Mask Optimization for Directed Self-Assembly Lithography: Inverse DSA and Inverse Lithography

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Outline

• Introduction
  • DSAL, Guide pattern (GP), Mask synthesis process

• **Inverse DSA**: Synthesizing ideal GP shape
  • Parameterizing GP, Synthesis algorithm

• **Inverse lithography**: Synthesizing GP mask image
  • Approximate cost gradient, Synthesis algorithm

• **DSAL mask design with lithography variations**
  • GP error tolerance, SRAF insertion

• Conclusion
Directed Self-Assembly (DSA)

Diblock copolymer (BCP)

Heat + anneal

[Courtland, IEEE spectrum 2012]
DSA using Guide Patterns (GPs)

- Contact and via in sub 10-nm cannot be patterned using optical lithography
- In DSAL: Local contacts are grouped $\rightarrow$ GP is patterned through optical litho $\rightarrow$ contacts are patterned through DSA (2 step process)

[Image: Graph showing technology nodes over years with notes Multiple-patterning, EUV, DSA highlighted]

[Intel developer forum 2014]
DSA Lithography (DSAL)

Optical lithography

Contact → Cluster → GP images → Mask image

GP → Polymer-A → Polymer-B → Contacts after etch

DSA process
DSAL Mask Synthesis

Mask synthesis for optical lithography

Contact layout → Litho target → OPC → Mask image

Inverse DSA

Contact layout → DSA target → GP image

Inverse litho

Contact layout → Litho target → GP mask image

Mask synthesis for DSAL
Inverse DSA

Problem definition

- **Input**: A contact cluster
- **Output**: Ideal GP image
- **Objective**: Minimize max edge placement error (EPE)
Inverse DSA

Parameterizing GP

- Represent a GP as a function of a few geometry parameters
  \[ G = f(g) = f(g_1, g_2, g_3, \cdots, g_n) \]
- Reduce complexity of inverse DSA
Inverse DSA

Algorithm

Input: a DSA image $\mathcal{D}_{in}$ of a cluster of contacts
Output: a GP image $\mathcal{G}$

1. $\mathcal{G} \leftarrow$ an initial GP image
2. $\mathcal{D} \leftarrow$ DSA_Simulation($\mathcal{G}$)
3. $e \leftarrow$ Measure_EPE($\mathcal{D}_{in}, \mathcal{D}$)
4. repeat for max_iterations
5. $M \leftarrow$ Calc_Matrix($\mathcal{D}_{in}, \mathcal{G}$)
6. $\mathcal{G} \leftarrow f(g)$, where $g^T \leftarrow g^T - M^{-1} \times e^T$
7. $\mathcal{D} \leftarrow$ DSA_Simulation($\mathcal{G}$)
8. $e \leftarrow$ Measure_EPE($\mathcal{D}_{in}, \mathcal{D}$)
9. if $\max_{i \in \mathcal{V}}( |e_i| ) \leq \max_{EPE}$ then Exit loop
10. return $\mathcal{G}$
**Inverse DSA**

**Experimental observations**
- Inverse DSA is applied to each group of **congruent clusters** one by one
- Runtime increases with larger and more **complex** clusters

{1, 5, 7, 8, 9} {3, 4, 6, 10, 11} {2} {12}

Groups of congruent clusters (GPs)
Inverse Lithography

Problem definition

- **Input**: an ideal GP image
- **Output**: a GP mask image
- **Objectives**: minimize $\sum_k |EPE_k|^2$
Inverse Lithography

Algorithm

**Input:** a GP litho image $\mathcal{L}_{in}$

**Output:** a GP mask image $\mathcal{M}$

1. $\mathcal{M} \leftarrow$ an initial GP mask image
2. $\mathcal{L} \leftarrow$ Litho_Simulation($\mathcal{M}$)
3. $C \leftarrow$ Cost($\mathcal{L}_{in}$, $\mathcal{L}$)
4. repeat for max_iterations
   5. $\mathcal{M} \leftarrow \mathcal{M} - k\nabla C$
   6. $\mathcal{M} \leftarrow$ Convert $\mathcal{M}$ to a binary mask
   7. $\mathcal{L} \leftarrow$ Litho_Simulation($\mathcal{M}$)
   8. $C \leftarrow$ Cost($\mathcal{L}_{in}$, $\mathcal{L}$)
   9. if $C$ increases OR $|\nabla C| \leq \epsilon$ then
      Roll back $\mathcal{M}$; exit loop
10. return $\mathcal{M}$

$\nabla C = \left( \frac{\partial C}{\partial g_1}, \frac{\partial C}{\partial g_2}, \frac{\partial C}{\partial g_3}, \ldots, \frac{\partial C}{\partial g_n} \right)$
Inverse Lithography

Approximate cost gradient

- Calculation of $\nabla C$
  \[
  \frac{\partial C}{\partial g_i} = \sum_k |EPE'_k|^2 - \sum_k |EPE_k|^2
  \]
  
  $n$ times convolutions for $n$ pixels

- Approximate $\nabla C$
  \[
  \frac{\partial C}{\partial g_i} = \sum_k (\Delta EPE_k)(2EPE_k + \Delta EPE_k)
  \]
  
  $\Delta EPE_k = \frac{I'(x_k) - I(x_k)}{dI(x_k)/dx}$
  From $I(x)$

  Much faster than convolution

$\Delta EPE_k = I'(x_k) - I(x_k)$
From $I(x)$

Introducing:

- $\Delta EPE_k$: The change in EPE for a single pixel
- $I'(x_k)$: The derivative of the intensity at $x_k$
- $I(x_k)$: The intensity at $x_k$

Introducing $\Delta EPE_k$ significantly speeds up the convolution process, allowing for faster calculations in inverse lithography.
Inverse Lithography

Experiments: compare 2 methods

- **Exact method:** perform explicit litho simulations for computing $\nabla C$
- **Our (approximate) method:** 6X faster, comparable accuracy

### Comparison of Exact and Approximate Inverse Lithography

<table>
<thead>
<tr>
<th>Layout</th>
<th>Exact method</th>
<th>Approximate method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># Iter</td>
<td>Time (hours)</td>
</tr>
<tr>
<td>Via 1</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Via 2</td>
<td>5</td>
<td>1.8</td>
</tr>
<tr>
<td>Via 3</td>
<td>6</td>
<td>4.2</td>
</tr>
<tr>
<td>Contact 1</td>
<td>7</td>
<td>4.8</td>
</tr>
<tr>
<td>Contact 2</td>
<td>7</td>
<td>6.8</td>
</tr>
<tr>
<td>Contact 3</td>
<td>10</td>
<td>16.7</td>
</tr>
<tr>
<td>Average</td>
<td>6.7</td>
<td>5.9</td>
</tr>
</tbody>
</table>

More iterations & longer runtime due to less accuracy of approx.

2X more iterations due to approximation
**Mask Design with Litho Variations**

- GP may have errors due to **litho variations** → **final contact error**
- **Contact error tolerance**: DSA images should reside within some tolerance (e.g. ±10% contact size)
- **GP error tolerance**: GP litho images should reside within some tolerance
Mask Design with Litho Variations

DSAL SRAF

- **SRAF**: sub-resolution assist feature for constructive light interference
- **DSAL SRAF**: no problem of SRAF printing if no residue after DSA process
- # GPs with violation: 6.6% (no SRAF) → 0% (with SRAF)

![Litho images](image-url)
Conclusion

• **Inverse DSA**: Synthesizing ideal GP shape
  • Parameterizing GP

• **Inverse lithography**: Synthesizing GP mask image
  • Approximate cost gradient

• **DSAL mask design with lithography variations**
  • GP error tolerance, SRAF insertion
Thank you