An Automatic Optical-Simulation-Based Lithography Hotspot Fix Flow for Post-Route Optimization

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This work summarized in one picture
Motivation

- Lithography hotspots impacts IC manufacturing
- Reroute makes too much change, OPC makes too little change
- Local Fix in post-route stage is most suitable for fixing litho hotspots
- Issues in local fix:
  - Generation of local fix
  - How many local fix is enough to fix?
Outline

- Lithography & OPC Introduction
- Previous Work
- Our Optical Simulation Engine
- Correlation between Pre-OPC & Post-OPC Schemes
- Fix Action & Fix Guidance
- Fix Flow
- Experiment Result
- Conclusions
Lithography Introduction (1)

Illumination

- Light source, $\lambda$
- Condenser pupil
- Condenser lens

Projection

- Mask/Reticule
- Projection pupil
- Projection lens
- Photoresist wafer
Lithography Introduction (2)

- Impact of process node shrinking down
  - Gets serious as wavelength is comparable with feature. (Diffraction)
  - 193 nm to expose 90 nm $\rightarrow$ 65 nm $\rightarrow$ 45 nm...

.. Courtesy of Numerical Technologies
OPC

- OPC – Optical Proximity Correction
  - Add features to original shapes
  - Hammer Head (Mickey Ear), Line Biasing, Serif...

Original Layout
Lithography Hotspot

Litho Hotspot
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Previous Work

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Our Optical Simulation Engine

- Derived from Hopkin’s equation, the intensity function can be approximated as:
  \[ I(x_i, y_i) \approx \sum_{k=1}^{n} \alpha_k |(f \otimes \phi_k)(x_i, y_i)|^2, \]

- We use sinc \((kx)\) as the kernel function.
Our Optical Simulation Engine v.s. Prolith Simulation
Our Optical Simulation Engine v.s. Prolith Simulation

- Skipped detailed manufacturing parameters
- Fast
  - Our engine: 4 seconds
  - Prolith: 232 seconds
- Acceptable precision to be used in router.
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Pre- v.s. Post-OPC intensity map

(a) Simulation Cut Line

Polygon Moved Direction

(b) Normalized Intensity Profile

Location Along Simulation Cut Line

Post-OPC before Move
Pre-OPC before Move
Post-OPC after Move
Pre-OPC after Move
Pre-OPC v.s. Post-OPC schemes

- Much difference in the simulated contours
- Similarity observed in terms of shape move
- The fix percentage of a HS → Area integration of light intensity

\[
\Delta O_A = \int I_{A}^{\text{posc}}(x, y) dx dy - \int I_{A}^{\text{prsc}}(x, y) dx dy
\]  

\[
\Delta O_B = \int I_{B}^{\text{posc}}(x, y) dx dy - \int I_{B}^{\text{prsc}}(x, y) dx dy
\]
Correlation Coefficient = 0.88

(a) Jog shift
(b) Line end extension
(c) Wire break & move
(d) $\Delta O_A$ v.s. $\Delta O_B$ Statistics
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Optimal Shape Change
Amount
Optimal Shape Change in Taylor Expansion

- Expand \( I(x_i, y_i) \approx \sum_{k=1}^{n} \alpha_k \left| (f \otimes \phi_k)(x_i, y_i) \right|^2 \), with Taylor Expansion.

- Try every “Manufacturing grid” in the following equation

\[
I(d_x, d_y) \equiv I(a, b) + \frac{1}{1!} \left[ \frac{\partial I(a, b)}{\partial d_x} (d_x - a) + \frac{\partial I(a, b)}{\partial d_y} (d_y - b) \right] \\
+ \ldots + \frac{1}{n!} \left[ \frac{\partial^n I(a, b)}{\partial d_x^n} (d_x - a)^n + \ldots + \frac{\partial^n I(a, b)}{\partial d_y^n} (d_y - b)^n \right] \\
R(d_x, d_y) = \frac{1}{(n+1)!} \left[ \frac{\partial^{n+1} I(c_x, c_y)}{\partial d_x^{n+1}} (d_x - a)^{n+1} + \ldots + \frac{\partial^{n+1} I(c_x, c_y)}{\partial d_y^{n+1}} (d_y - b)^{n+1} \right],
\]

\((c_x, c_y) \in [a, b], (d_x, d_y) \in [(a - \frac{h_x}{2}, b - \frac{h_y}{2}), (a + \frac{h_x}{2}, b + \frac{h_y}{2})]\)
Fix Action v.s. Fix Guidance

FA is “Fix Action”, Fix Guidance is composed by one or several FAs.
For Ex:
FG1 = \{FA1\}
FG2 = \{FA1, FA2\}
FG3 = \{FA1, FA3, FA4\}
Fix Rate v.s. FA # (K) in FG

Fix Rate

$k$ (number of fix actions in the fix guidance)

- C
- A
- B
Generate Fix Guidances

- The more FA, the better fix rate
- FG generation Algorithm (Kmax = 14, \( \rho \approx 0.2 \), from experiments.)
  1. Get All fix action sets, \( Sfa = \{ fa1, fa2, \ldots \} \).
  2. Choose \( K, K-1, K-2 \) exclusive FAs from \( Sfa \) that yields gain > \( Th \). Name the set of FG as FGs.
  3. Sort FGs according to gain
DRC Avoidance

(a) Original fix action (line end ext) will create DRC violation
(b) Taylor the line end extension to avoid DRC
(c) Original fix action (shift) will create DRC violation
(d) Taylor the shift to avoid DRC violation
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Algorithm OSELF (design $D$, hotspot set $hss$)

Begin

    $fix\_count = 0$

    foreach (hotspot $hs$ in $hss$) do

        $fas = \text{Fix\_Action\_Set\_Generation\_By\_Aerial\_Image\_Simulation}(D, hs);$ 
        $fgs = \text{Fix\_Guidance\_Set\_Generation}(fas);$ 
        \text{Sort\_Fix\_Guidance\_By\_Gain}(fas); 
        $is\_hotspot\_clean = \text{False};$

        foreach (fix guidance $fg$ in $fgs$) do 

            $DRC\_number = \text{Try\_Fix}(D, fg);$ 
            \textbf{if} ($DRC\_number > 0$) \textbf{then} 
                \text{Try\_Tailor\_Fix\_Actions}(D, fg);  
                $is\_hotspot\_clean = \text{Local\_Lithographical\_Compliance\_Check}(D, hs);$ 
                \textbf{if} ($is\_hotspot\_clean = \text{True}$) \textbf{then do} 
                    \text{Accept\_Fix}(D, fg); 
                    \textbf{break;} 
                \textbf{end}

        \textbf{end}

    \textbf{end}

\textbf{end}
**OSelf Fix Flow**

1. Get suitable litho optical simulation parameters of pre-OPC layout for litho optical calculating engine.
2. Perform full-chip lithography check to get hotspots by commercial tool.
3. Local optical calculation to get fix actions.
4. Fix guidance generation from fix action set.
5. Layout modify in router by choosing one fix guidance.
6. Perform local litho graphic check in changed area by commercial tool.
7. Keep best result.
8. Tried all fix guidances?
   - Yes: Accept new layout.
   - No: Hotspot fixed?
     - Yes: Accept new layout.
     - No: Tried all fix guidances?
Time Complexity of Our Alg-
Linear

- # of manufacturing grids in one pitch is fixed.
- Constant run time in substituting the positions into Taylor expansion eq.
- Limited # of shape changes to 14 in one FG.
- For every changeable shape, the max shape change is 8 (Ext in 4 directions, move in 4 directions)
- Max Fix guidance is limited due to only K, K-1, K-2 fix actions will be selected, max K is 14.
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Testcases

- Testcase info: Three 65-nm industry designs. Pitch: 200 nm (low layers), 400 nm (high layers)
- DVR: Double-Via rate

<table>
<thead>
<tr>
<th>Design</th>
<th>Size(mm^2)</th>
<th>#Layers</th>
<th>#Nets</th>
<th>#Pins</th>
<th>DVR*</th>
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<tbody>
<tr>
<td>A</td>
<td>1.5 × 1.5</td>
<td>6</td>
<td>30981</td>
<td>199856</td>
<td>3.26%</td>
</tr>
<tr>
<td>B</td>
<td>0.9 × 4.0</td>
<td>7</td>
<td>7915</td>
<td>41552</td>
<td>59.7%</td>
</tr>
<tr>
<td>C</td>
<td>0.6 × 0.6</td>
<td>9</td>
<td>31290</td>
<td>129823</td>
<td>45.6%</td>
</tr>
</tbody>
</table>
Experiment Result (1) - OSELF

(a)  

(b)  

(c)  

(d)  

Graduate Institute Electronic Engineering, NTU
Experiment Result (2) – unfixed HS
Experiment Result (2) – fixed HS
Experiment Result (3) - OSELF

- Fix Rate > 86% for three 65-nm real designs
- 1.4X ~ 1.9X fix rate compared with Industry tool.
- No circuit timing impact

<table>
<thead>
<tr>
<th>General Info</th>
<th>Our Flow</th>
<th>Industry Flow</th>
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</thead>
<tbody>
<tr>
<td>Design</td>
<td>Detected Hotspot Number</td>
<td>Fixed Hotspot Number</td>
</tr>
<tr>
<td>A</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>B</td>
<td>341</td>
<td>295</td>
</tr>
<tr>
<td>C</td>
<td>162</td>
<td>146</td>
</tr>
</tbody>
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Conclusions

- Fast optical simulation engine
- 0.88 correlation coefficient between pre-OPC and post-OPC schemes
- Automatic Fix Action generation
- An effective & efficient heuristic to generate Fix Guidance.
- High Fix Rate in OSELF (1.4~1.9X)
Acknowledgements

- Thank for Synopsys RDs to provide suggestions and help.
- Thank for Prof. Way-Seen Wang, National Taiwan Uni., for building up the optical simulation engine.
- Thank for Prof. Tsung-Yi Ho, National Cheng-Kong Uni., for suggesting us to submit to ISPD.
Thank you for your attention!

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