Model Based Layout Pattern Dependent Metal Filling Algorithm for Improved Chip Surface Uniformity in the Copper Process

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Outline of Talk

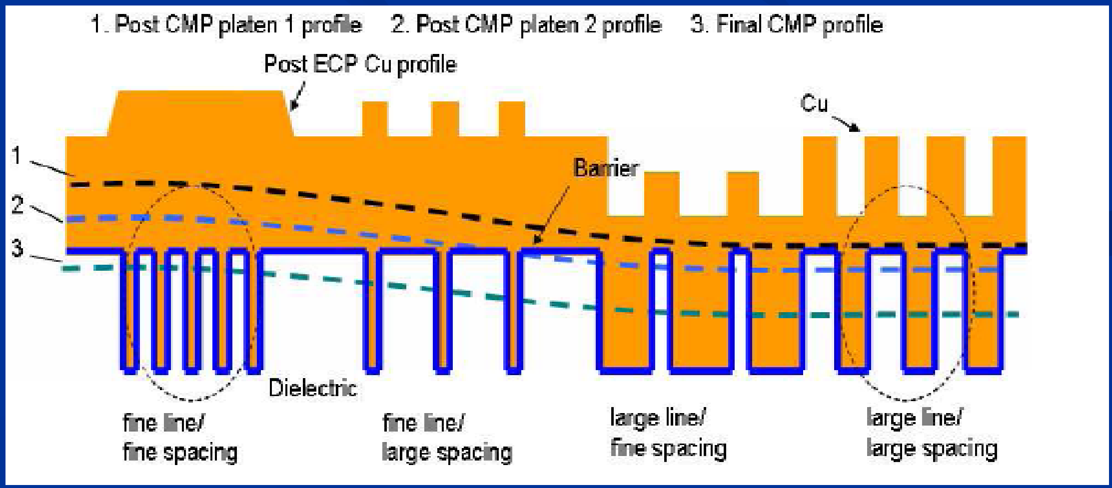
- **Motivation & Background**
- Predictors
- Proposed Metal Filling Algorithm
- Results and Conclusions

Motivation

- Aggressive scaling of feature sizes has necessitated better planarization of chip surface topography.
- Planar chip surface topography affects both:
  - Functional Yield: Depth of Focus (DOF) budget of lithography.
  - Parametric Yield: Metal and Dielectric Thickness Variation can adversely affect chip timing.
- Measure of planarization and key indicator of yield: Thickness Range
  - Thickness Range: Difference between the highest point and lowest point on the chip surface.

Factors affecting Thickness Range

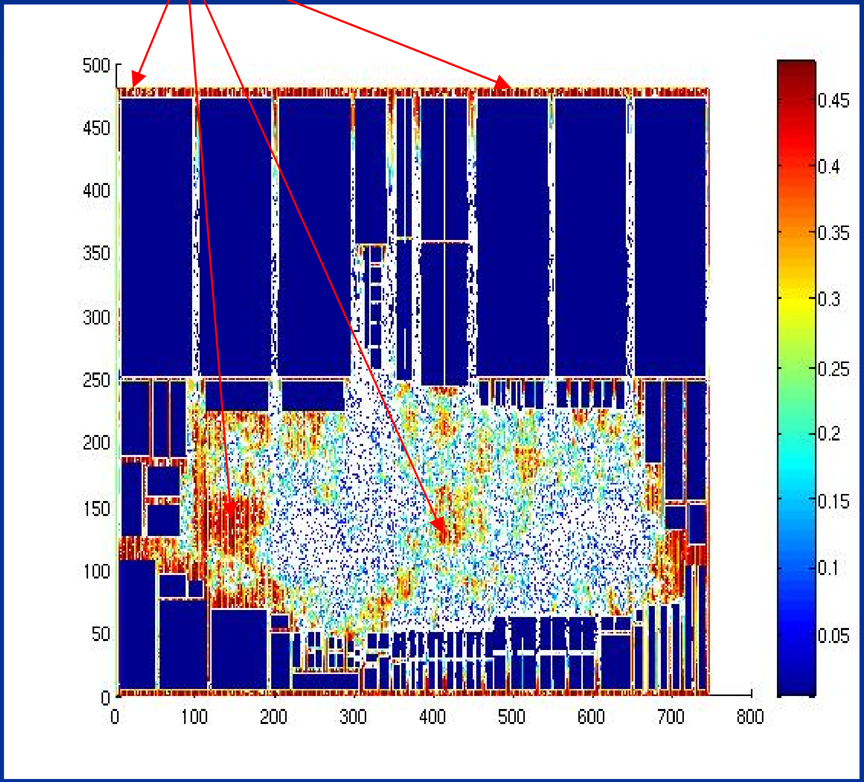
- Process Factors that decide thickness range in Dual-Damascene:
  - Electroplating (ECP): Process by which Cu is deposited in the Damascene process.
  - Chemical Mechanical Polishing (CMP): Process by which the overburden Cu is removed to create clearly defined interconnect wires.
- Design Factors that affect thickness range:
  - Variations in key layout parameters.
- Layout parameters in question depend on the process.
  - Density was the only key parameter for Al.
  - No longer true for Cu.



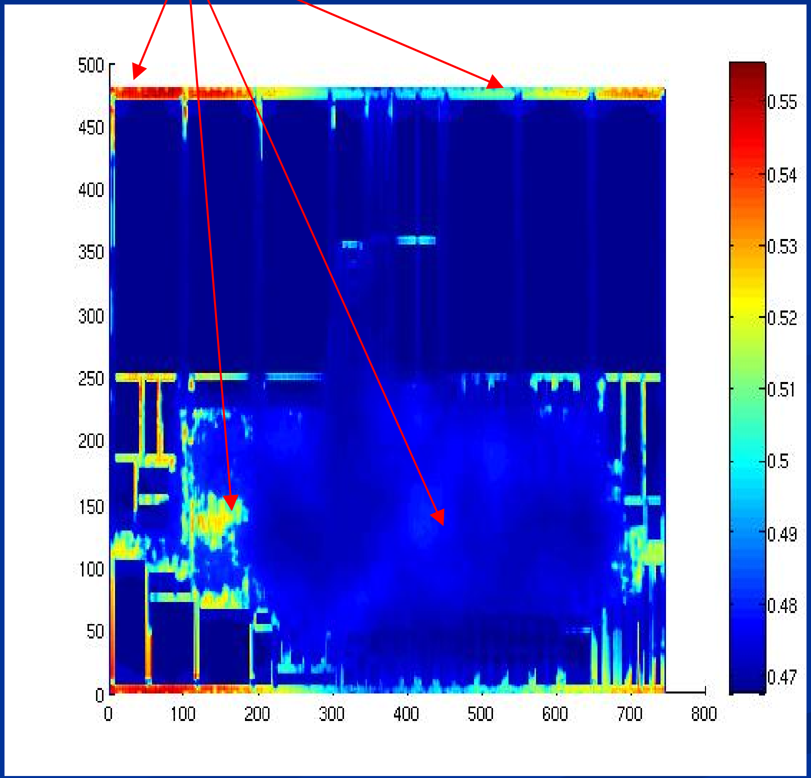
Density is not Enough!

Same Density

Different Thickness



Density Map



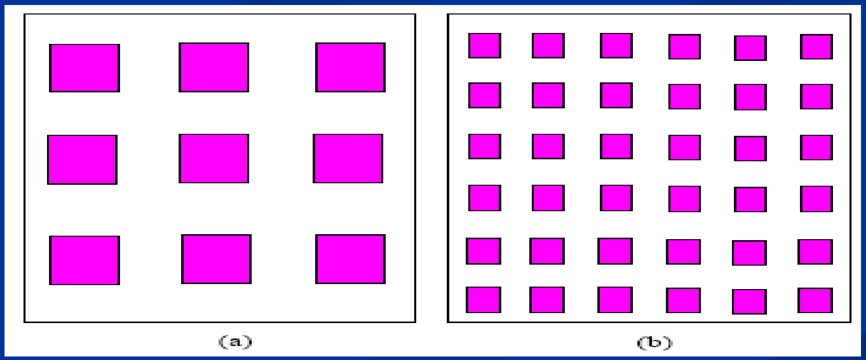
Thickness Map

Fixes at the Design Stage: Previous Work

- Metal filling:
  - Insert electrically inactive metals to alter relevant layout parameters and reduce their variations across chip.
- Previous solutions were primarily density-driven.
  - Developed primarily for Al.
  - Idea was to reduce the density variation across the chip with fill insertion.
  - Both rule-based and model-based solutions manipulated only density or some function of it.
  - Rule-based solutions are most commonly used in current EDA tools.
- Pure density-driven metal filling is not sufficient for planarization in the Cu process.

Key idea of our approach

- Re-target metal filling algorithm to look at both ECP (deposition) and CMP processes.
  - Deposition plays an important role in deciding final chip topography and is not considered in current metal filling algorithms.
- Metal filling algorithm needs to incorporate more layout characteristics than current metal filling solutions:
  - Density.
  - Perimeter.
  - Shrink Density.
  - Expansion Density.
  - …



Dummy patterns (a) and (b) need to be distinguished during filling [1].

Model used in Our Metal Filling

- Too computationally expensive to incorporate a comprehensive ECP+CMP simulator during metal filling.
  - Typical runtimes for a 8mm*8mm chip is 20 mins/layer.
  - Metal filling is inherently an iterative process.
- To make it computationally feasible, reliable predictors of final thickness range that can be efficiently computed have been identified.

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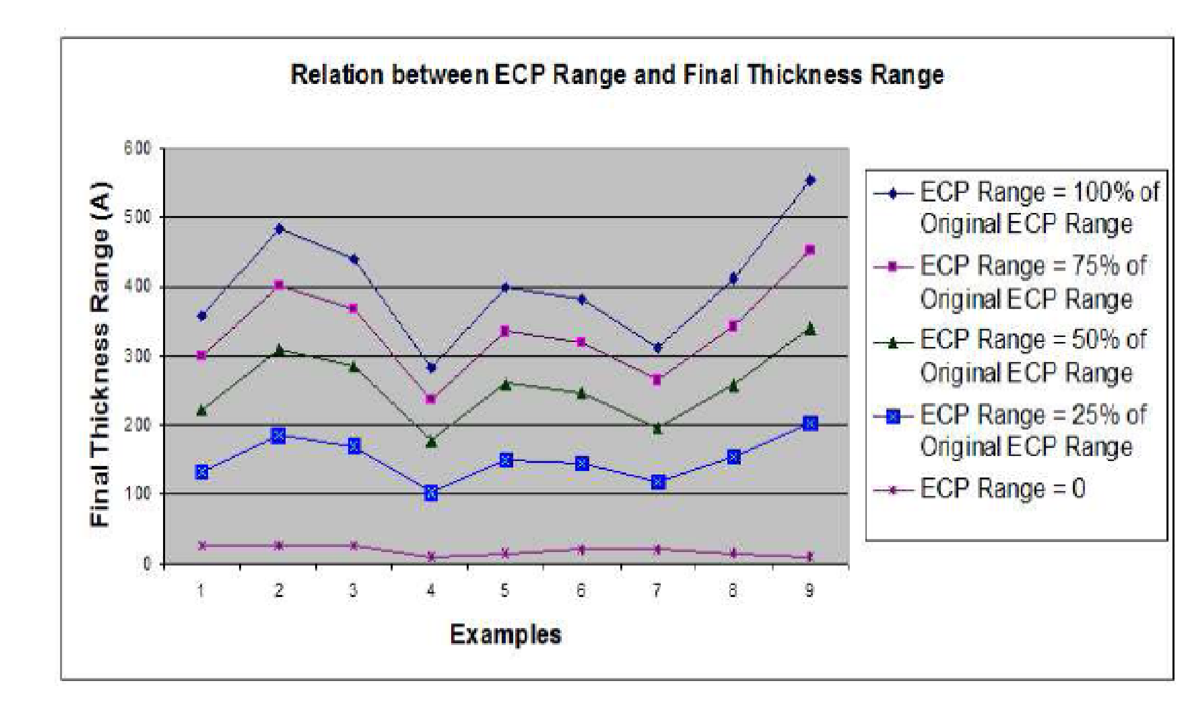
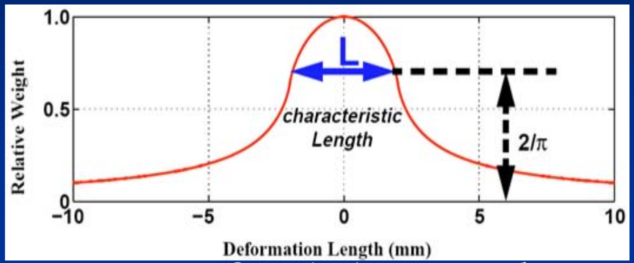
Predictors of Final Thickness Range (1)

- ECP thickness range: Difference between highest point and lowest point on the chip surface after ECP.



- For each example, CMP thickness range monotonically decreases as ECP thickness range is reduced.
- Thus, ECP thickness range is one predictor of final thickness range.
- Key Layout Parameters in ECP model:
  - Density and Perimeter.

Predictors of Final Thickness Range (2)



- Effective density range during CMP.
  - Effective density (ρ) = Convolution (d , w).
  - d = metal density.
  - w = weighting function which accounts for deformation of polishing pad.
    - Typical radius of weighting function: 40-120 um for Cu CMP.
- For same incoming ECP profile:
  - Smaller effective density range → Smaller final thickness range.
- Thus, effective density range is another predictor of final thickness range.

1. Both predictors can be efficiently computed, either analytically or using a look-up table.
2. Density and perimeter both need to be considered during metal filling.

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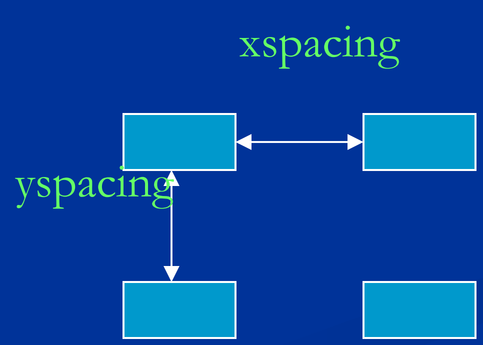
Overview of Model-Based Layout Parameter Dependent Metal Filling

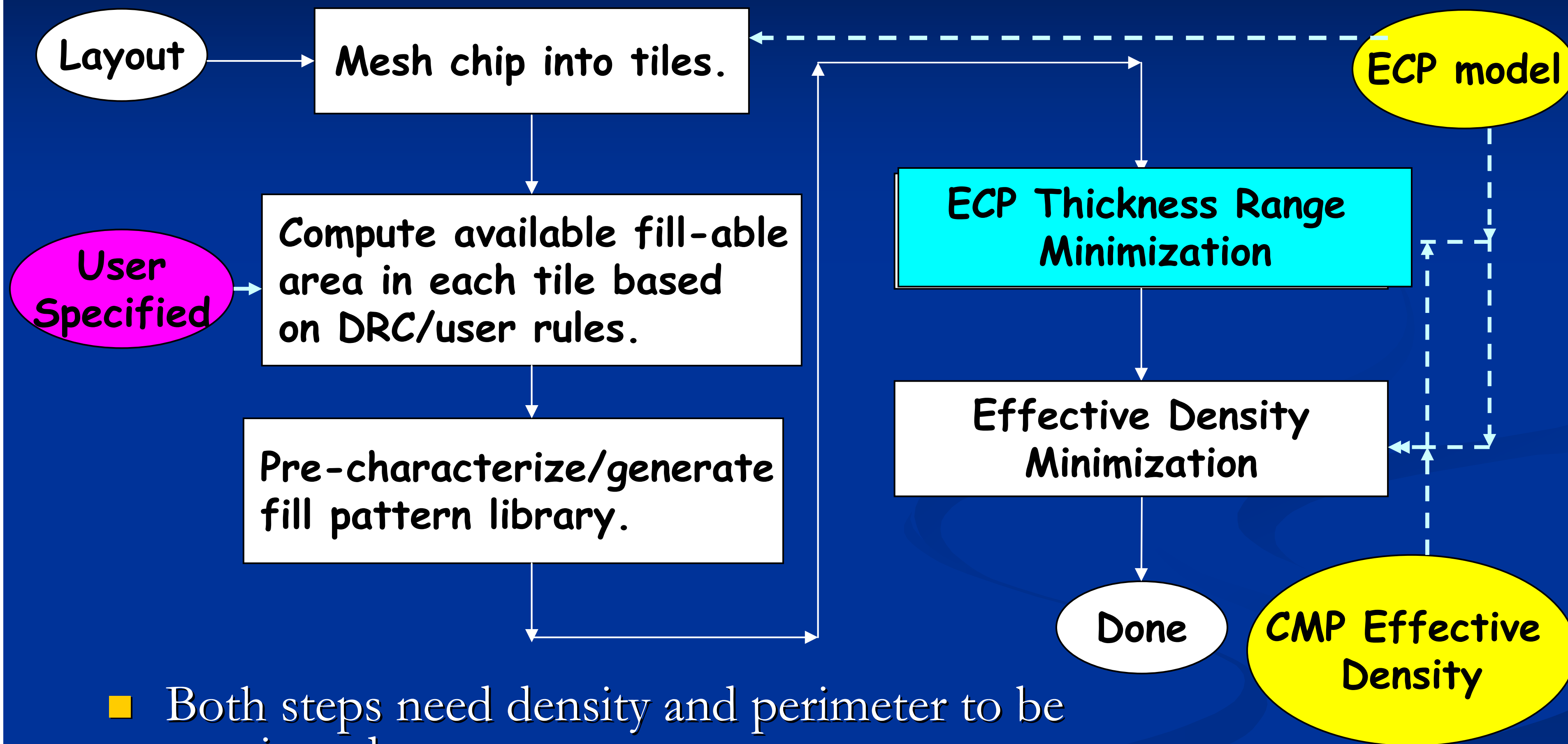
- Metal Filling Algorithm is tile-based.
  - Layout is divided into non-overlapping tiles and manipulations are in terms of tiles.
- Proposed metal filling is divided into two sequential steps:
  - Parameter Assignment
    - Determine the best density and perimeter targets for all tiles in the layout.
    - Predictors defined earlier are used in this step to guide the assignment process.
  - Fill Placement
    - Fills are selected to best match density and perimeter targets computed in assignment step.
- Parameter Assignment and Fill Placement are de-coupled for runtime efficiency.
  - To ensure predictable results, both steps use the same input information about the different types and configurations of fills that can be inserted.

Fill Pattern Library

- The same library of fill patterns is used both for parameter assignment and for metal filling.
- Each element in the library is a tuple: (length, xspacing, width, yspacing).
  - Fill dimensions = (length, width).
  - Spacing in the X-direction equal to xspacing and spacing in the Y-direction equal to yspacing.
  - Length can vary from minimum or user-defined width for the layer to maximum tile size.



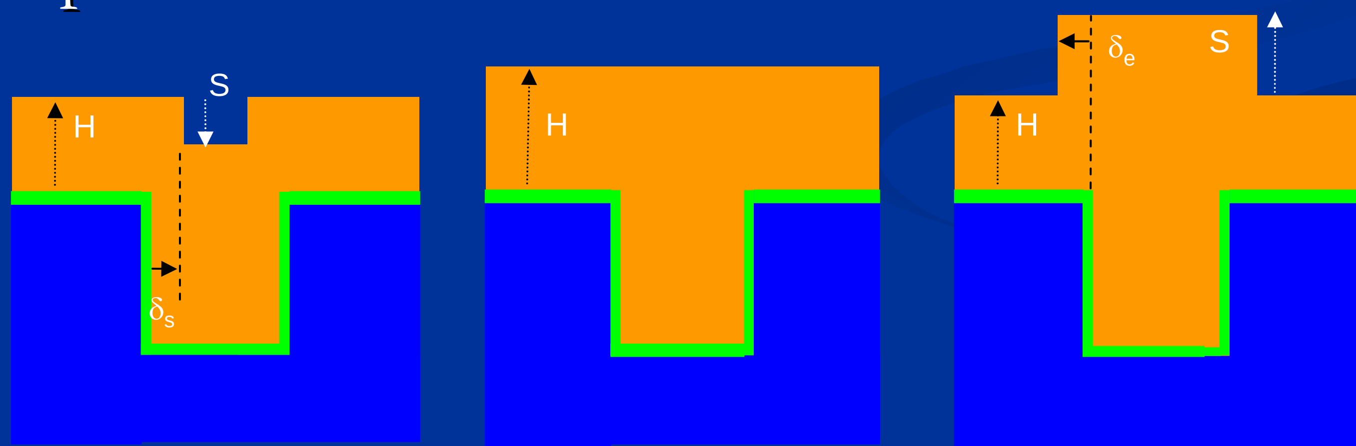
Parameter Assignment Algorithm



- Both steps need density and perimeter to be monitored.

Brief Overview of Post-ECP topography

- Based on underlying layout characteristics, three types of topography can appear after ECP.
  - Dependence of ECP thickness of tile on layout parameters varies the case of the tile.



(Conformal Fill) (Super Fill) (Over Fill)

$T = k(1\text{-den.})/(1\text{-shr den.})$

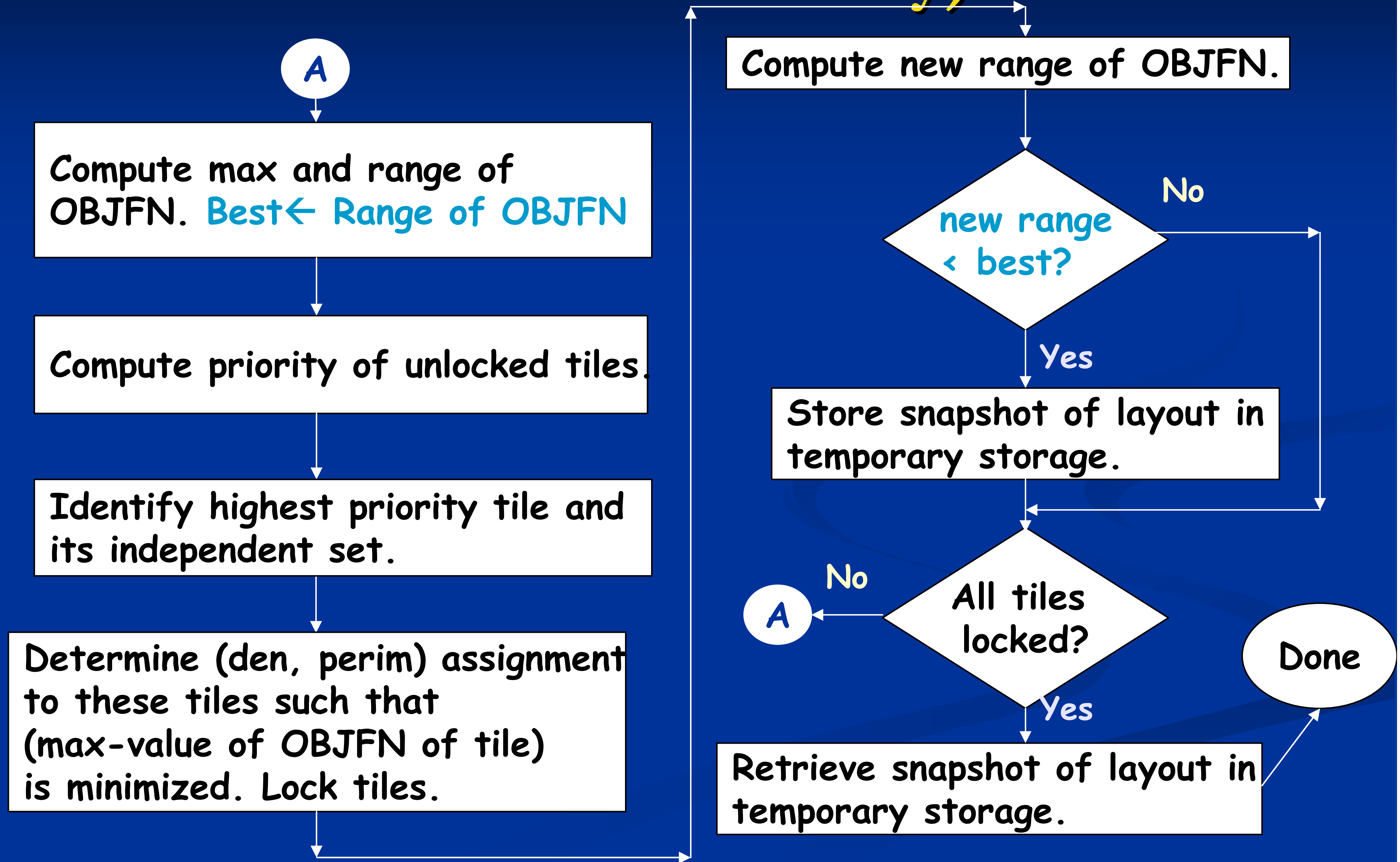
$T = k_1 + k_2{*}\text{perim-}k_3{*}\text{den.}$

$T = k_1' + k_2'{*}\text{perim-}k_3'{*}\text{den./exp. den.}$

ECP Thickness Range Minimization: Key Observations

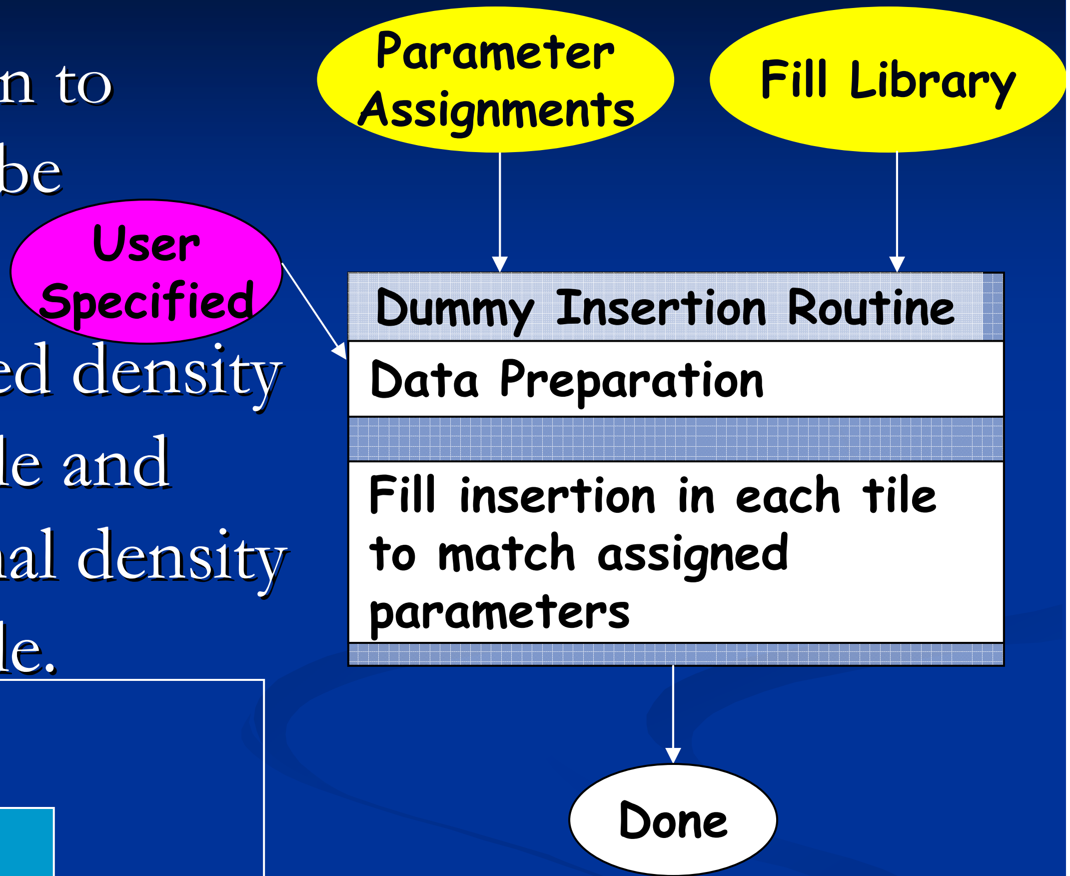
- ECP thickness as a function of layout parameters may oscillate between iterations depending on its case.
- Easier for optimization to push all tiles into one case and then minimize thickness range.
- Super-fill is the case of choice.
  - Most tiles in typical layouts belong to the super-fill case.
  - Super-fill tiles rarely become over-fill or conformal-fill if the only layout modification being done is fill insertion.
  - Cu surface is smooth within a tile.
- ECP Thickness Range Minimization step:
  - Push all the tiles to super-fill with minimal layout modification.
  - Perform ECP thickness range minimization.

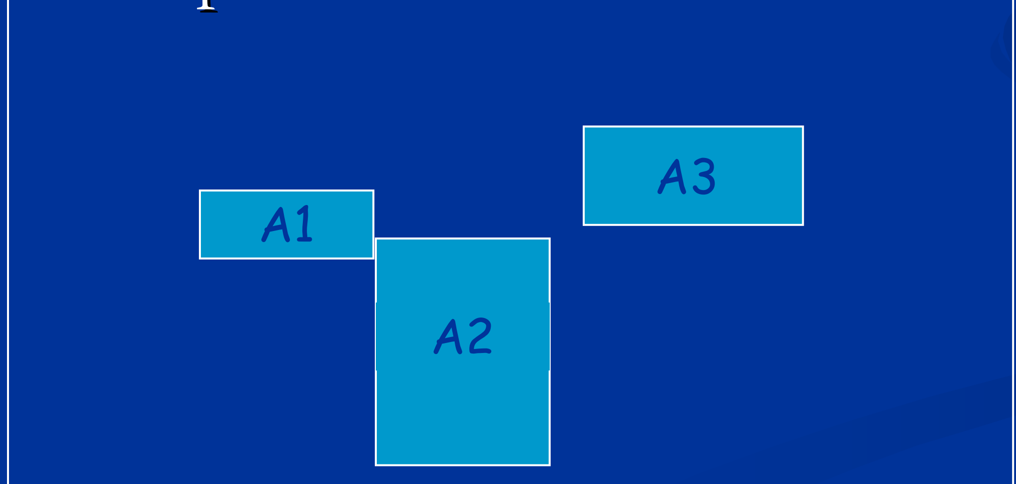
Minimization Algorithm (ECP & Effective Density)



Fill Placement

- Place grids on the design to indicate where fills can be inserted.
- Let (d,p) be the assigned density and perimeter of the tile and (d_{org}, p_{org}) be the original density and perimeter of the tile.





TA = Tile Area

FA = Fill-able area = A1+A2+A3.

$d_i = (d-d_{org})*(TA)/FA.$

$p_i = (p-p_{org})*A_i/FA.$

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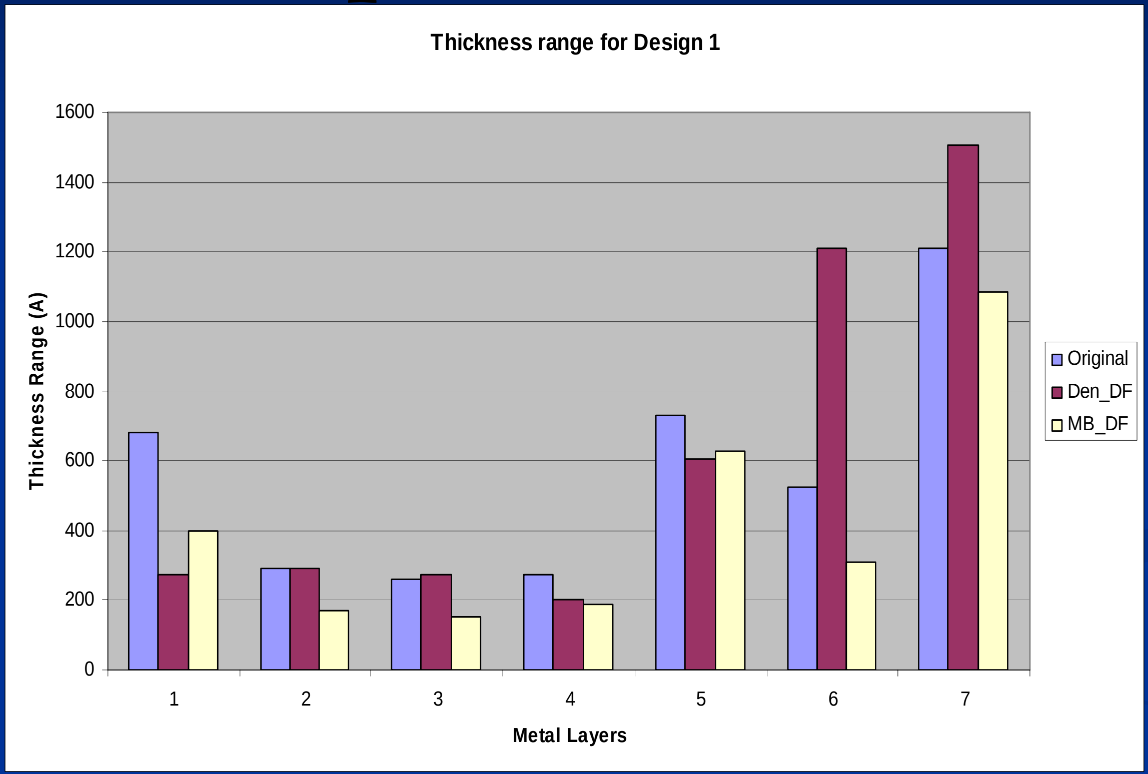
Results for Design1: Thickness Improvement & Fill Amount

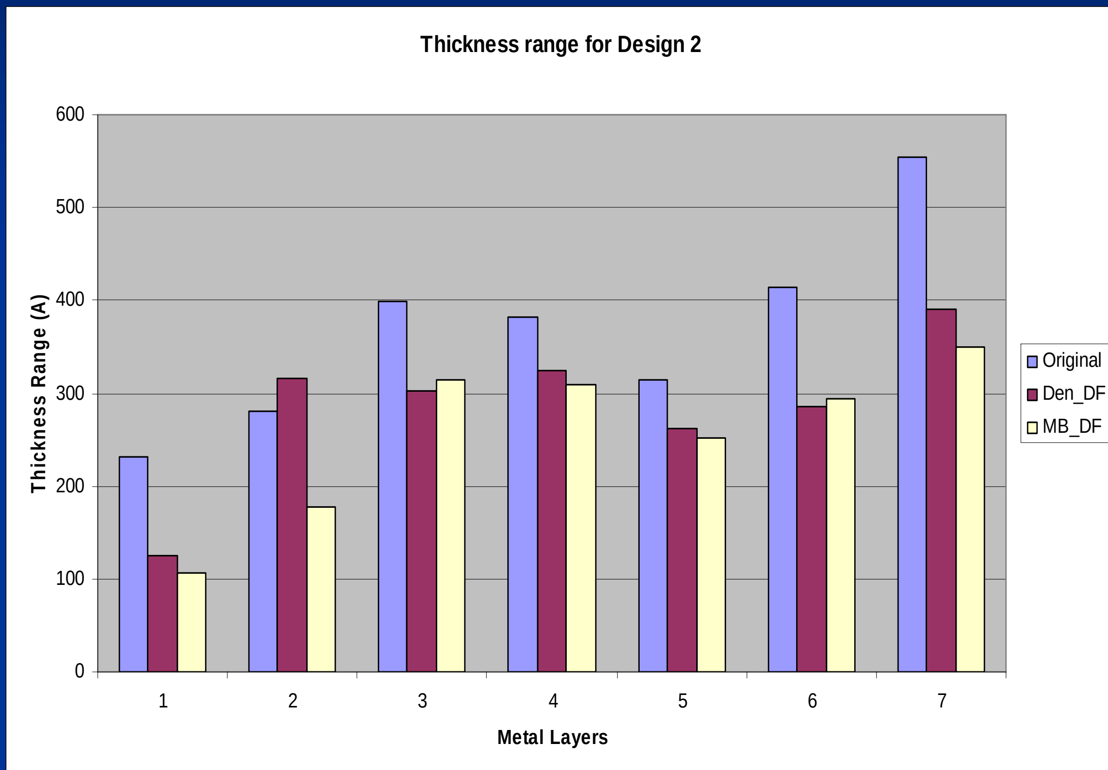


Fill% (MB_DF)	Fill% (Den_DF)
5.77	17.0
5.80	11.59
4.75	11.19
1.84	3.60
2.37	5.57
6.79	13.94
3.60	7.75

Avg range reduction of MB_DF: 31.29%; Avg range reduction of Den_DF: 14.79%*; Avg ratio of (MB-Fill/Den-Fill) = 0.45.

*If thickness range increases after metal fill, thickness range after metal fill = thickness range of original design.

Results for Design 2: Thickness Improvement and Fill Amount

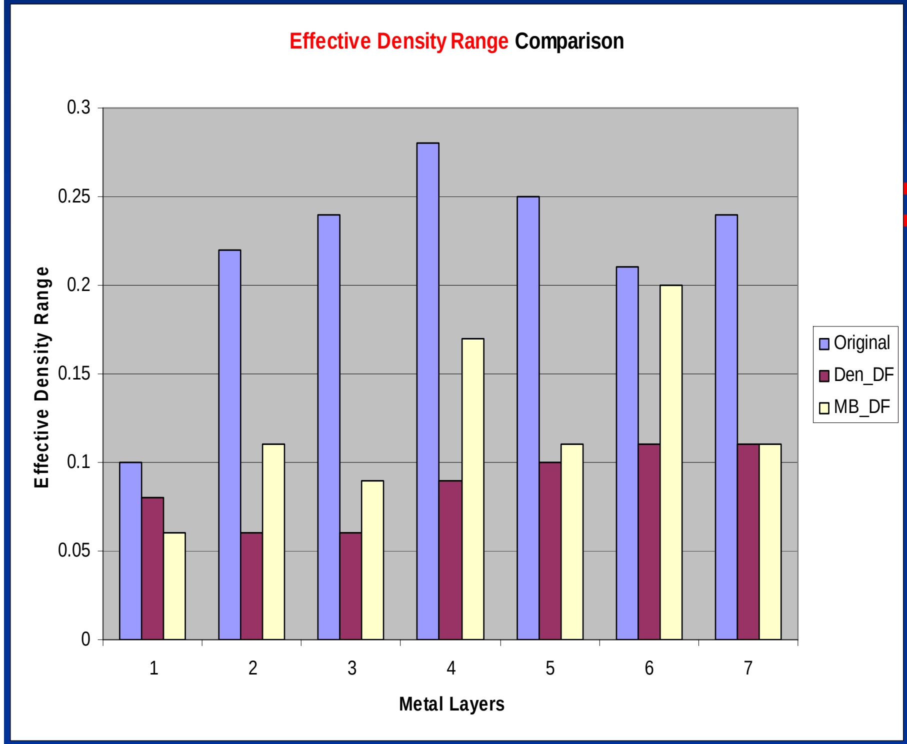


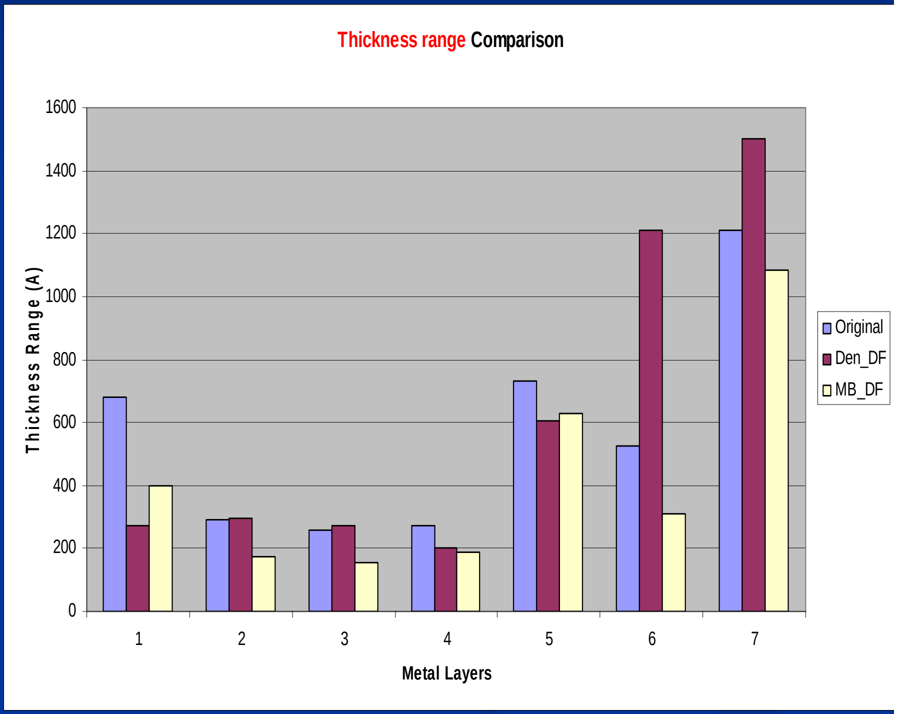
Fill% (MB_DF)	Fill% (Den_DF)
1.44	2.58
4.52	13.52
5.51	15.34
5.86	15.58
5.24	13.47
4.48	8.80
7.16	12.57

Avg range reduction of MB_DF: 30.98%; Avg range reduction of Den_DF: 23.24%*; Avg of (MB-Fill/Den-Fill) ratio= 0.44.

If thickness range increases after metal fill, thickness range after metal fill = thickness range of original design.

Density ≠ Thickness





✓ Proposed metal filling consistently improves the WID Thickness Range.

Conclusions and Future Work

- Current density-based metal filling solutions were developed mainly to work for Al and are not suitable for Cu.
- Proposed a novel and computationally efficient metal filling solution tuned for the Cu fabrication process.
- Advantages of Proposed Solution:
  - Always improves planarity of chip surface topography.
  - Obtains greater planarity of chip surface compared to previous pure density-based solutions.
  - Introduces smaller amount of fill.
- Future work includes:
  - Consider accumulative effects during metal filling.
  - Timing-driven model-based metal filling.

Thank You!