# Design for Manufacturing

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# Photo-Lithographic Process

optical mask

oxidation

photoresist coating

photoresist removal (ashing)

stepper exposure

Typical operations in a single photolithographic cycle (from [Fullman]).

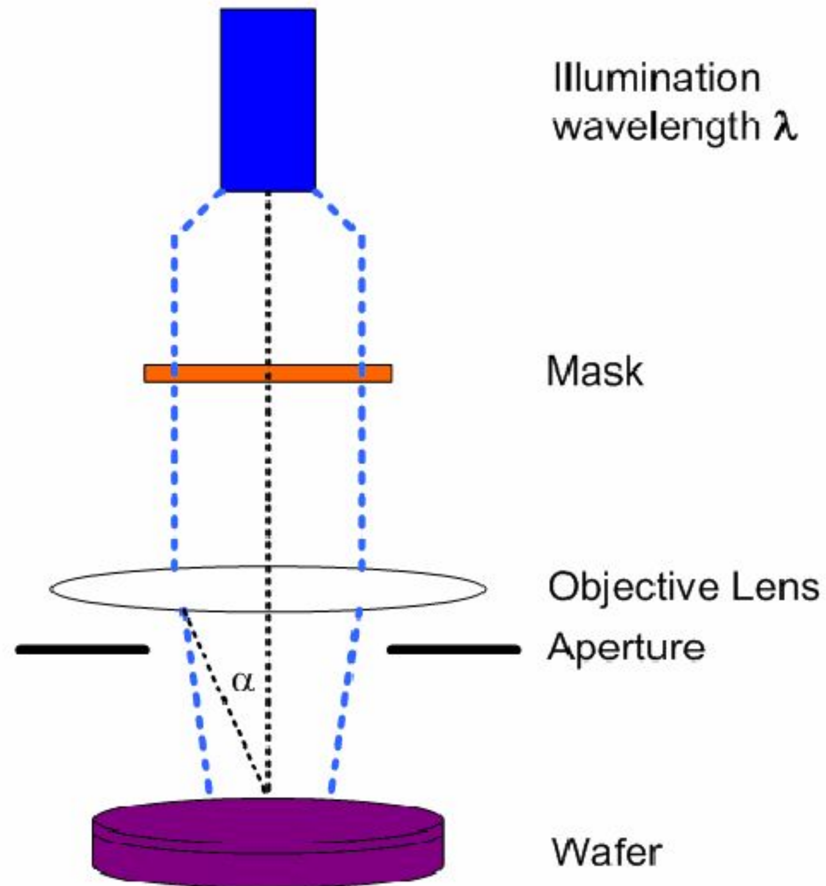
photoresist development

acid etch

spin, rinse, dry

process step

# Lithography systems



# Lithography Primer: Basics

- The famous Raleigh Equation:

$$Resolution = k_1 \frac{\lambda}{NA}$$

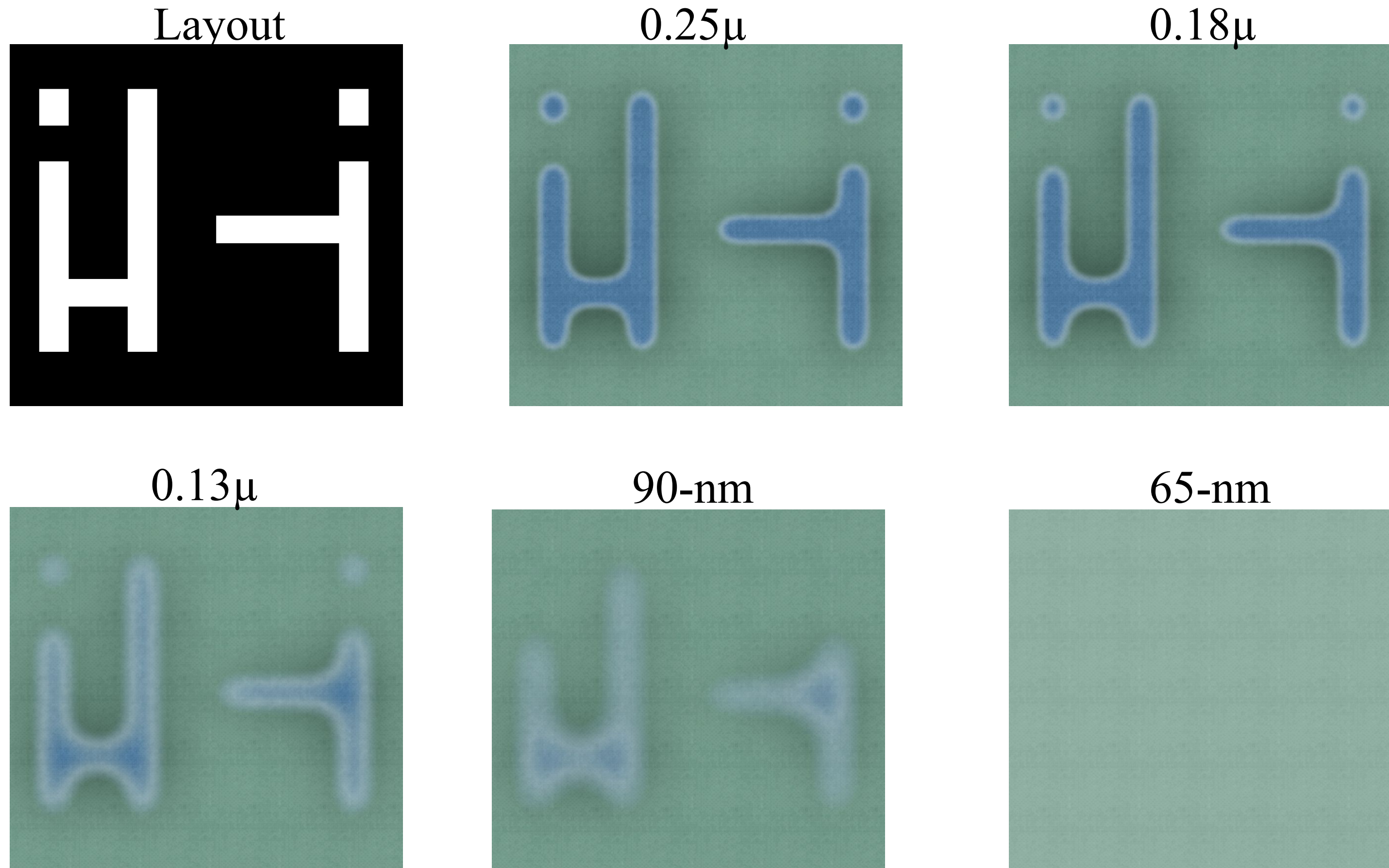
$\lambda$: Wavelength of the exposure system

NA: Numerical Aperture (sine of the capture angle of the lens, and is a measure of the size of the lens system)

$k_1$: process dependent adjustment factor

- Exposure = the amount of light or other radiant energy received per unit area of sensitized material.
- Depth of Focus (DOF) = a deviation from a defined reference plane wherein the required resolution for photolithography is still achievable.
- Process Window = Exposure Latitude vs. DOF plot for given CD tolerance

# Mask versus Printing




Figures courtesy Synopsys Inc.

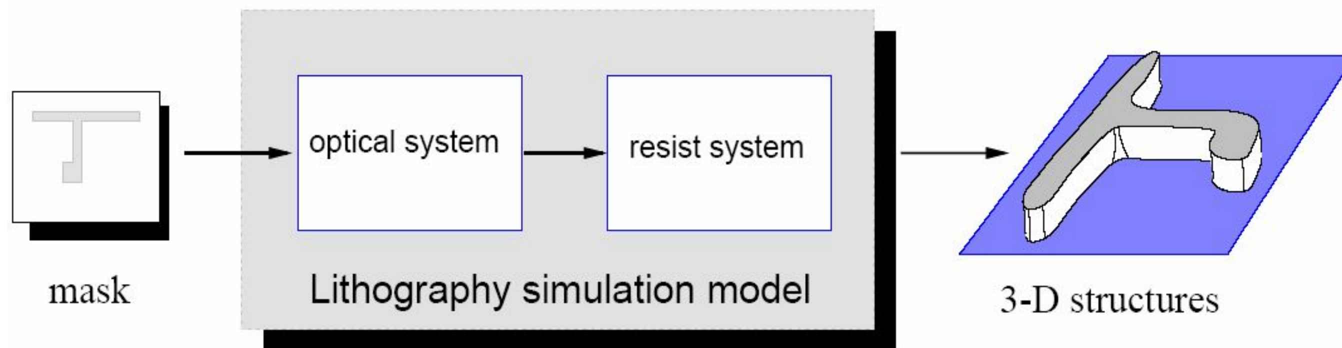
# Lithography Model

To guide lithography aware physical design, *fast* yet *high-fidelity* lithography modeling/metrics are essential

Two key stages in litho-model (in a simplified view)

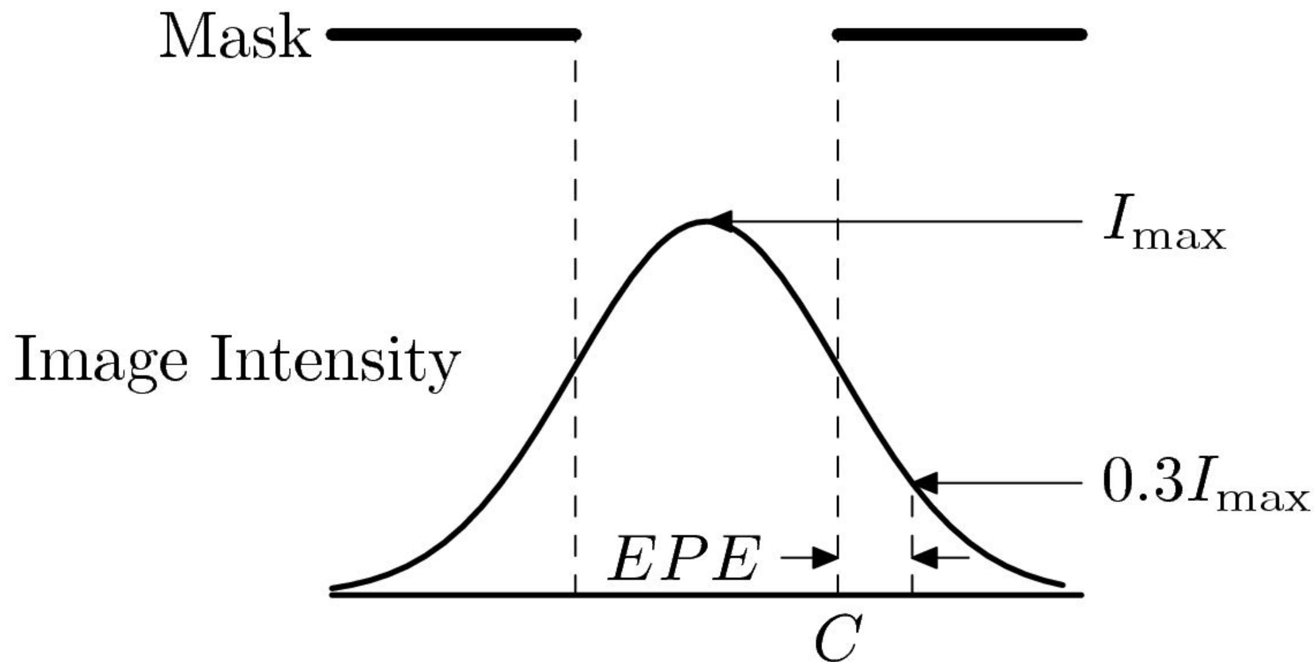
Optical system: will generate aerial image from mask

Resist system: photoresist and patterning inside the wafer



# Simple Threshold Resist Model

- From the aerial image => printed image (resist model)
- Example: simple threshold model (e.g., $0.3I_{max}$) to decide where to etch based on image intensity distribution

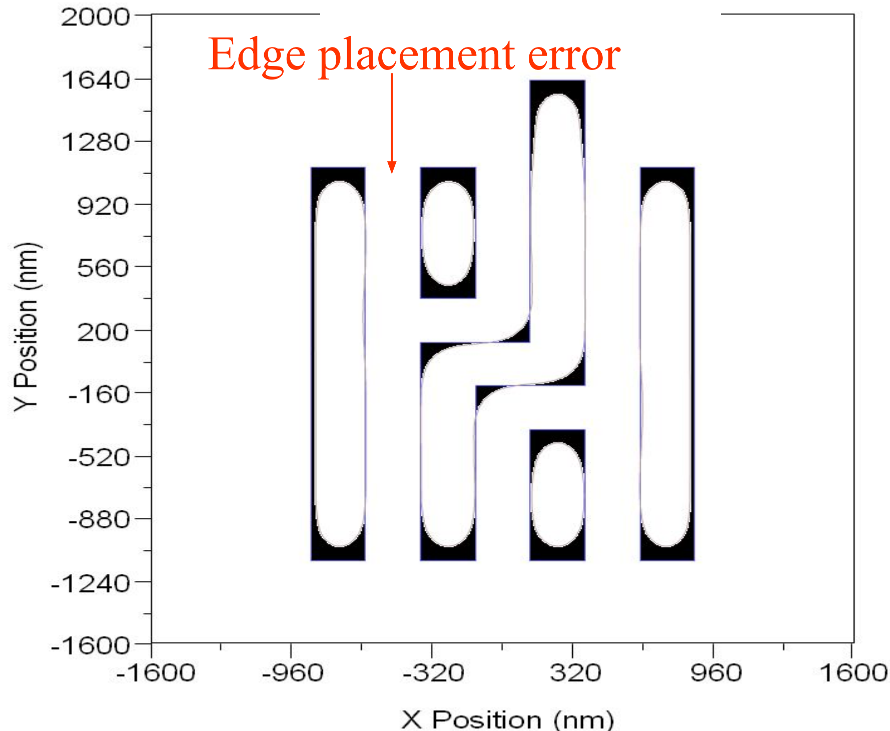


# Edge Placement Error Map

A concept similar to congestion or thermal hotspot map

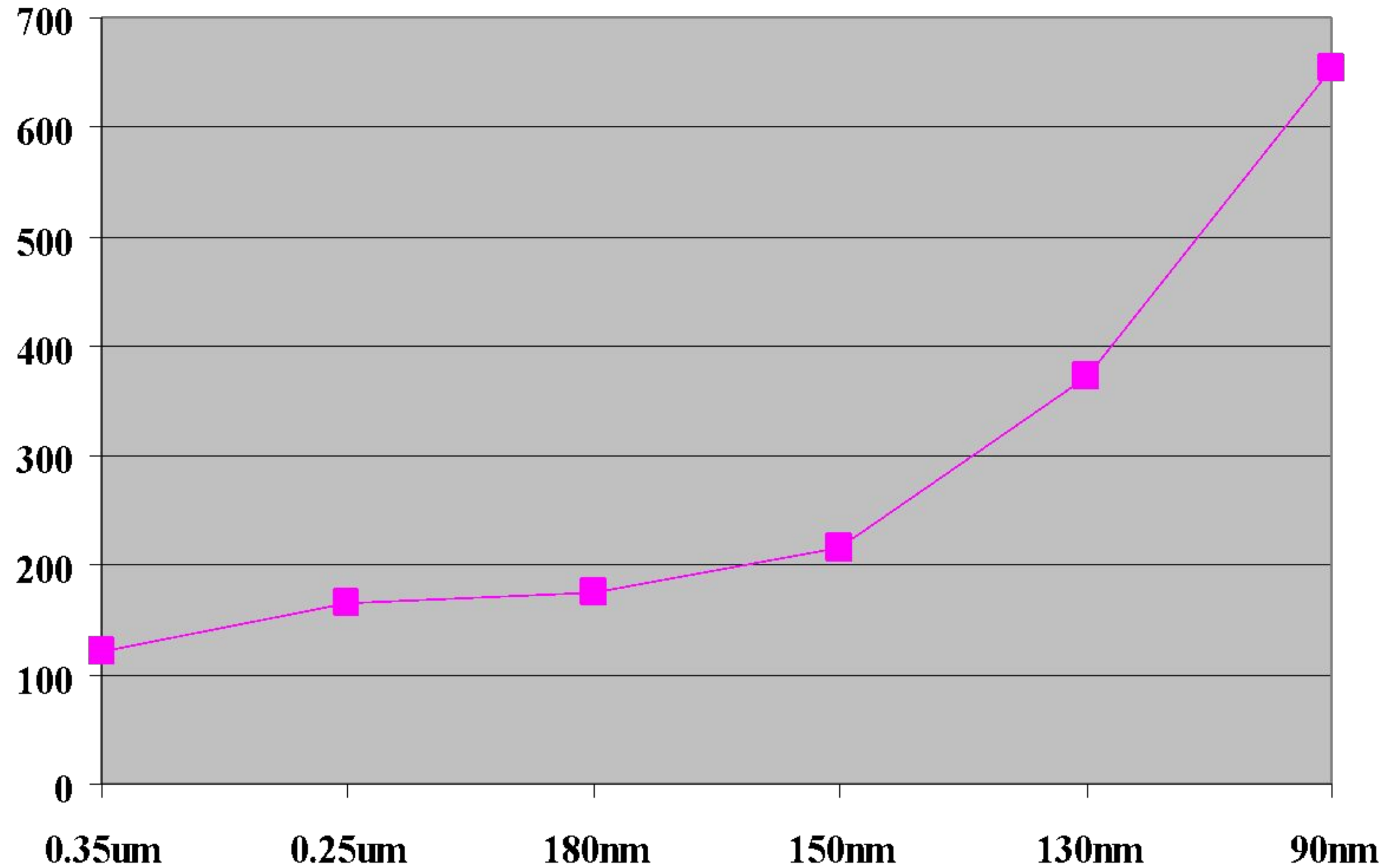
Measurement of RET effort

Work seamlessly with existing CAD flow




- Generate EPE for each "control point" (points that may have large edge placement errors) in design
- Each EPE control point has a ranked list of neighboring wires that contribute to the EPE
- Normalized EPE density for an entire segment

# Design Rules Explosion

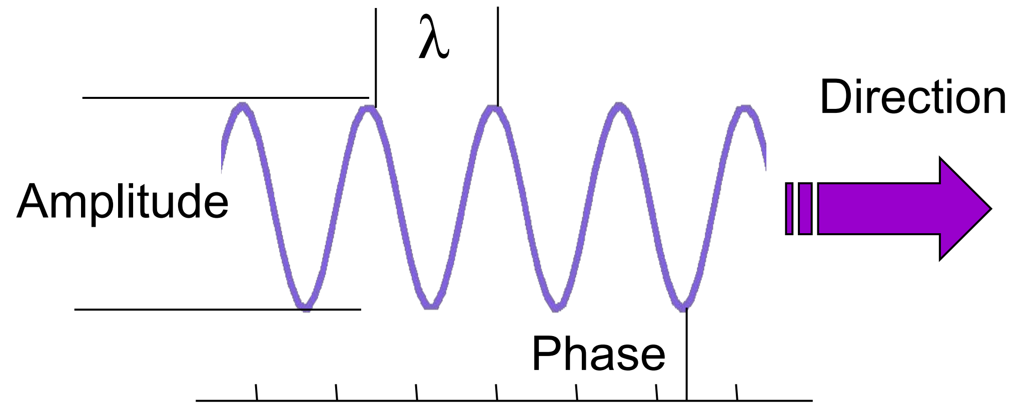


# RET Basics

The light interacting with the mask is a wave

Any wave has certain fundamental properties

- Wavelength (λ)
- Direction
- Amplitude
- Phase




RET is wavefront engineering
to enhance lithography
by controlling these properties

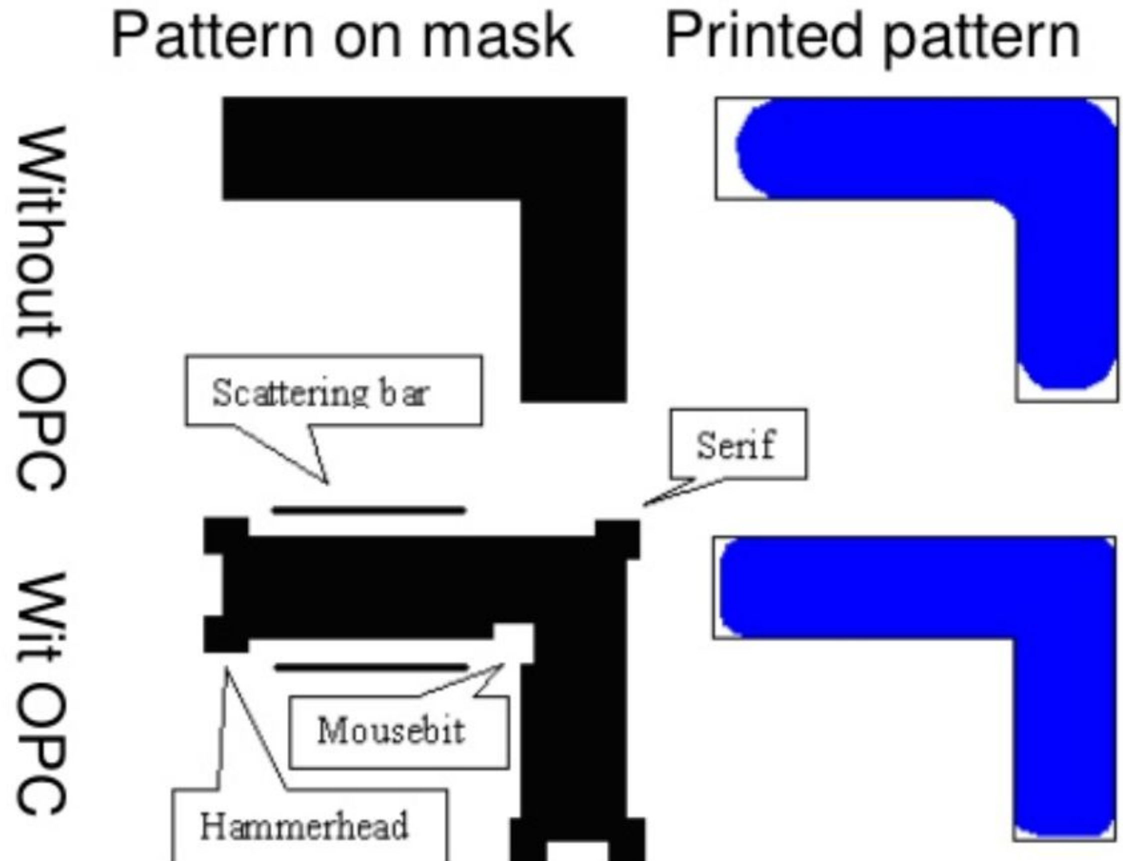
Courtesy F. Schellenberg, Mentor Graphics Corp.

# Amplitude: OPC

Optical Proximity Correction (OPC) modifies layout to compensate for process distortions

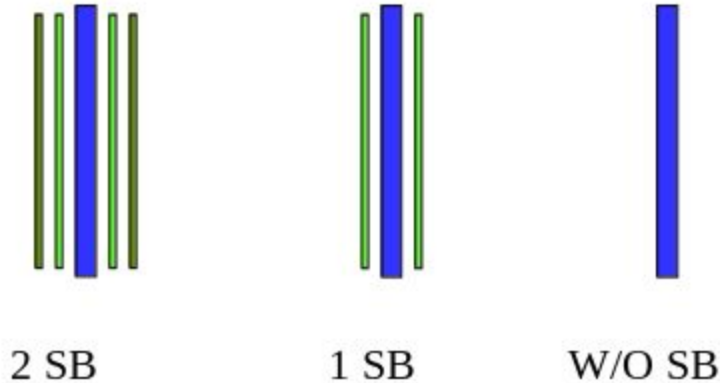
Add non-electrical structures to layout to control diffraction of light

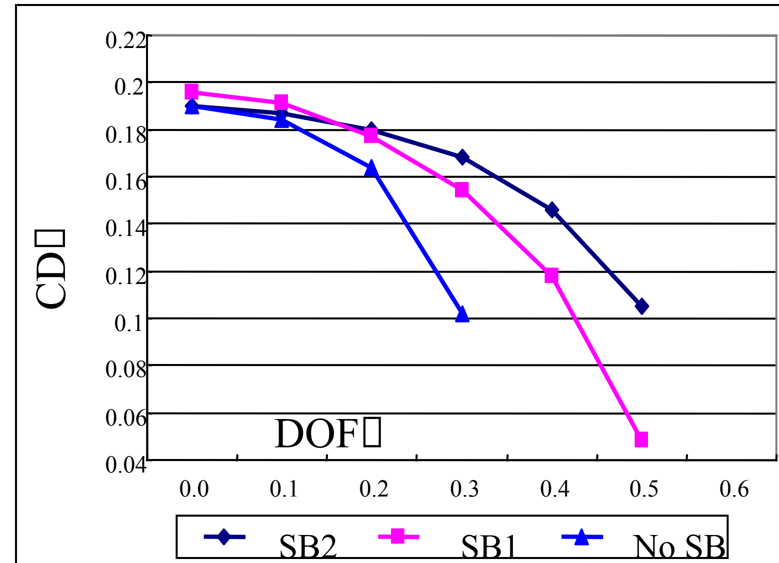
Rule-based or model-based



# Assist Features and Variation

SB = Scattering Bar ≡ SRAF



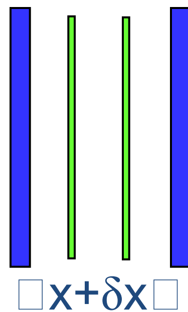

SRAFs are dummy geometries

Improve process window overlap for dense and isolated features

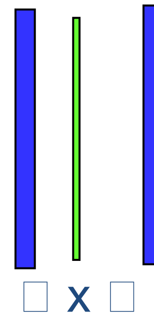
Not supposed to be printed

Unavoidable for 90nm poly

# Layout Composability for SRAFs




Better than

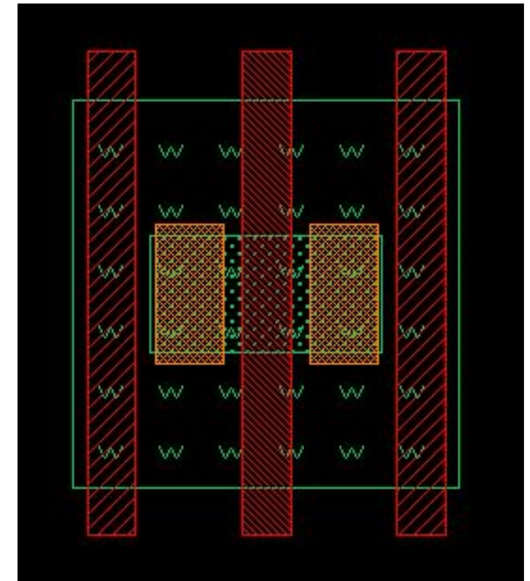



- Feature spacings are restricted to a small OR FIXED set
- Two components
  - Assist-correct library layouts □ Inter-device spacing within a standard cells □ Intelligent library design
  - Assist-correct placement □ space between cells needs to be adjusted □ Intelligent whitespace management

# Dual Patterning

It has gotten so bad, that some critical layers (e.g. metal1 and poly) are split into two separate masks.

No adjacent shapes are on the same mask to prevent diffraction problems.



# Phase: PSM

Phase Shifting Masks (PSM) etch topography into mask

Creates interference fringes on the wafer Interference effects boost contrast Phase Masks can make extremely small gates

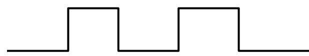
conventional mask

glass

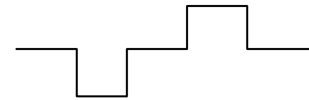
Chrome

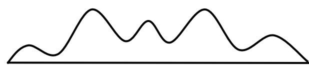
phase shifting mask

Phase shifter

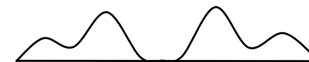


Electric field at mask



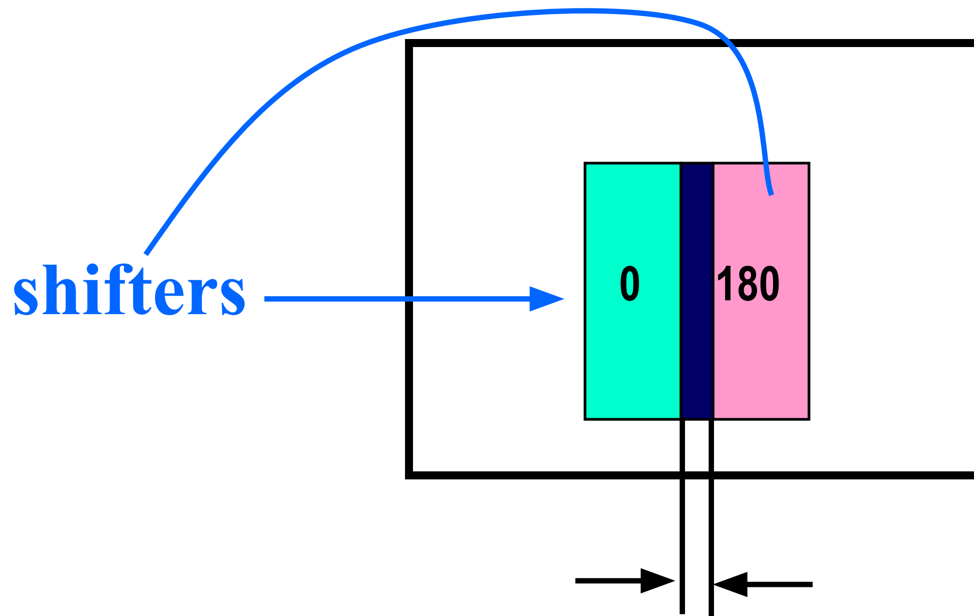


Intensity at wafer



# The Phase Assignment Problem

Assign 0, 180 phase regions such that critical features with width < B are induced by adjacent phase regions with opposite phases

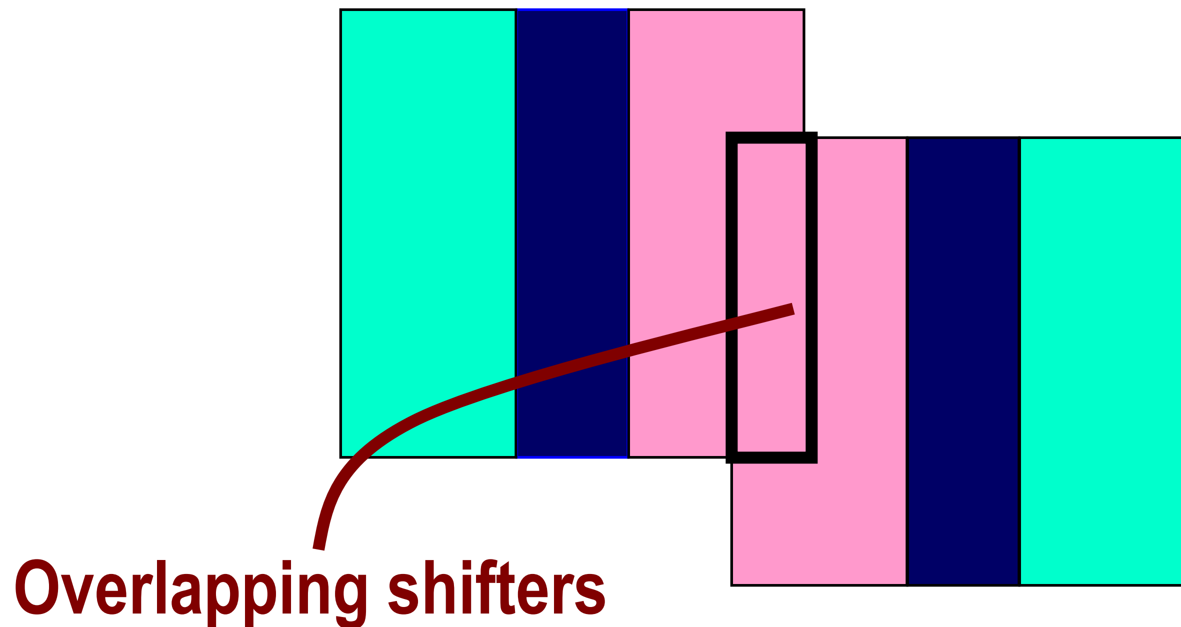


# Phase Assignment for Bright-Field PSM

**PROPER Phase Assignment:**

**Opposite** phases for opposite shifters

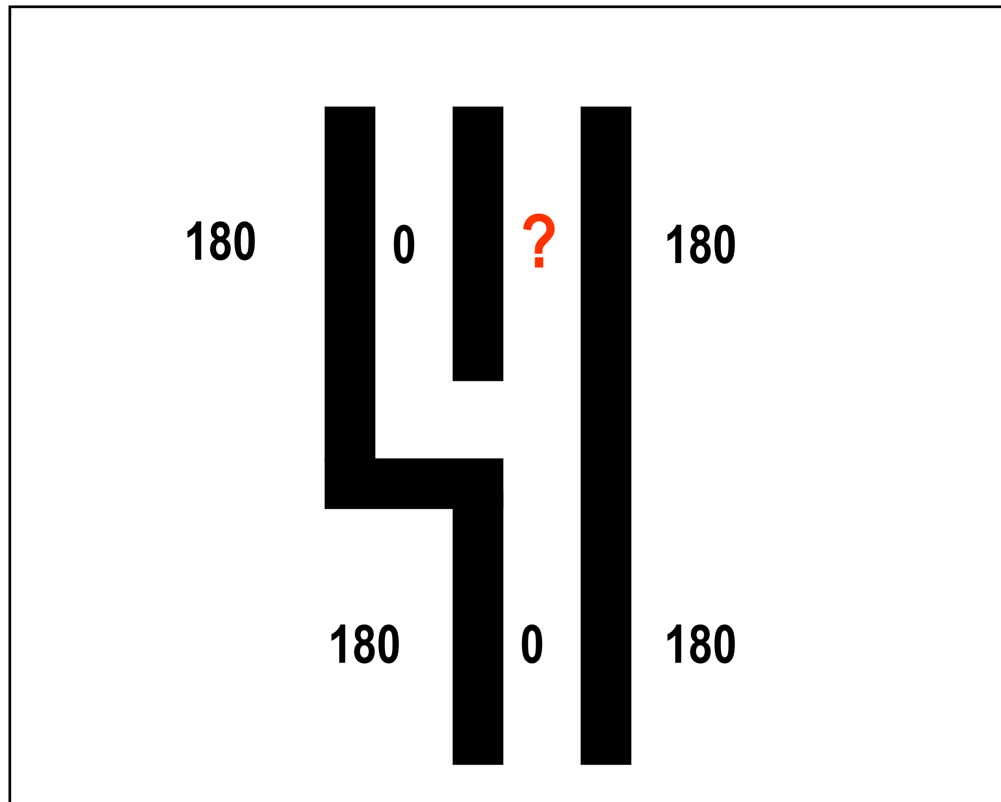
**Same** phase for overlapping shifters



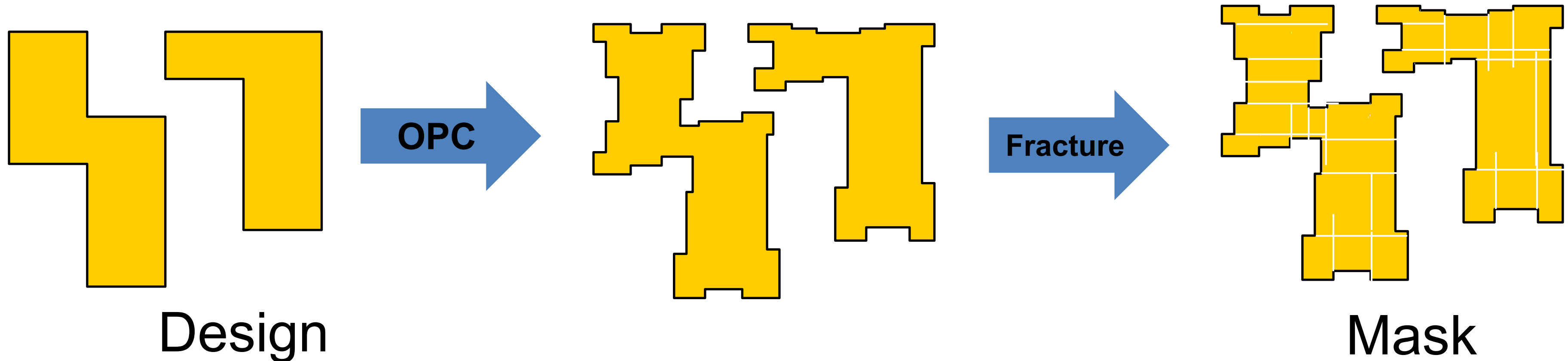
# Key: Global 2-Colorability

Odd cycle of "phase implications" → layout cannot be manufactured

layout verification becomes a global, not local, issue



# Mask Costs




**Mask Cost ∝ Data Volume**

OPC, PSM, Fill  increased feature complexity
 increased mask cost

Figure courtesy Synopsys Inc.