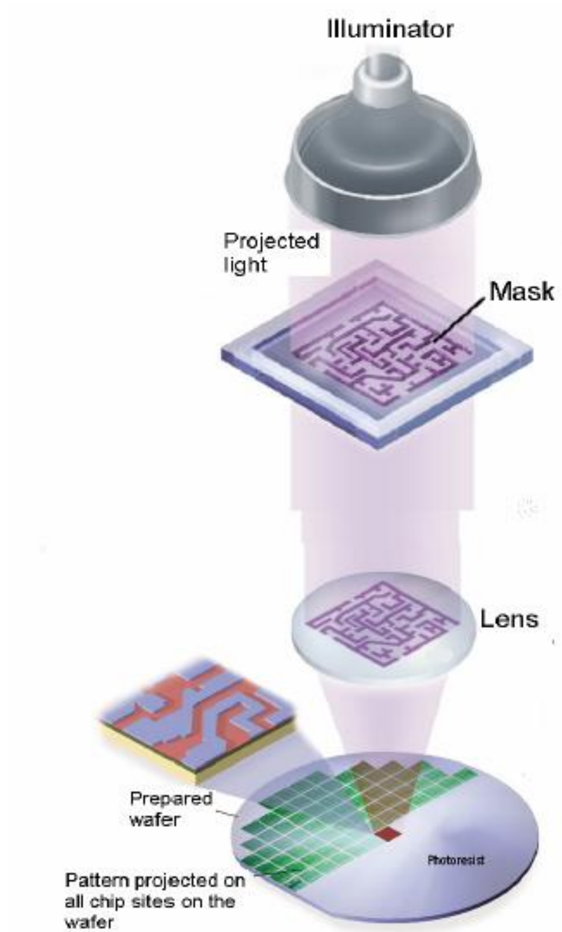
Why Resolution Enhancement ?



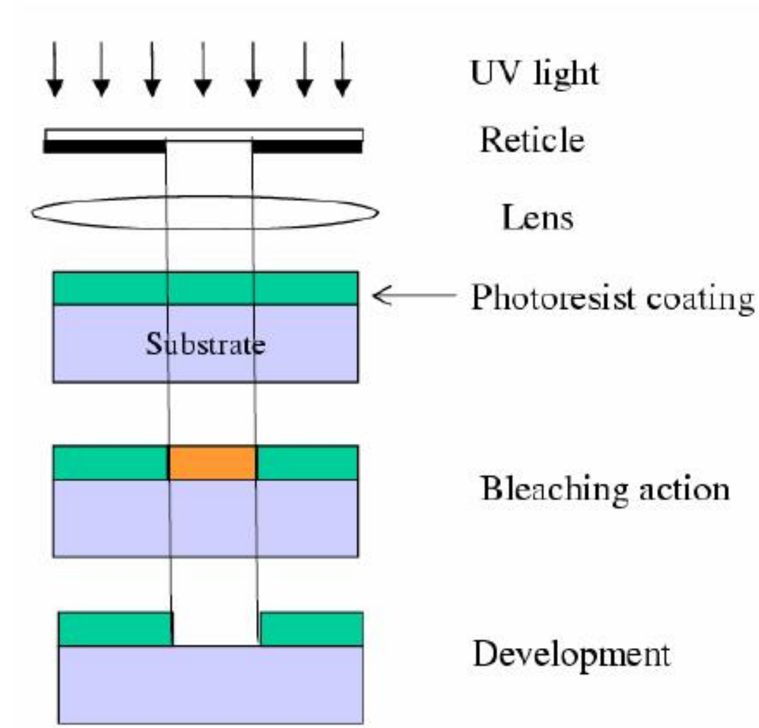
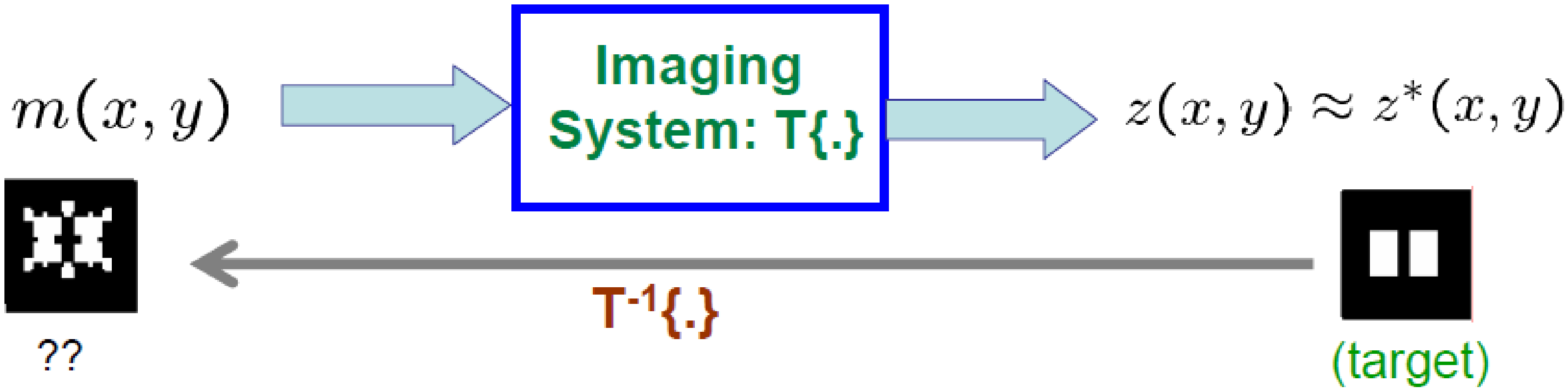


Figure from F.Schellenberg, “A little light magic”, IEEE Spectrum, 2003

The main problem is sub-wavelength patterning.

Inverse Lithography Problem Formulation



$$\hat{m}(x,y) = \arg\min_{m(x,y)} d(z^*(x,y), T\{m(x,y)\})$$

Equation and Figure taken from A.Poonawala and P.Milanfar, AIP 2007

Discrete approaches

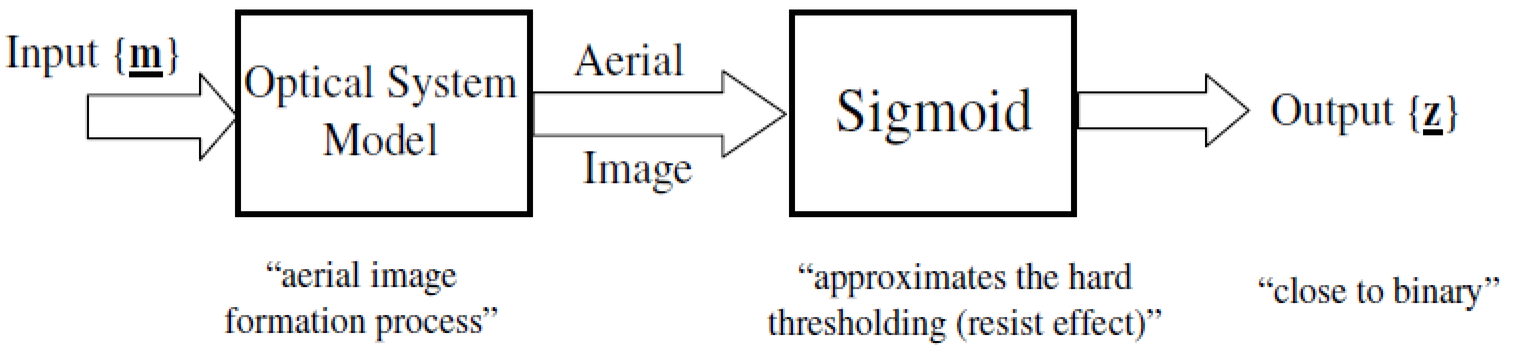
- Many “pixel flipping” based discrete approaches using SA, genetic algorithms, ILP

- One recent “gradient-inspired” pixel flipping by J. Zhang et al at ICCAD 2008 [“A Highly Efficient Optimization Algorithm for Pixel Manipulation in ILT”]

$$\Delta E_C = \frac{\partial E_C}{\partial m} \circ \Delta m + \frac{1}{2}\frac{\partial^2 E_C}{\partial m^2} \circ (\Delta m)^2 + O\left[(\Delta m)^3\right]$$

  - Flip the most cost reducing pixels which are not too close to each other for every iteration
  - Terminate when no pixel flip reduces cost by more than ε

Gradient based continuous method



- Objective: Minimize $||z^* - sig(|Hm|^2)||_2$
- Relax m = {0, 1} to 0<m<1 then transform m = (1+cosθ)/2 to make it an unconstrained optimization
- Reduce rounding error by adding m(1-m) to the objective
- Added regularization terms for manufacturability

Level set based method

- Numerical PDE based algorithm to model moving surfaces

- Formulation of Y.Shen, et. al.[Dec. 2009]

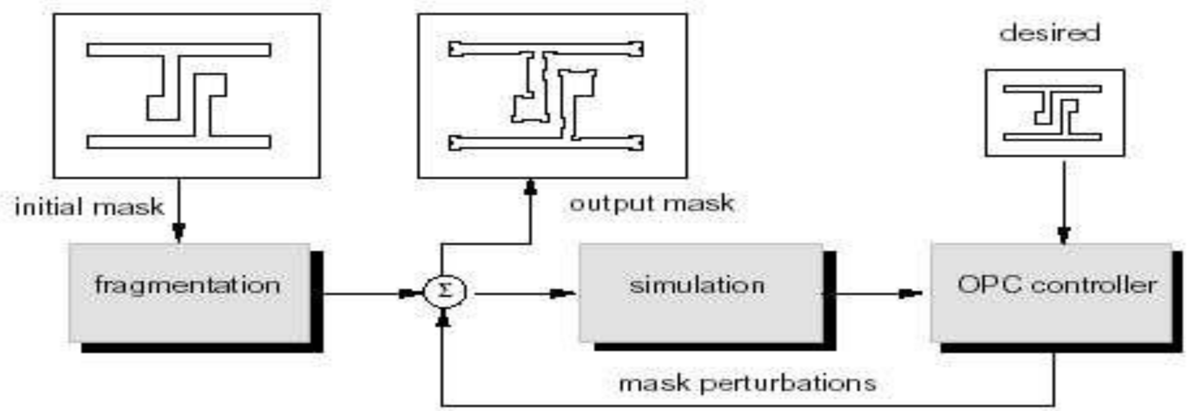
$$\text{minimize} \quad \int_\Omega |\nabla U| \, \mathrm{d}\mathbf{x}$$

$$\text{subject to} \quad \int_\Omega (\mathrm{sig}(|H * U|^2) - I_0)^2 \, \mathrm{d}\mathbf{x} = \varepsilon,$$

- Final level set PDE solved using methods proposed by Osher et. al.

$$\frac{\partial U}{\partial t} = -\alpha(\mathbf{x}, t) + \lambda \nabla \cdot \left(\frac{\nabla U}{|\nabla U|} \right),$$

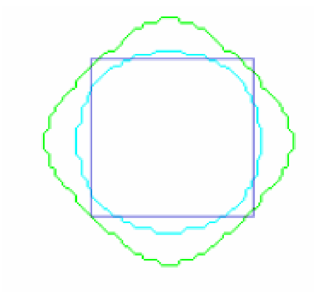
Comparison with OPC



OPC algorithm. Figure taken from N. Cobb's PhD thesis

- Main advantage of OPC is more manufacturable masks
  - Speed used to be another one but it scales worse than ILT
- ILT has better litho performance
  - Not restricted to local solutions
  - No need for separate rule-based assist feature insertion step.

Some unintuitive ILT patterns: Contact Array



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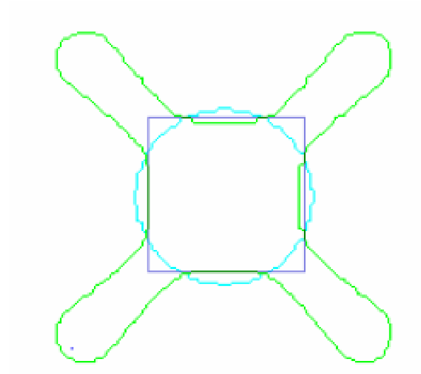

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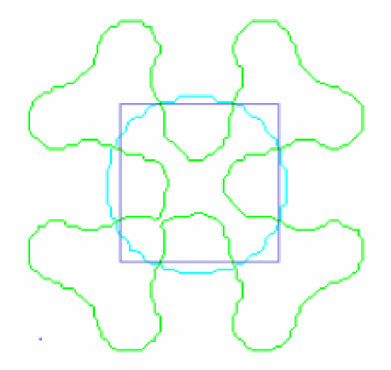

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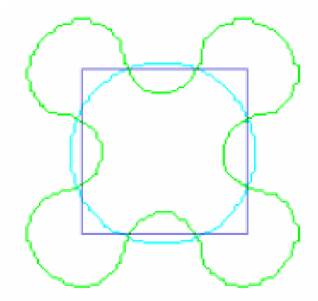

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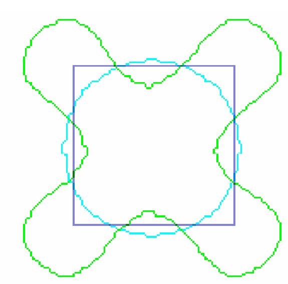

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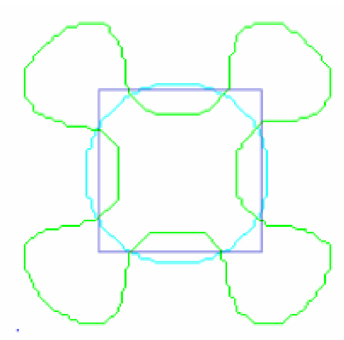

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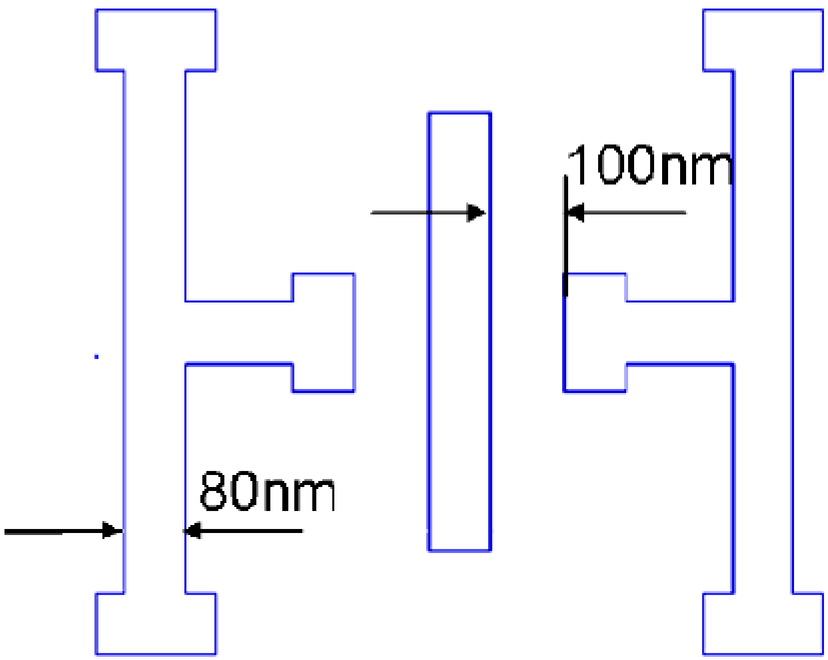
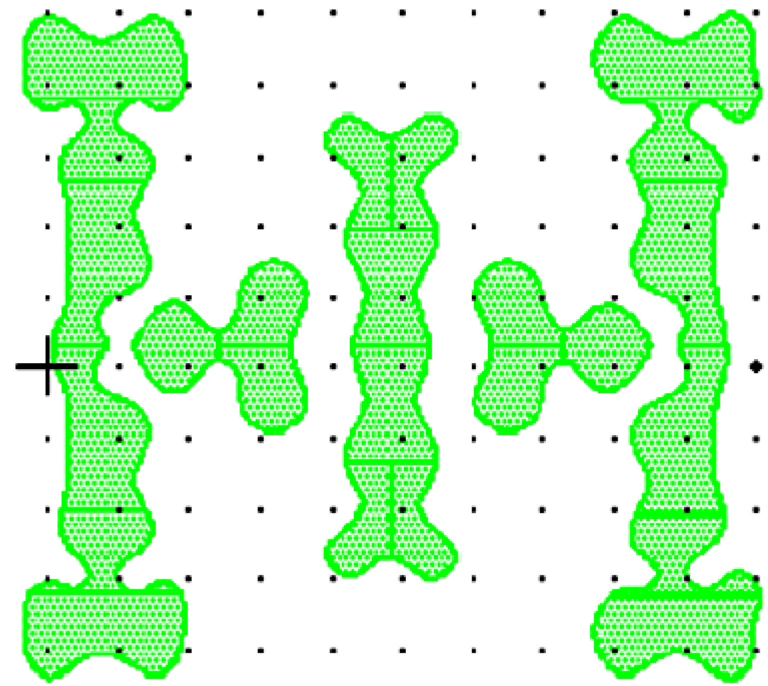
Some unintuitive ILT patterns: Poly Pattern





Some current results: Full chip ILT (Samsung + Luminescent)

	Contact		Poly	
	Conv. OPC	ILT	Conv. OPC	ILT
Input File Size (OASIS)	0.13 GB	4.2 GB	3.3 GB	7.8 GB
Output File Size (VSB12)	1.7 GB	58 GB	6.4 GB	165 GB
Data Conversion (Patacon)	0.5 hrs	2 hrs	1.2 hrs	12 hrs
Shot Count (Mshots)	209M	1,496M	2,123M	4,608M
Max Shot Density (Mshots/mm^2)	4.7	32.6	28.2	62.5
Writing Time (EBM6000)	10.2 hrs	24.5 hrs	30.2 hrs	56.7 hrs
Estimated Writing Time (EBM7000)	7.1 hrs	17.2 hrs	21.1 hrs	39.7 hrs

Some current results: Full chip ILT (Samsung + Luminescent)

	Contact			Poly			
	Conv. OPC	ILT (Seg20)	ILT* (Seg40)	Conv. OPC	ILT (Seg20)	ILT* (Seg50)	ILT* (Seg70)
Shot Count (Mshots)	209M	1,496M	980M	2,123M	4,608M	3,686M	2,300M
Max Shot Density (Mshots/mm^2)	4.7	32.6	24	28.2	62.5	44	29
Writing Time (EBM6000)	10.2 hrs	24.5 hrs	16.7 hrs	30.2 hrs	56.7 hrs	48.2hrs	31.2 hrs
Estimate Writing Time (EBM7000)	7.1 hrs	17.2 hrs	11.7 hrs	21.1 hrs	39.7 hrs	33.7hrs	21.8 hrs