Post-Routing Layer Assignment for Double Patterning

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Outline

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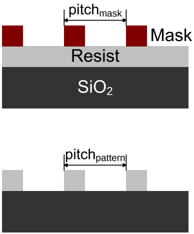
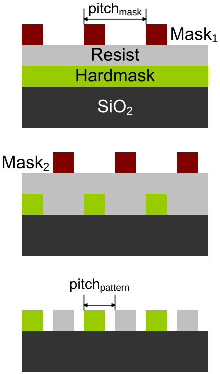
Double Patterning Lithography

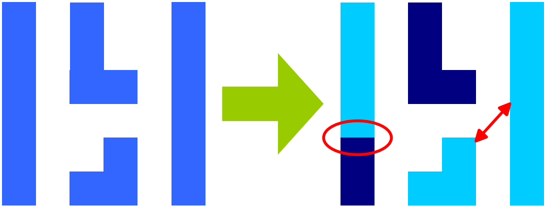
- As feature sizes keep shrinking, single exposure cannot support any more
- Extra one time of exposure is used to get the fine line in Double Patterning Lithography





Layout Decomposition

- During decomposing dense layout onto two masks, pattern can be split to resolve conflicts, which results in stitch
- Pattern split cannot resolve all conflicts
- Stitch has influence on electrical connection of the circuit
- The number unresolvable conflicts and stitches should be minimized in double patterning problem



Layout Decomposition

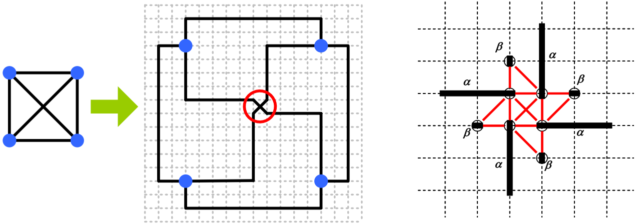
- Graph $G = (V, E)$ is constructed by nodes indicating rectangles and edges indicating electrical connections or adjacency between rectangles
  - Electrical connection corresponds to touching edge, which has negative weight
  - Adjacency corresponds to conflict edge, which has positive weight
- A bi-coloring solution is needed to decomposing the layout
- Max-Cut problem

NP-Hardness of Single Layer Double Patterning

- It is obvious that double patterning problem is NP
- Double patterning problem is at most NP-complete
  - Reduce from 4-degree Max-Cut problem to a special case of single layer double patterning
    - 4-degree Max-Cut is NP-complete
    - The reduction is polynomial time achievable
    - There is mapping relation between the Max-Cut and the double patterning solution

Reduction

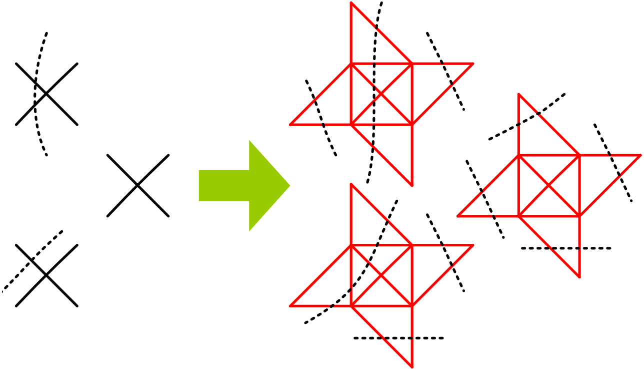
- Mesh drawing of any 4-degree undirected graph
- Cross point substitution with gadget



- 0 line width, $\sqrt{2}$ double patterning conflict length, mesh based layout
  - Black lines and nodes in gadget can be viewed as layout pattern
  - Red lines in gadget are conflict edges

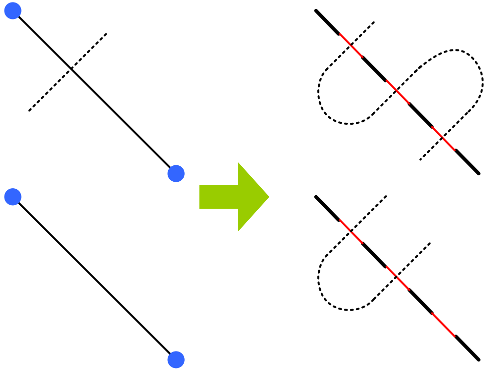
Reduction

- Each gadget substitution makes 8 edges contribution on Max-Cut in generated layout



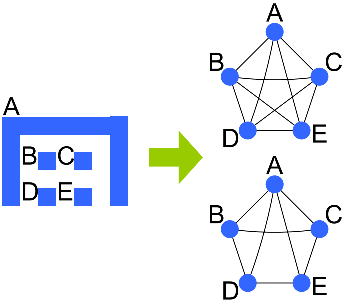
Reduction

- Outside of the gadget, the edges are subdivided
  - Turn an edge into $2i$ pattern sections, which are connected by $2i - 1$ double patterning edges
  - They make $2i - 2$ edges contribution on Max-Cut in generated layout



NP-Hardness of Single Layer Double Patterning

- Single layer double patterning problem in NP-complete
- When Manhattan distance is considered as double patterning conflict distance
  - The double patterning conflict graph is always planar
  - Max-Cut problem on it is not NP-hard



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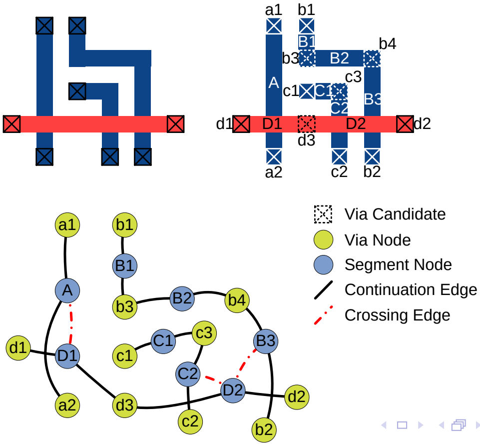
Multi Layer Assignment

- In multi-layer interconnection, wire sections must connect to some and must not connect to some others
  - Node: wire section, via candidate
  - Crossing edge: overlap sections from different net
  - Continuation edge: electrically connected sections



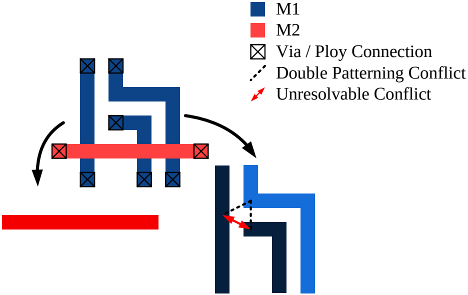
Layer Assignment for Via Minimization

- Layer assignment for each node
- Weight vector for each via candidate node
  - The number of layers this via goes through under this assignment
- Weight matrix for each edge
  - Whether short circuit happens on crossing edge (∞ or 0)
  - Whether open circuit happens on continuation edge (∞ or 0)

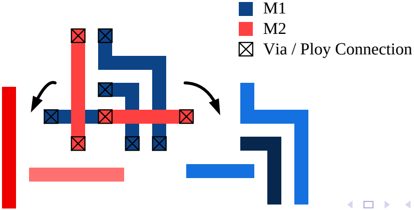
- When the graph is tree, dynamic programming can find the layer assignment to minimize the total weight
- Heuristic
  - Begin from a feasible layout
  - Randomly choose root node to expend a tree in the graph
  - Dynamic programming on the tree
  - Iteratively repeat until no more improvement is made

Outline

Influence of Layer Assignment on Double Patterning

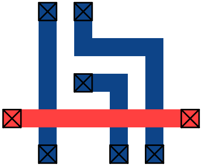


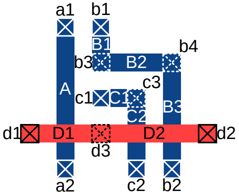
- The double patterning conflict can be resolved if we change the layer assignment of a rectangle

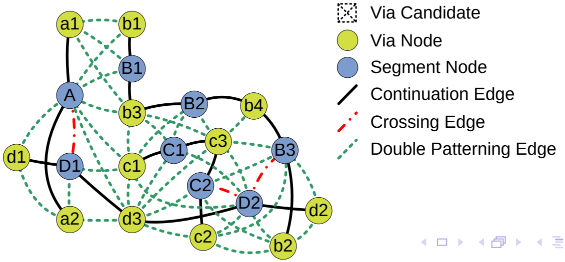


Graph Construction

- Consider double patterning distance in the multi layer graph
  - Double patterning edge: adjacent sections from different net, whose distance from each other is smaller than double patterning conflict distance and not zero.







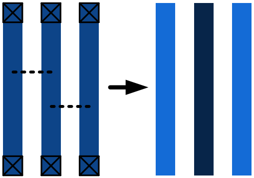
Weight Matrix on Double Patterning Edge

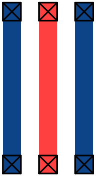
- If the layer assignments of two nodes has common metal layer, double patterning conflict would happen
- Otherwise, zero weight
- Similar as crossing edge, the difference is the penalty value

Framework

- Similar dynamic programming strategy is used to solve the weight minimization problem
- Single layer double patterning algorithms can be used on each reassigned metal layers separately

- In the weight minimization problem, the double patterning edge number is optimized instead of unresolvable conflict





- One more step to reduce the redundant vias is needed

Via Reduction

- Color information assigned in single layer double patterning is also considered into multi layer graph
- If changing a rectangle's layer can result in via reduction without increase of unresolvable conflict, we would accept that change.
- Weight matrix on double patterning edge indicates unresolvable conflict number
- Weight matrix on continuation edge indicates stitch number
- Dynamic programming on the updated graph

Outline

Unresolvable Conflict and Stitch Improvement

- Implemented in C++, tested on CBL testcases and compared with [Xu and Chu ICCAD09] and [Chang and Cong TCAD99]

Cases	#Node	#Edge	#URC	#Stitch	#Via
test1	4328	88708	12.41%	59.66%	111.38%
test2	8606	307086	31.44%	83.69%	103.16%
test3	11204	472908	29.86%	89.13%	102.99%
mcc1-75	11649	332446	27.97%	63.41%	112.37%
mcc2-75	67555	5350970	35.54%	67.44%	117.70%
average			27.44%	72.66%	109.52%

Improvement on bottom two metal layers

- Usually only the lowest two metal layers are double patterning layers
- Conduct the algorithm only on the bottom two layers

Cases	#Node	#Edge	#URC	#Stitch	#Via
test1	3600	51750	25.53%	86.21%	101.06%
test2	5585	82540	31.43%	88.95%	100.62%
test3	7394	122132	27.20%	89.81%	100.09%
mcc1-75	9323	185598	49.28%	99.01%	100.29%
mcc2-75	47917	1499986	57.67%	98.22%	100.04%
average			38.22%	92.44%	100.42%

Conclusions

- Single layer double patterning problem is NP-complete
- Layer assignment can be employed to reduce the number of unresolvable conflicts and stitches
- The three step algorithm we proposed is effective

Thank you!