Mask Design for Resolution Enhancement: An Inverse Problem in Optical Microlithography

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Outline

- Introduction to Optical Lithography and RET
- Inverse Lithography Framework
- Regularization Framework
- Results
- Double Exposure Lithography and Conclusions
Optical Microlithography

Figure from F. Schellenbeg, “A Little Light Magic”, IEEE Spectrum, 40 (2003)
Distortions

- Band limited → higher frequencies lost.
- Corner rounding, line-end shortening, poor fidelity.
- Pattern collapse
Resolution Limit and RET

\[ w_{\text{min}} = \frac{k_1 \lambda}{\text{NA}} \]

\( \lambda \rightarrow \) Wavelength.
\( \text{NA} \rightarrow \) Numerical Aperture.
\( k_1 \rightarrow \) Process Constant (min=0.25).
\( w_{\text{min}} \rightarrow \) Minimum line-width.

**Options**

- Decrease the wavelength.
- Increase NA.
- Decrease \( k_1 \) \rightarrow Resolution Enhancement Techniques (RET)

- Optical Proximity Correction (OPC)
- Phase Shift Masks (PSM)
- Assist Bars
- Double Exposure

\{ Mask Design Problem \}
Optical Proximity Correction (OPC)

Pre-distort the pattern such that it cancels out for the process losses to come.

Figure from F. Schellenbeg, “A Little Light Magic”, *IEEE Spectrum*, 40 (2003)
Phase-Shift Masks (PSM)

180 degree phase-shift creates destructive interference giving a dark line and good contrast.
Inverse Lithography Mask Design (ILT)

\[ z(x, y) = T\{m(x, y)\} \]

Output intensity function \( z(x, y) \)

Known Forward Model \( T\{\cdot\} \)

Input intensity function \( m(x, y) \)

Imaging System: \( T\{\cdot\} \)

\[ z(x, y) \approx z^*(x, y) \]

\[ \hat{m}(x, y) = \arg \min_{m(x,y)} d(z^*(x, y), T\{m(x, y)\}) \]
Imaging System

**Past Work:** Integer Optimization, Genetic Algorithms, etc.

**Our Goal:** Continuous function formulation.

\[
\Gamma(u) = \begin{cases} 
0, & u \leq t_r \\
1, & u > t_r 
\end{cases}
\]
Approximated Forward Model (Coherent Imaging)

\[ \mathbf{m}, \mathbf{z}, \mathbf{z}^* \in \mathbb{R}^{MN \times 1} \rightarrow \text{Sampling and lexicographic ordering.} \]

Aerial Image

- Convolution (H)
  - Cutoff = NA/\( \lambda \)

- \(|Hm|^2\)
  - Intensity

Resist

- Sigmoid
  - Thresholding

\[ z = \text{sig}(|Hm|^2) \]

Close to binary

\[ h(x, y) = jinc(r) = \frac{J_1(2\pi r \frac{NA}{\lambda})}{2\pi r \frac{NA}{\lambda}} \]

\( J_1(.) \rightarrow \text{Bessel function of the first kind} \)
Sigmoid Function and Process Model

Continuous function which approximates the hard-threshold operation.

\[
\text{sig}(u) = \frac{1}{1 + e^{-a(u-t_r)}}
\]

- \(a\) → steepness of the function.
- \(t_r\) → resist threshold.

\[
z(m) = z = \text{sig}(\|Hm\|^2)
\]

\[
z_i = \frac{1}{1 + \exp \left[ -a \left( \sum_{j=1}^{MN} h_{ij} m_j \right)^2 + at_r \right]}
\]

for \(i = 1, \ldots, MN\)
Optimization Problem

\[ \widehat{m} = \arg \min_m F(m) = \arg \min_m |z^* - z|^2 \]

\[ = \arg \min_m \sum_{k=1}^{MN} (z_k^* - z_k)^2 \]

subject to the following constraints:

<table>
<thead>
<tr>
<th>RET</th>
<th>Allowable transmission values (constraints on ( m_j ) for j=1,…,MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>0 or +1</td>
</tr>
<tr>
<td>6% attenuated PSM</td>
<td>-0.2449 or +1</td>
</tr>
<tr>
<td>18% attenuated PSM</td>
<td>-0.4243 or +1</td>
</tr>
<tr>
<td>Strong PSM (100% transmission)</td>
<td>-1 or +1</td>
</tr>
<tr>
<td>Strong PSM (With chrome)</td>
<td>-1 or 0 or +1</td>
</tr>
</tbody>
</table>

Integer Optimization Problem!
Continuous Function Formulation

Consider **OPC** mask design for **coherent** systems

\[ m_j = 0 \text{ or } 1 \]

\[ 0 \leq m_j \leq 1 \Rightarrow \text{Bound constraints (continuous)} \]

\[ \theta \text{ is the unconstrained parameter vector} \]

\[ \nabla F^c(\theta) = a(H^T[(z^* - z) \cdot z \cdot (1 - z) \cdot (Hm)] \cdot \sin(\theta) \]

**Relax the constraints**

**Parametric transformation**

\[ m_j = \frac{1 + \cos(\theta_j)}{2} \]

**Convolution**

**Element-by-element multiplication**

**Convolution**
Regularization Framework

- Inverse Lithography is an ill-posed problem.
- Estimated masks still have continuous transmission values.
- Pixel-based masks are complex and difficult to manufacture.
- We prefer certain solutions more than others. This information can be incorporated as a prior knowledge about the solution.
- Regularization framework can be employed to promote certain desirable properties in the solution.

\[
\hat{m} = \arg \min_m \left[ \gamma_{fid} F(m) + \gamma_{reg} R(m) \right]
\]

- Contour Fidelity term
- Regularization function (penalty term)
- Weighing parameters \( \gamma_{fid}, \gamma_{reg} \)
Regularization Framework

Discretization Penalty \( (R_{\text{dis}}(m)) \)
Penalize and curb transmission values not equal to 0 or 1 using quadratic or quartic penalty terms.

\[
R_{\text{dis}}(m) = \sum_{j=1}^{MN} \left[ 1 - (2m_j - 1)^2 \right]
\]

Complexity Penalty \( (R_{TV}(m)) \)
An \( L_1 \) norm based penalty term to curb the complexity of the masks,

\[
R_{TV}(m) = \|\nabla m\|_1
\]
1: OPC for Incoherent System

$\text{NA} = 1.2$, $\lambda = 193\text{nm}$, $\sigma = 1$, $t_r = 0.5$, $\gamma_{fid} = 1$, 5nm sampling

60nm features $\Rightarrow k_1 = 0.37$
1: OPC for Incoherent System (Reg)

\[ \gamma_{fid} = 1, \quad \gamma_d = 0.005, \quad \gamma_c = 0.2 \]

Binary Masks

Binary Output

Error = 1150  Error = 177

60nm features \( \Rightarrow k_1 = 0.37 \)
2: Compare with Integer Optimization

Square aperture, incoherent illumination.

✓ Fidelity was the same (equal to zero).
✓ Run-time 5 seconds (compared to 20-25 minutes reported in 1995).

3: Assist bars for 100nm contact hole (Coherent System)

\[ \text{NA} = 0.85, \ \lambda = 193\text{nm}, \ \sigma = 0, \ t_r = 0.3, \ k_1 = 0.44, \ 10\text{nm pixels.} \]

- Assist features are small features below the resolution limit of the imaging system.
- Help improve contrast of the main feature.
4: 50nm feature using PSM \((NA=0.85, \lambda=193\text{nm}, \sigma=0, t_r=0.3)\)

**Estimated mask**

- **6% EPSM**
  - Black = -0.2449
  - White = 1

- **Strong PSM**
  - Gray = -1
  - Black = 0
  - White = 1

- **100% transmission PSM**
  - Black = -1
  - White = 1

**Aerial Image**

**Binary Output**

**Unintuitive Masks!!**
The aerial image slices show a good contrast especially for strong PSM.
Side-lobes are below the resist threshold.
5: Intel Fab Results (0.93NA/60nm feature/$k_1=0.289$)

CPL: Black=-1, White=1

sigma = 0.2 (partial coherence)
Impact and Conclusions

- Mask design problem was formulated as continuous function unconstrained optimization problem.

- First ones to calculate and report analytic gradient. Computationally efficient \(\Rightarrow\) extendible to full-chip level.

- Regularization framework introduced to incorporate user-constraints.

Double Exposure

**Why Double Exp?**

- Aerial image contrast poor for very low $k_1$ values → Sensitive to process variations.
- Single exp has phase conflict problem if odd number cycles present.

```
Input Mask # 1
   ^
  |   
Exposure # 1
  |   
Exposure # 2
  |   
Develop

T{,}

Input Mask # 2
  |   
\hvec{b} \quad \hvec{a}

DEL-ILT

\hvec{b} \quad \hvec{a}
```

Output (Wafer) Pattern $z$

Desired $z^*$
DEL-ILT Result

Aerial Image 1
Aerial Image 2
Combined Aerial Image

Single Exp