Metal-Density Driven Placement for CMP Variation and Routability

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Outline

• Introduction
• Review of NTUplace3
• Metal-density driven placement
• Experimental results
• Conclusion
Placement

• Fundamental VLSI problems
  – Placement
  – Routing

• Significant impact on VLSI
  – Wirelength
    ■ Performance
  – Routability
    ■ Routing complete rate
  – Manufacturability
    ■ Topography variation after CMP
Chemical Mechanical Polishing (CMP)

- CMP: Key multilevel metallization technique in deep submicron design

- CMP variation
  - Performance degradation due to increase resistance
  - Printability issues due to non-uniform surface (depth-of-focus)
  - Systematic variation due to non-uniform metal density distribution (dummy fills)
Placement Objectives

- Placement is a fundamental VLSI physical synthesis problem
  - Wirelength-driven placement
  - Timing-driven placement
  - Routability-driven placement
  - Cell-density driven placement

Metal-density has never been considered!
Metal-Density Driven Placement

• Metal-density driven routing was studied by Cho et al., in ICCAD-2006.
  – The average CMP variation is reduced by 7.5%.
  – Metal density is highly related to placement since the metal density optimization in routing is often limited by pin locations.

• Effectively distributing pins and cells into a placement region with metal density consideration can provide better flexibility for routing, leading to better wire density topography.
Outline

• Introduction
• *Review of NTUplace3*
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NTUplace3

• T.-C. Chen, Z.-W. Jiang, T.-C. Hsu, H.-C. Chen and Y.-W. Chang, "A high-quality mixed-size analytical placer considering preplaced blocks and density constraints" [ICCAD-2006]

• NTUplace3
  – Handles preplaced blocks and density constraints
  – Is based on the multilevel framework
  – Uses an analytical model
  – Obtained the best average placement quality based on the results reported in [Viswanathan et al., DAC-2007] (Was tied with RQL.)
Placement with Density Constraint

- Given the chip region and block dimensions, divide the placement region into bin grids
- Determine \((x, y)\) for all movable blocks

\[
\begin{align*}
\min & \quad W(x, y) \quad \text{-- wirelength function} \\
\text{s.t.} & \quad 1. \; \text{Density}_b(x, y) \leq \text{MaximumDensity}_b \\
& \quad \text{for each bin } b \\
& \quad 2. \; \text{No overlap between blocks}
\end{align*}
\]

\[
\text{Density} = \frac{A_{\text{block}}}{A_{\text{bin}}}
\]
Multilevel Global Placement

Cluster the blocks based on connectivity/size to reduce the problem size.

Iteratively decluster the clusters and further refine the placement.

Initial placement

clustering

clustering

declustering & refinement

declustering & refinement

clustered block

....... chip boundary
Analytical Placement Model

• Global placement problem (allow overlaps)

\[
\begin{align*}
\min & \quad W(x, y) \\
\text{s.t.} & \quad D_b(x, y) \leq D_b^{\text{max}}
\end{align*}
\]

Minimize HPWL
\(D_b: \) density for bin \(b\)
\(D_b^{\text{max}}: \) max density for bin \(b\)

• Relax the constraints into the objective function

\[
\min \quad W(x, y) + \lambda \sum (D_b(x, y) - D_b^{\text{max}})^2
\]

– Use the gradient method to solve it
– Increase \(\lambda\) gradually to find the optimal \((x, y)\)
Placement Process

Increase density weight

Increase density weight

STOP! Spreading enough!
Outline

• Introduction
• Review of NTUplace3
• *Metal-density driven placement*
• Experimental results
• Conclusion
Framework

1. Placement Database
2. Predictive CMP model
3. Wire Density Estimator
4. Wire Density / Metal Density
5. Analytical Placer

Move cells to reduce metal density variation.
Wire Density Estimator

- Wire density of a bin is computed by the number of track go through the bin boundary and the internal routing in the bin.
- To predict the track usage, we decompose multi-terminal nets into Steiner trees using FLUTE. [Chu, ISPD04]
- Track usage is estimated by the probabilistic routing model. [Lou, Thakur, and Krishnamoorthy, TCAD02]
Predictive CMP Model

• A fast CMP model is desired
  - Use the predictive CMP model [ICCAD-2007]
• Cu thickness is systematically dependent on metal density
  \[ Cu_{\text{Thickness}} = \alpha \star (1 - \frac{Metal_{\text{density}}^2}{\beta}) \]

• Metal density = wire density + dummy fill density
• Wire density \rightarrow Dummy fill \rightarrow Metal density
Concept of Reducing Metal Density

- Move cells out from high metal-density regions.
- Add forces to blocks in high metal-density regions.
- Result in more uniform metal density.
Metal-Density Driven Placement Formulation

- \[ \min W \]
- \[ \text{s.t.} \quad D_b \leq D_{b,\text{max}} \]
- \[ M_{b,v} \leq M_{b,v,\text{max}} \]
- \[ M_{b,h} \leq M_{b,h,\text{max}} \]

- Relax all constraints to objective function may cause instability of the solver and may not converge to a feasible solution.

- Instead, we solve the following equation to ensure the stability:

  \[ \min W + \lambda_1 \sum (D_b - D_{b,\text{max}})^2 + \lambda_2 \sum (M_{b,v} - M_{b,v,\text{max}})^2 \]
  \[ + \lambda_3 \sum (M_{b,h} - M_{b,h,\text{max}})^2 \]

- Instead of

  \[ \min W + \lambda \sum (D_b - D'_{b,\text{max}})^2 \]

  \(D'_{b,\text{max}}\) maximum combined density (preplaced density + metal density)
Computing Maximum Combined Density

\[ D'_{b_{\text{max}}} = \text{target}_\text{utilization}(1.0 - \text{combined}_\text{density}) \]

\[ \text{combined}_\text{density} = \text{preplaced}_\text{density} + \text{scaled}_\text{metal}_\text{density} \]

\[ \text{scaled}_\text{metal}_\text{density} = s_1( M_{b^v} - \min M_{b^v} ) + s_2 (M_{b^h} - \min M_{b^h}) \]
Density Smoothing

- A smooth objective function helps the gradient method to find a desired solution.

Gaussian smoothing
\[ G(x, y) = \frac{1}{2\pi \sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \]

Level smoothing
\[ p'(x, y) = \begin{cases} \frac{\bar{p} + (p(x, y) - \bar{p})}{\bar{p}} & \text{if } p(x, y) \geq \bar{p} \\ \frac{\bar{p} - (\bar{p} - p(x, y))}{\bar{p}} & \text{if } p(x, y) \leq \bar{p} \end{cases} \]

- Three smoothing parameters
  - \( k \) gradually increases to the user-specified whitespace ratio
  - \( \sigma \) controls the range of the Gaussian smoothing (15% to 1%)
  - \( \delta \) controls the degree of level smoothing (5 to 1)
Flow

- Loop 1 (L1)
  - Multilevel
- Loop 2 (L2)
  - Objective function
- Loop 3 (L3)
  - Solver

The metal density is updated inside the L3, and the base potential is updated accordingly.

The smoothing parameters are updated in L2.

<table>
<thead>
<tr>
<th>Multilevel Metal-Density Driven Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong>: a circuit hypergraph</td>
</tr>
<tr>
<td><strong>Output</strong>: desired block positions</td>
</tr>
</tbody>
</table>

01. create the clustering hierarchy;
02. initialize block positions;
03. do
04. initialize the bin structure and $\lambda$;
05. do
06. Update smoothing parameters;
07. // find min $W(x, y) + \lambda \sum (D_b - a_b)^2$;
08. do
09. compute the conjugate gradient direction;
10. update current block positions;
11. Estimate wire and metal density;
12. Update combined density;
13. until (the minimal value is found);
14. increase $\lambda$ by 2;
15. until (spreading enough);
16. decluster blocks;
17. until (all clusters are declustered);
18. legalize the placement;
19. return block positions;
Outline

• Introduction
• Review of NTUplace3
• Metal-density driven placement
• *Experimental results*
• Conclusion
Experiment Setup

- CPU: AMD Opteron 2.2GHz
- Benchmarks: adaptec from ISPD’06
- Placement: NTUplace3 (ICCAD’06)
- Routing: BoxRouter (DAC’06, ICCAD’07)
- Routing configurations (from ISPD’07)
  - Six metal layers; 20% tracks available in metal 1 and metal 2
  - Block porosity: the reaming routing resource above the macros
- Predictive CMP model for computing Cu thickness

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Placement</th>
<th>Routing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mov #</td>
<td>Fixed #</td>
</tr>
<tr>
<td>adaptec1</td>
<td>211k</td>
<td>543</td>
</tr>
<tr>
<td>adaptec2</td>
<td>254k</td>
<td>566</td>
</tr>
<tr>
<td>adaptec3</td>
<td>451k</td>
<td>723</td>
</tr>
<tr>
<td>adaptec4</td>
<td>495k</td>
<td>1329</td>
</tr>
<tr>
<td>adaptec5</td>
<td>842k</td>
<td>646</td>
</tr>
</tbody>
</table>

B.P.: macro block porosity
Placement Techniques Compared

1 Wirelength-driven placement (WLD)
   - Minimize wirelength
   - Target utilization = 1.0

2 Cell-density driven placement (CDD)
   - Evenly distribute cells over the chip
   - Target utilization = design density

3 Metal-density driven placement (MDD)
   - Spread cells to minimize metal density variation
   - Set $\text{max } k = 90\%$ to use 90% whitespace for metal density optimization
## Results

### Wirelength-Driven (WLD)

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Placement</th>
<th>Routing</th>
<th>CMP (Hor. Layer)</th>
<th>CMP (Vert. Layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HPWL</td>
<td>CPU</td>
<td>WL</td>
<td>Over-</td>
</tr>
<tr>
<td>adaptec1</td>
<td>8.15 (× e7)</td>
<td>14</td>
<td>11.87 (× e7)</td>
<td>1.46</td>
</tr>
<tr>
<td>adaptec2</td>
<td>9.02 (× e7)</td>
<td>15</td>
<td>12.38 (× e7)</td>
<td>1.37</td>
</tr>
<tr>
<td>adaptec3</td>
<td>22.35 (× e7)</td>
<td>32</td>
<td>26.27 (× e7)</td>
<td>1.18</td>
</tr>
<tr>
<td>adaptec4</td>
<td>20.02 (× e7)</td>
<td>29</td>
<td>22.38 (× e7)</td>
<td>1.12</td>
</tr>
<tr>
<td>adaptec5</td>
<td>36.09 (× e7)</td>
<td>76</td>
<td>47.36 (× e7)</td>
<td>1.33</td>
</tr>
<tr>
<td>Comp.</td>
<td>0.81</td>
<td>0.76</td>
<td>0.89 (× e7)</td>
<td>1.29</td>
</tr>
</tbody>
</table>

### Cell-Density Driven (CDD)

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Placement</th>
<th>Routing</th>
<th>CMP (Hor. Layer)</th>
<th>CMP (Vert. Layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HPWL</td>
<td>CPU</td>
<td>WL</td>
<td>Over-</td>
</tr>
<tr>
<td>adaptec1</td>
<td>9.20 (× e7)</td>
<td>15</td>
<td>12.12 (× e7)</td>
<td>1.32</td>
</tr>
<tr>
<td>adaptec2</td>
<td>10.32 (× e7)</td>
<td>17</td>
<td>13.08 (× e7)</td>
<td>1.27</td>
</tr>
<tr>
<td>adaptec3</td>
<td>27.42 (× e7)</td>
<td>28</td>
<td>31.19 (× e7)</td>
<td>1.14</td>
</tr>
<tr>
<td>adaptec4</td>
<td>22.61 (× e7)</td>
<td>52</td>
<td>24.67 (× e7)</td>
<td>1.09</td>
</tr>
<tr>
<td>adaptec5</td>
<td>38.90 (× e7)</td>
<td>67</td>
<td>49.62 (× e7)</td>
<td>1.29</td>
</tr>
<tr>
<td>Comp.</td>
<td>0.92</td>
<td>0.90</td>
<td>0.96 (× e7)</td>
<td>1.22</td>
</tr>
</tbody>
</table>

### Metal-Density Driven (MDD)

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Placement</th>
<th>Routing</th>
<th>CMP (Hor. Layer)</th>
<th>CMP (Vert. Layer)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HPWL</td>
<td>CPU</td>
<td>WL</td>
<td>Over-</td>
</tr>
<tr>
<td>adaptec1</td>
<td>9.41 (× e7)</td>
<td>17</td>
<td>11.54 (× e7)</td>
<td>1.23</td>
</tr>
<tr>
<td>adaptec2</td>
<td>11.63 (× e7)</td>
<td>23</td>
<td>13.63 (× e7)</td>
<td>1.17</td>
</tr>
<tr>
<td>adaptec3</td>
<td>30.35 (× e7)</td>
<td>38</td>
<td>34.10 (× e7)</td>
<td>1.12</td>
</tr>
<tr>
<td>adaptec4</td>
<td>26.40 (× e7)</td>
<td>35</td>
<td>28.69 (× e7)</td>
<td>1.09</td>
</tr>
<tr>
<td>adaptec5</td>
<td>39.82 (× e7)</td>
<td>110</td>
<td>48.73 (× e7)</td>
<td>1.22</td>
</tr>
<tr>
<td>Comp.</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00 (× e7)</td>
<td>1.17</td>
</tr>
</tbody>
</table>
## Result Summary

<table>
<thead>
<tr>
<th></th>
<th>CMP</th>
<th>Routability</th>
<th>Place</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness variation</td>
<td>Dummy fills</td>
<td>Total Overflow</td>
</tr>
<tr>
<td>WLD</td>
<td>1.12</td>
<td>1.06</td>
<td>30,399</td>
</tr>
<tr>
<td>CDD</td>
<td>1.03</td>
<td>1.02</td>
<td>903</td>
</tr>
<tr>
<td>MDD</td>
<td>1.00</td>
<td>1.00</td>
<td>0</td>
</tr>
</tbody>
</table>
Metal-Density Map for adaptec5

Vertical Routing Layer

1. WLD: Cu-Std = 5.70
2. CDD: Cu-Std = 4.54
3. MDD: Cu-Std = 4.45

Horizontal Routing Layer

1. WLD: Cu-Std = 5.73
2. CDD: Cu-Std = 4.58
3. MDD: Cu-Std = 4.52
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Conclusion

• Presented the first metal-density driven placement
  ─ Predictive CMP model
  ─ Metal-density-aware cell spreading
  ─ Density smoothing

• Compared with the wirelength-driven placement, we
  ─ Reduced the copper thickness variation by 12%
  ─ Reduced the dummy fills by 6%

• Results also led to higher routability
  ─ Less overflow
  ─ Less routing time
Thank You!

Questions?