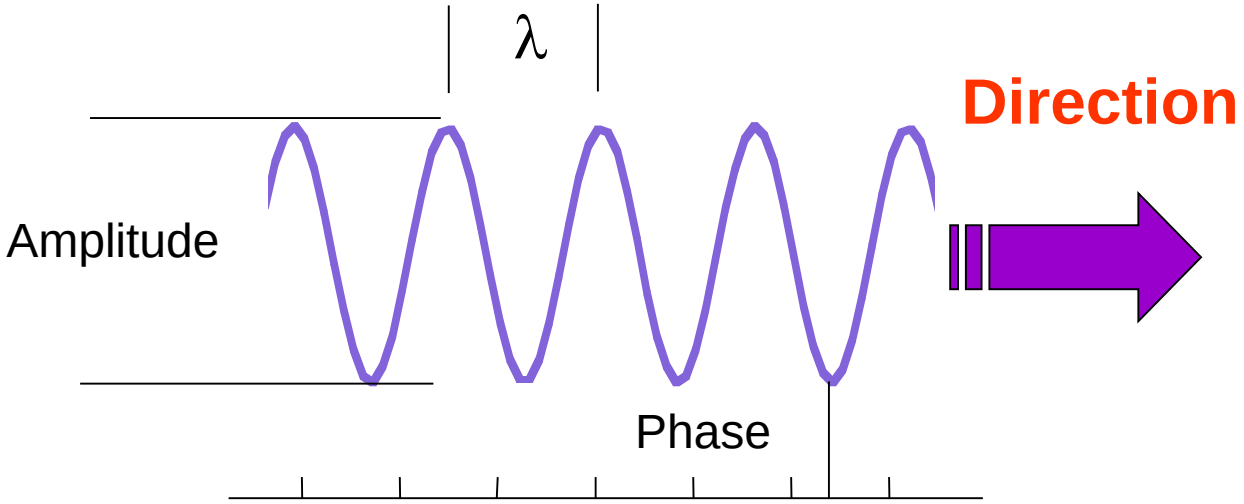
# Lecture 8

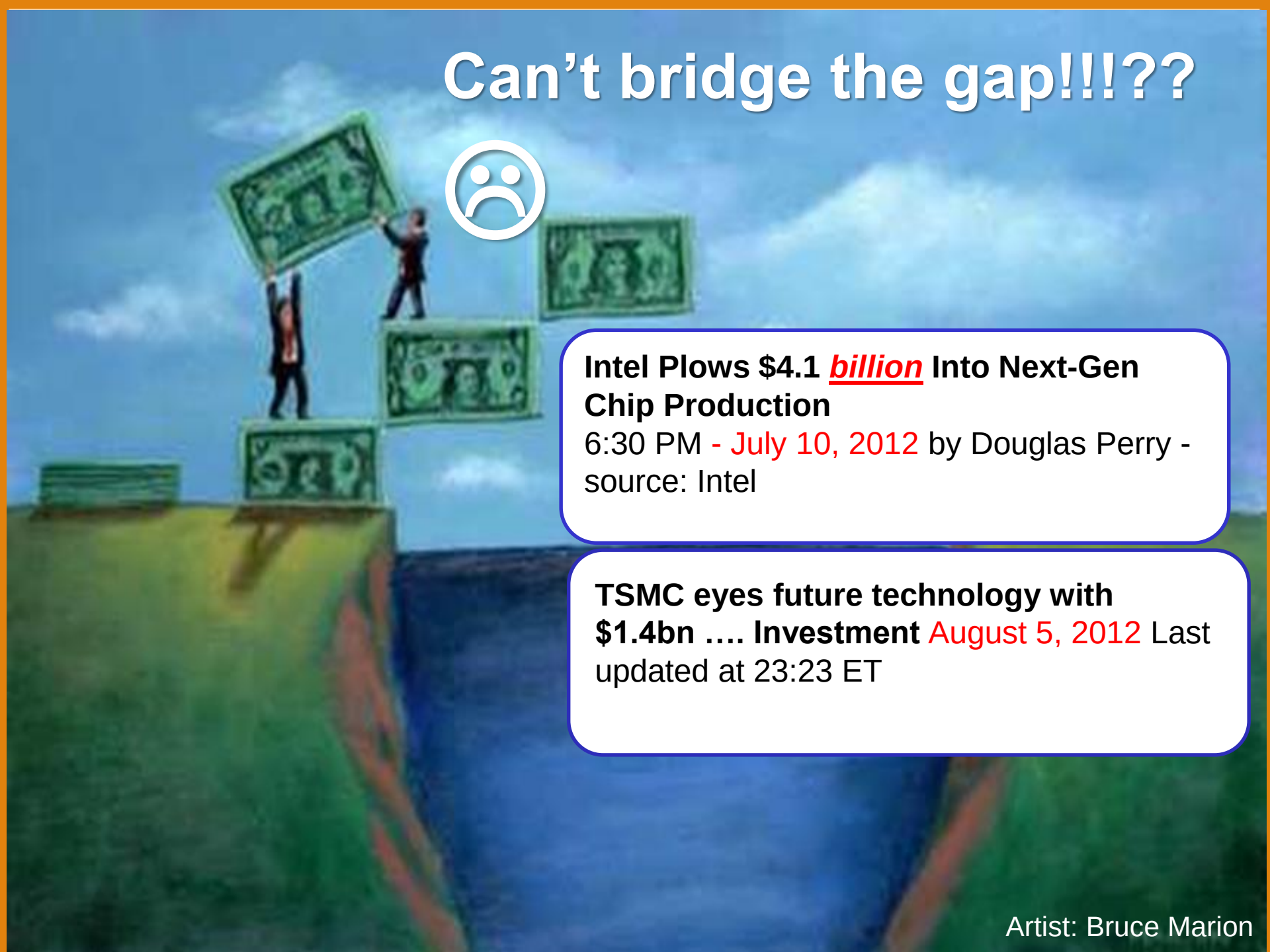
## Chemical Engineering for Micro/Nano Fabrication




Improving Resolution by Wavefront Engineering

# Is this our only option???

# Can’t bridge the gap!!!??



**Intel Plows $4.1 *billion* Into Next-Gen Chip Production**
6:30 PM - July 10, 2012 by Douglas Perry - source: Intel

**TSMC eyes future technology with $1.4bn …. Investment** August 5, 2012 Last updated at 23:23 ET

Artist: Bruce Marion

# Don’t worry EUV will work….


**and if it’s not ok….. it’s not the end!**

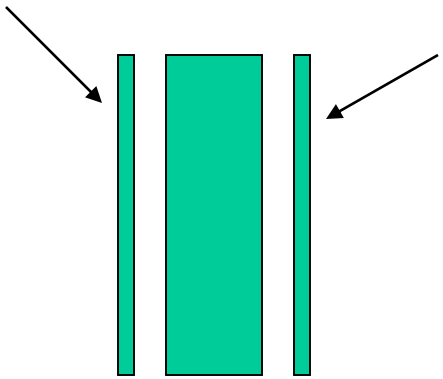
# So…we keep “tweeking” 193 immersion

- **Wave Front Engineering**
  - SRAFS (Sub resolution assist features)
  - OPC (optical Proximity Correction)
  - RET (Reticle Enhancement Techniques)
  - Phase Shifting masks
    - Of Various Designs.
  - Inverse Lithography Processes
- **Trying to survive until we are saved by an NGL (Next Generation Lithography)**
  - Ion Beam
  - Imprint in various Forms
  - E-Beam Lithography – Multi Beam. Projection, etc.
    - MAPEL, REBL, Scalpel, Mapper, Etc.
  - Etc, Etc, Etc..



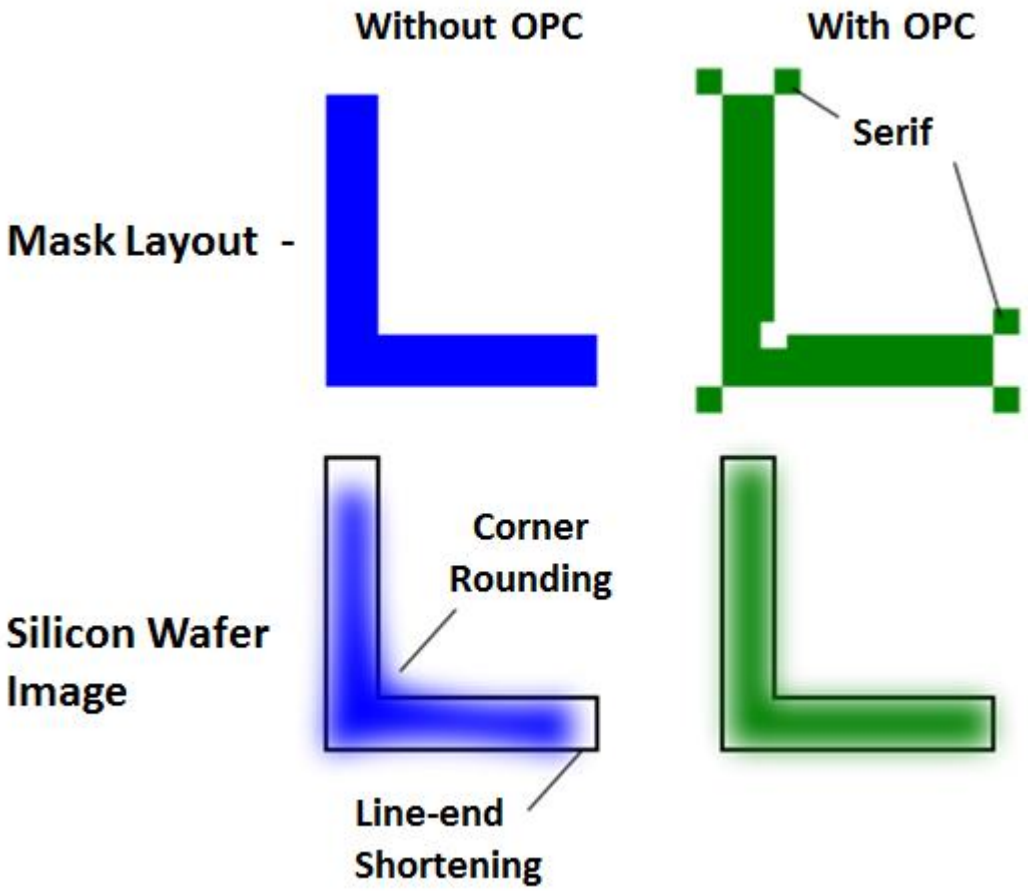
# Wavefront Engineering: OPC

- **Optical and Process Correction (OPC) for Amplitude Control**
- **Rule-Based OPC - modifies layout with sub-resolution assist features to compensate for process distortions**
  - **Add light where needed**
  - **Subtract light where not wanted**
  - **Add structures to layout to control diffraction of light**



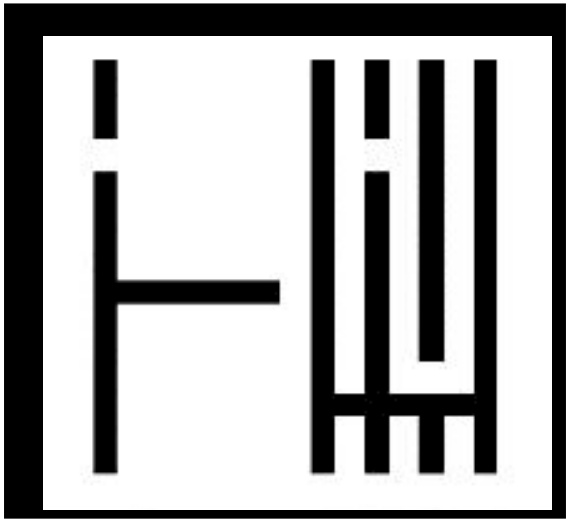
- **Lithography equipment does not form images of these features**
- **Scatter outside the lens NA**
- **Employs MANY engineers**

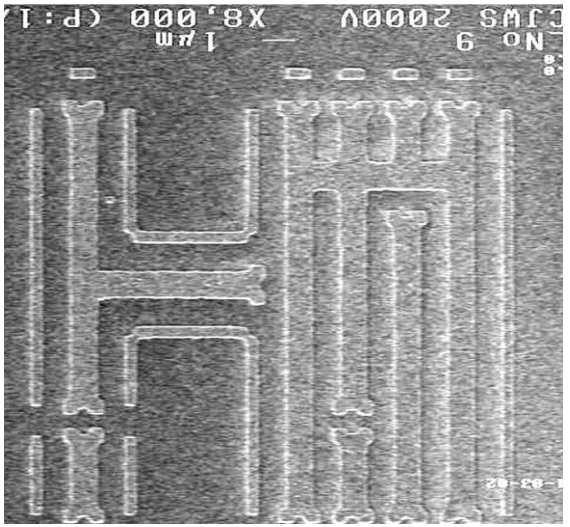
# Optical Proximity Correction SRAFs



# Impact of OPC on Physical Design

**Design Layout**



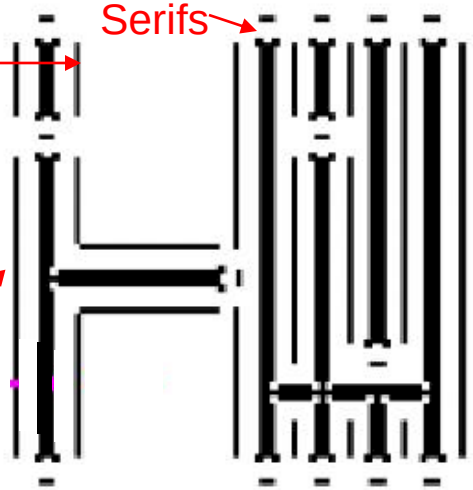


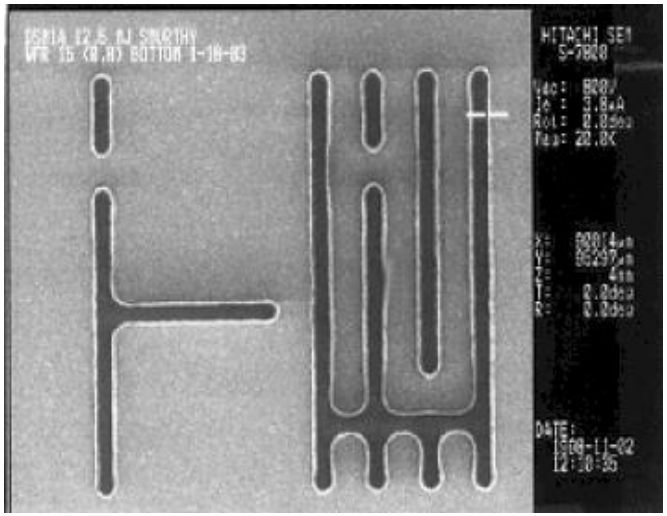
**Mask**

Scatter Bars

Serifs

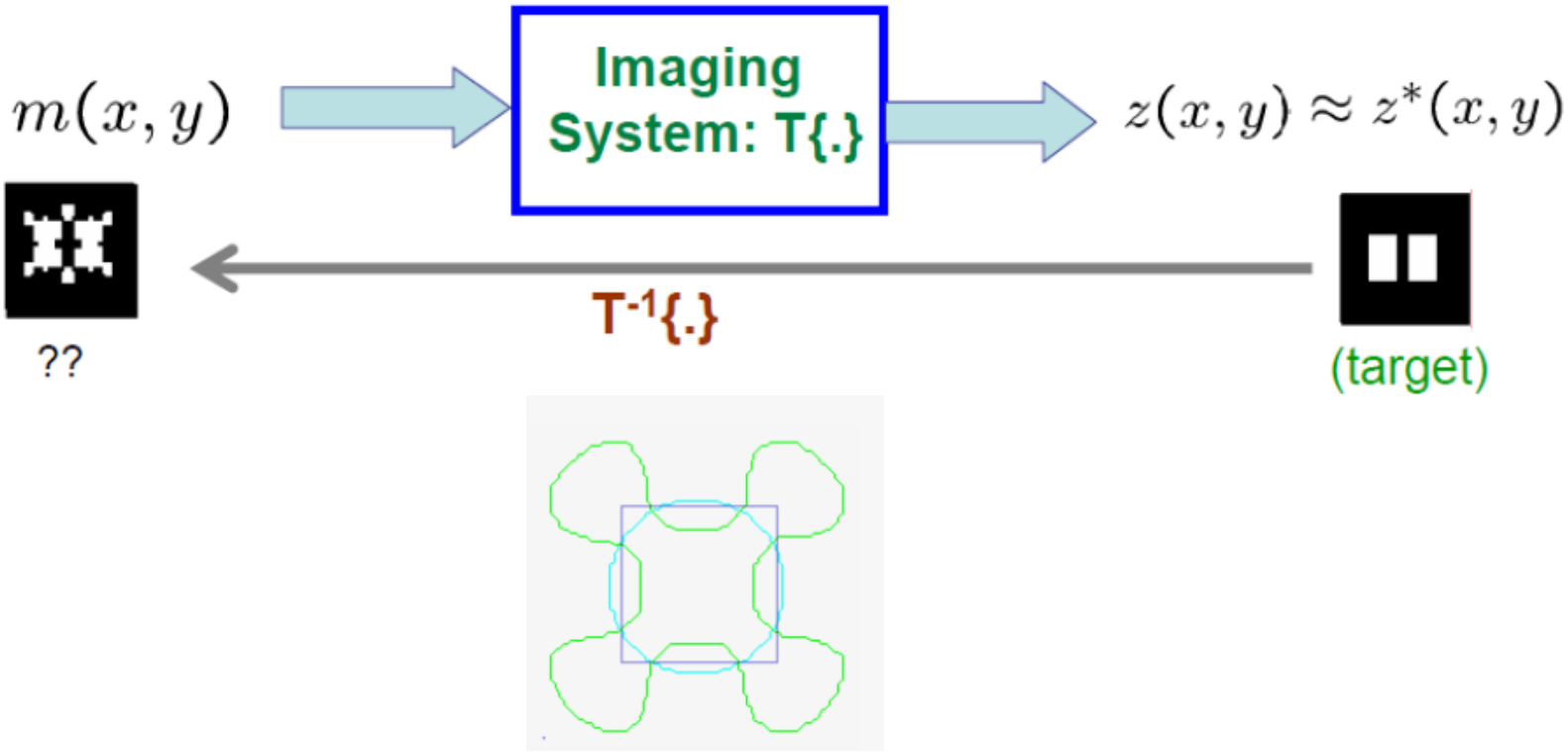
**Final Layout**



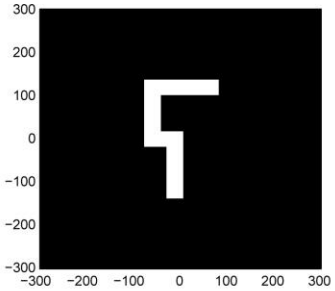


**Wafer**

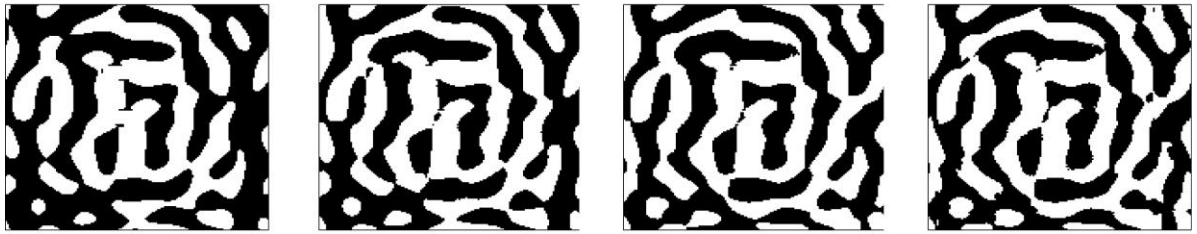
# Inverse Lithography Problem Formulation



# Inverse Lithography




(a) Test pattern

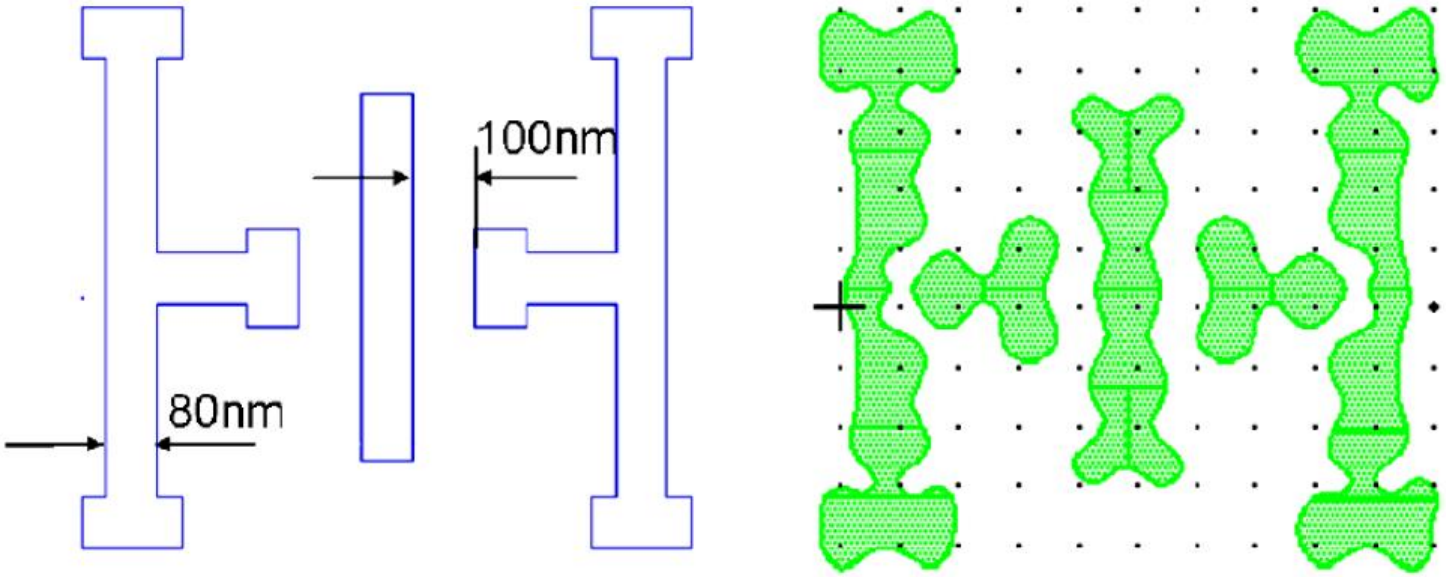


(b) $\mu = 80$ (c) $\mu = 472$ (d) $\mu = 1000$ (e) $\mu = 13650$

(f) $PE = 123$ (g) $PE = 131$ (h) $PE = 71$ (i) $PE = 66$

https://www.osapublishing.org/oe/abstract.cfm?uri=oe-21-7-8076

# Some Unintuitive Shapes




- **Very complex mask patterns are emerging**
  - Curved shapes…..very slow to write.

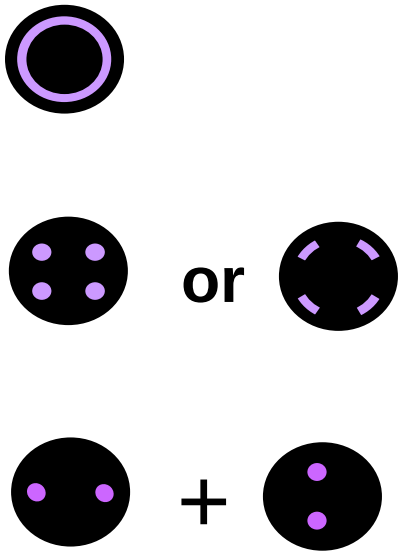
# Wavefront Engineering: Direction

## Off-Axis Designs

– Annular

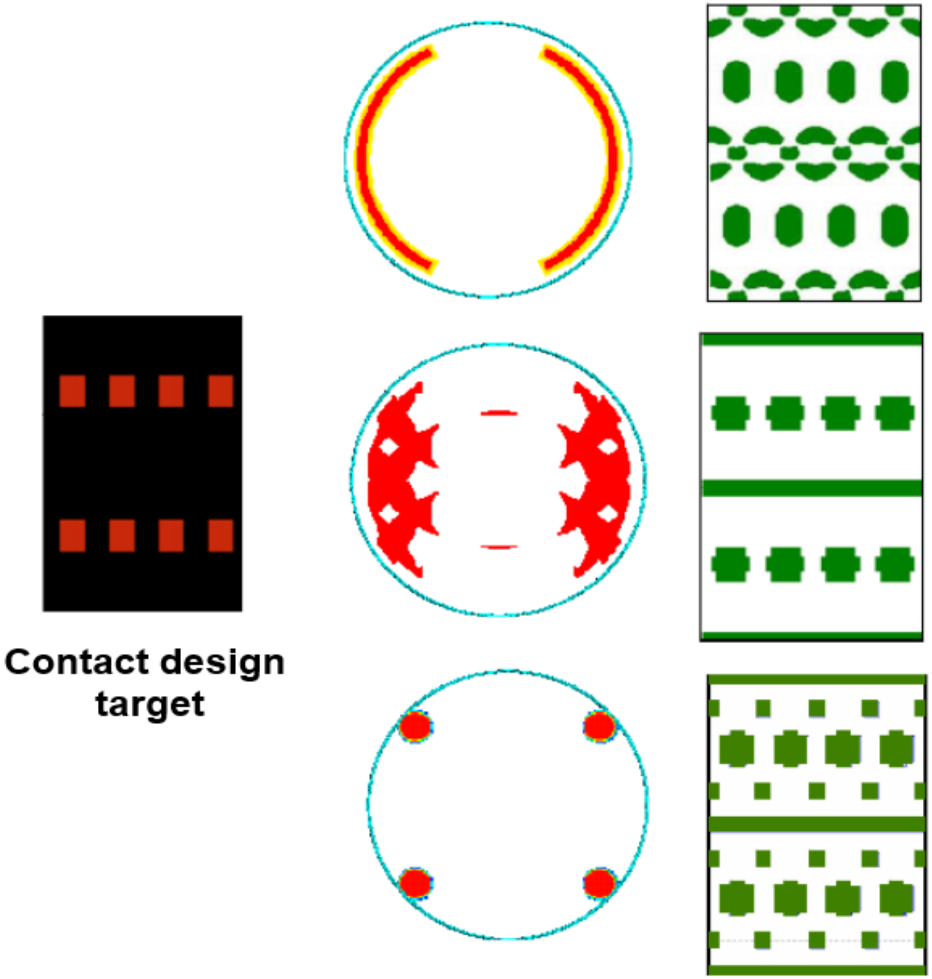
– Quadrupole

– Dipole




• **Eliminates on-axis zero order light - increases contrast**

# Some mask / illuminator options

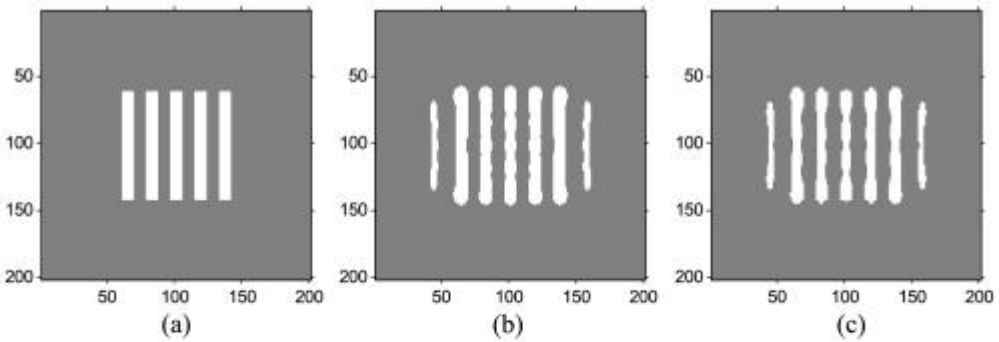


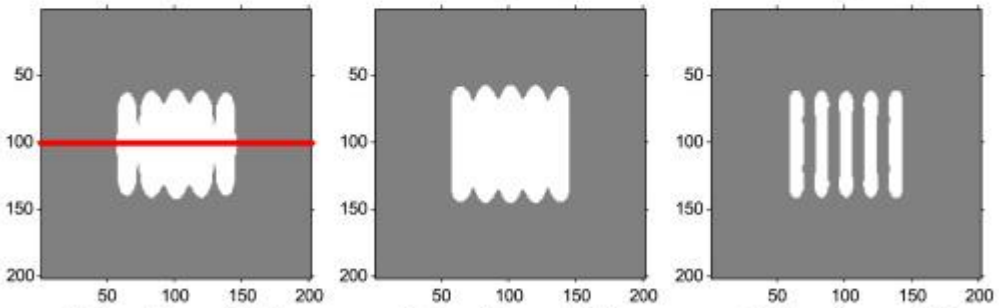
# Inverse Lithography

- **Makes the OPC and design people very happy**
- **Very complex mask patterns are emerging**
  - Curved shapes…..very slow to write.

- **But….the savior is on the way!**
  - IMS, has morphed into a multibeam mask writer!!
  - First tools are to be delivered “now”…
  - 262 beams, 12G/sec data path, air bearing vacuum stage (?)
  - DNP has tested this and is very high on the tool






(a) target patterns

(b) Manhattan patterns with edge-based OPC

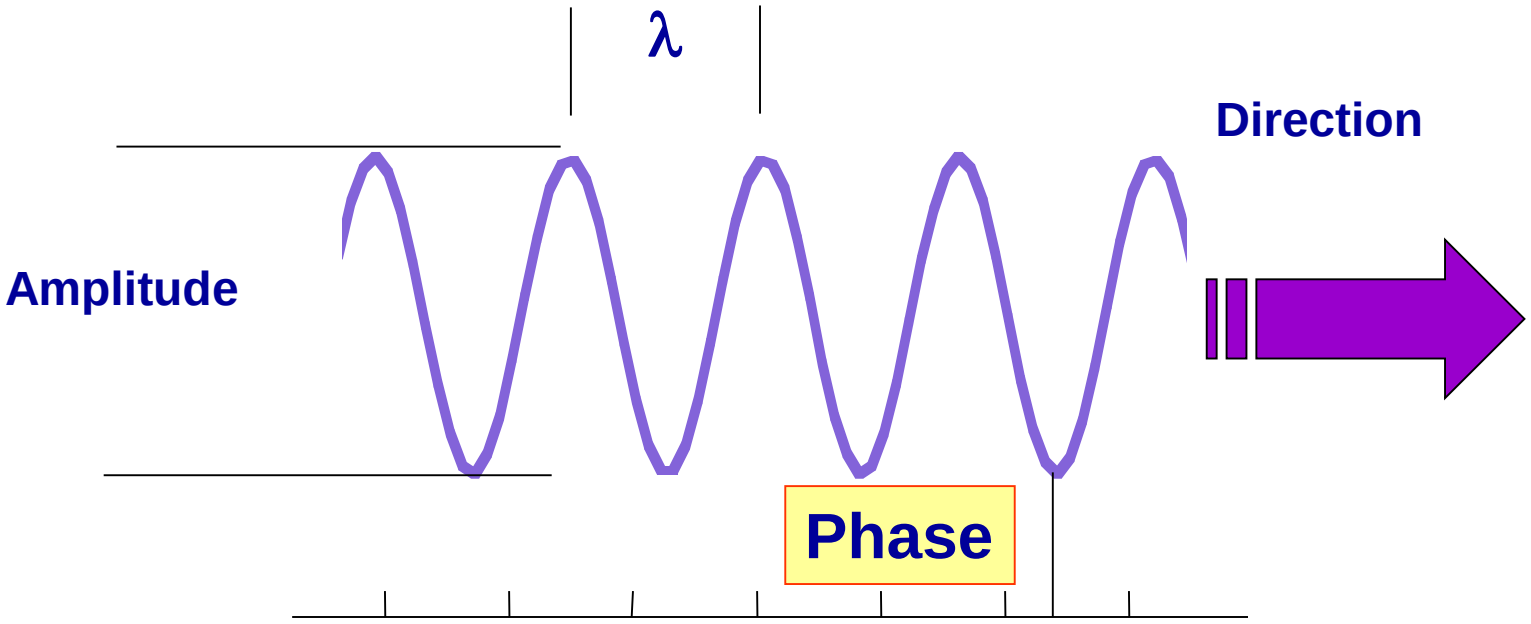
(c) curvilinear patterns with pixel-based ILT

# Further OPC Refinements

- **Model-Based OPC**
  - Not sufficient to consider just feature edges, but need to take a more holistic view
  - Takes advantage of the power of sophisticated process simulation to determine developed feature profiles according to the design layout and then modify the pattern features such that the simulated pattern is the same as the original design layout.
- **Design for manufacturing**
  - Litho-driven design optimization
  - Avoidance of structures that are problematic – redesign of circuit elements to eliminate troublesome pitches



# Wavefront Engineering: Phase



# Wavefront Engineering: Levenson Phase Mask

Marc

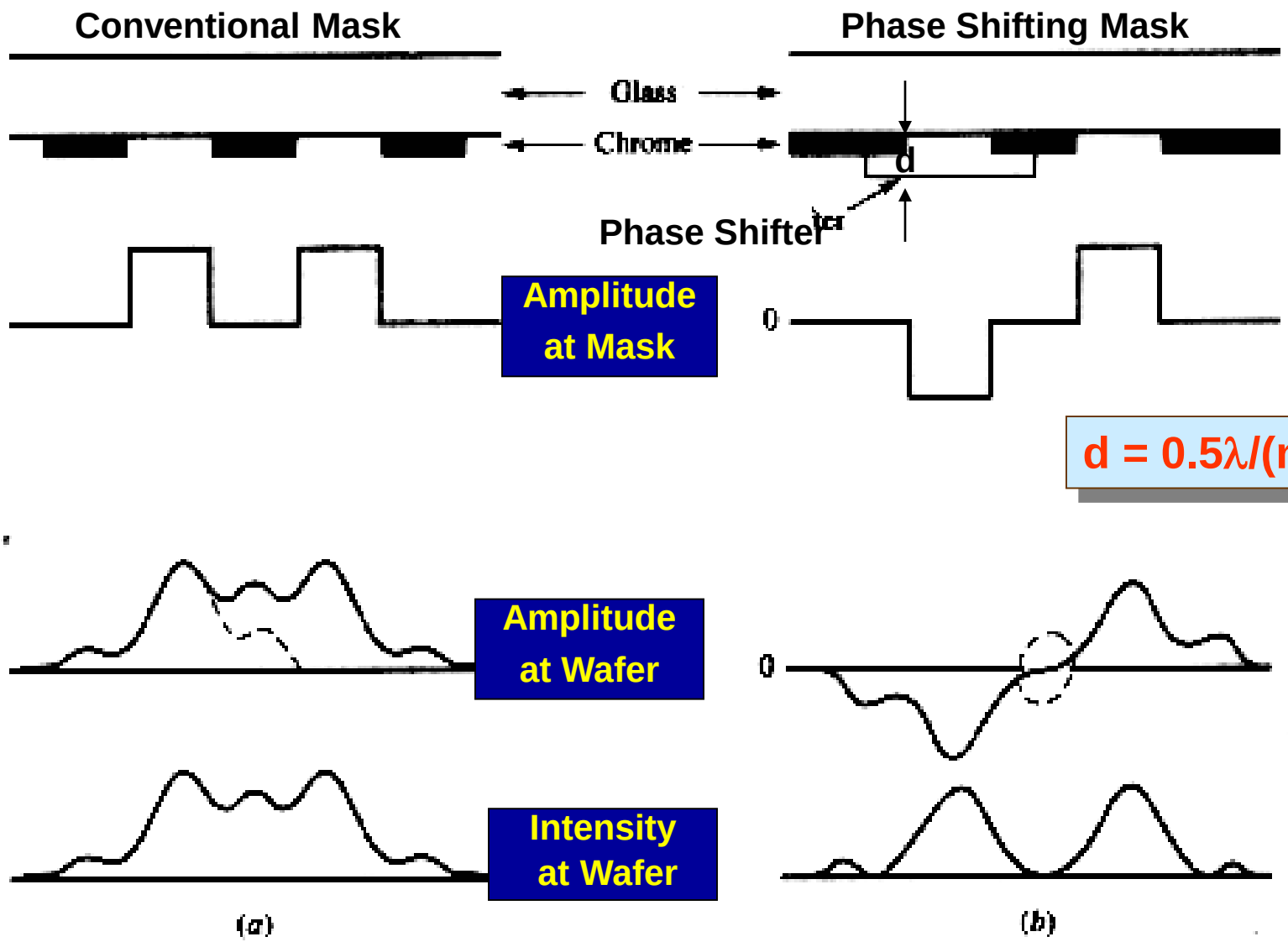
**Marc David Levenson**, through the pioneering development of phase shifting masks, laid the ground-work for the industry's efforts at wavefront engineering and resolution enhancement technology.

Here with the Fritz Zernike Award

http://www.betasights.net/wordpress/?p=923

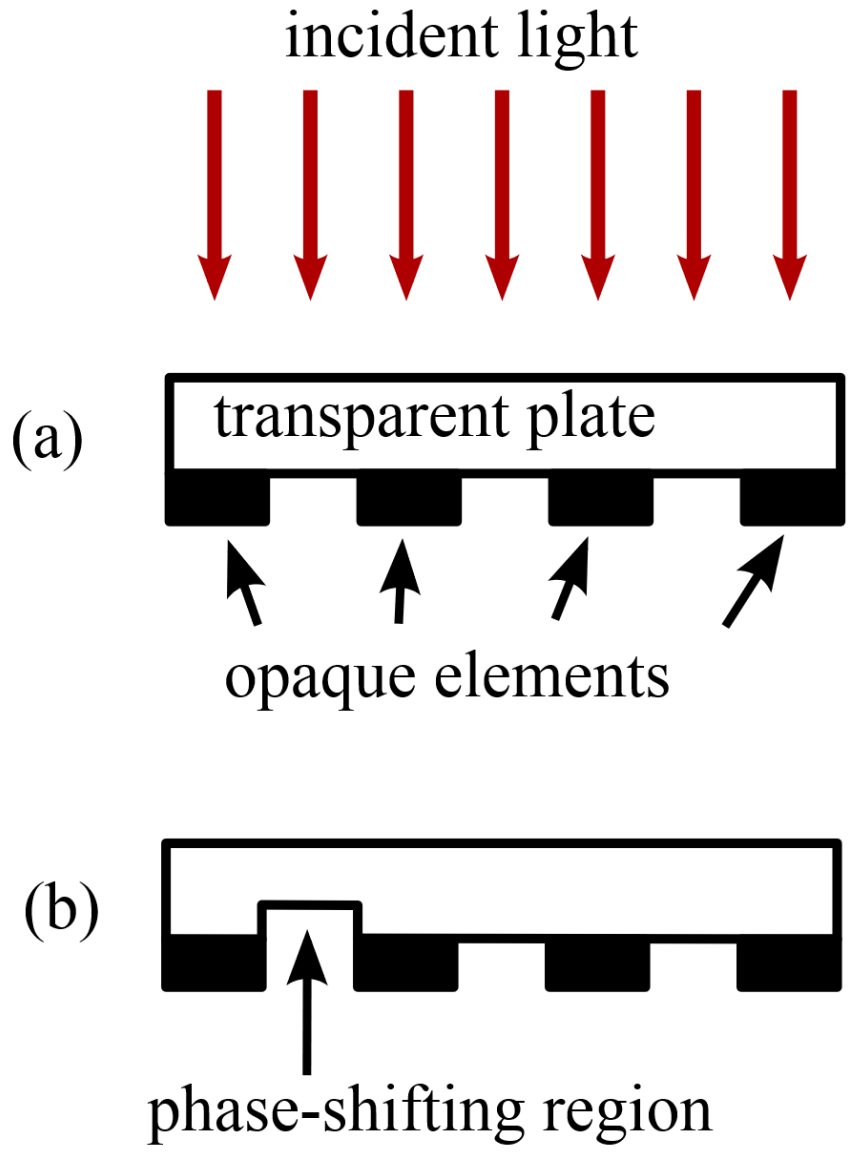
David

# Phase Shifting Principle

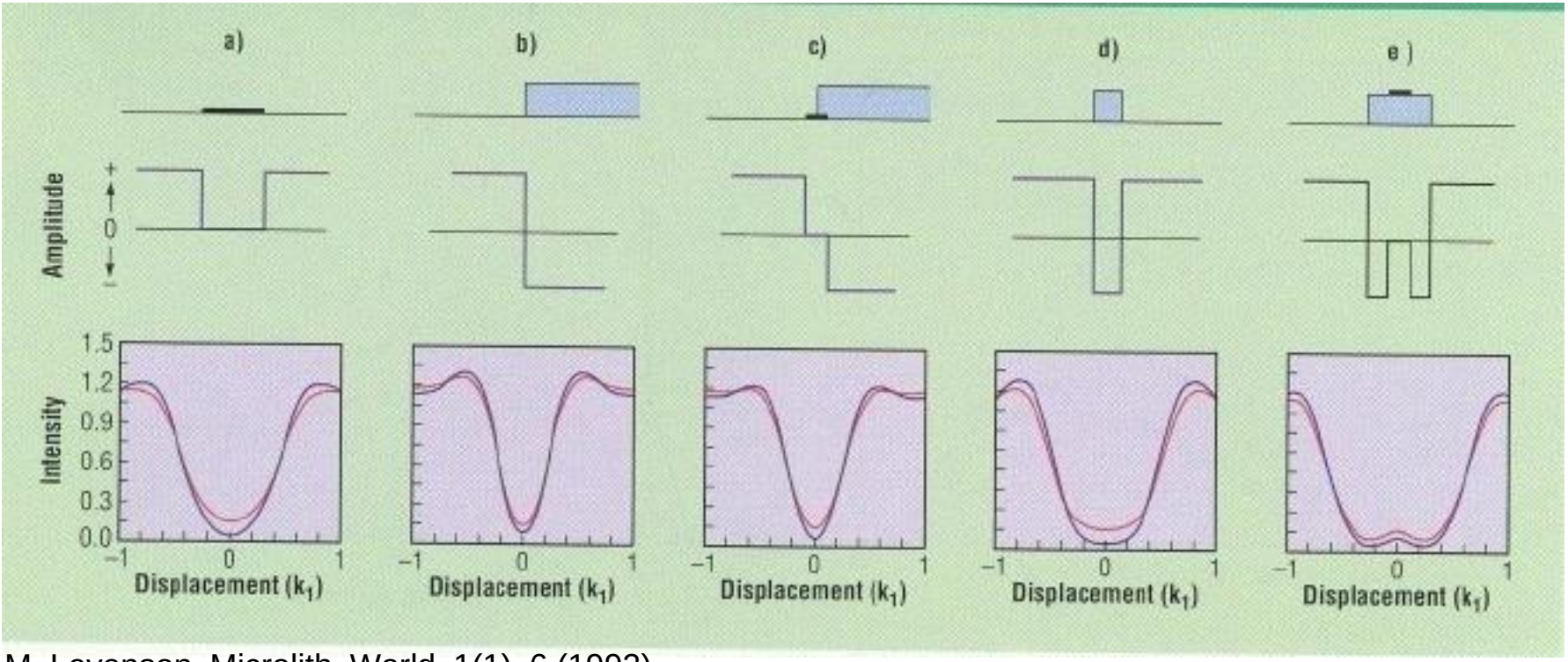


# Phase Shifting Mask

https://spie.org/publications/fg06_p78-80_phase-shift_masks



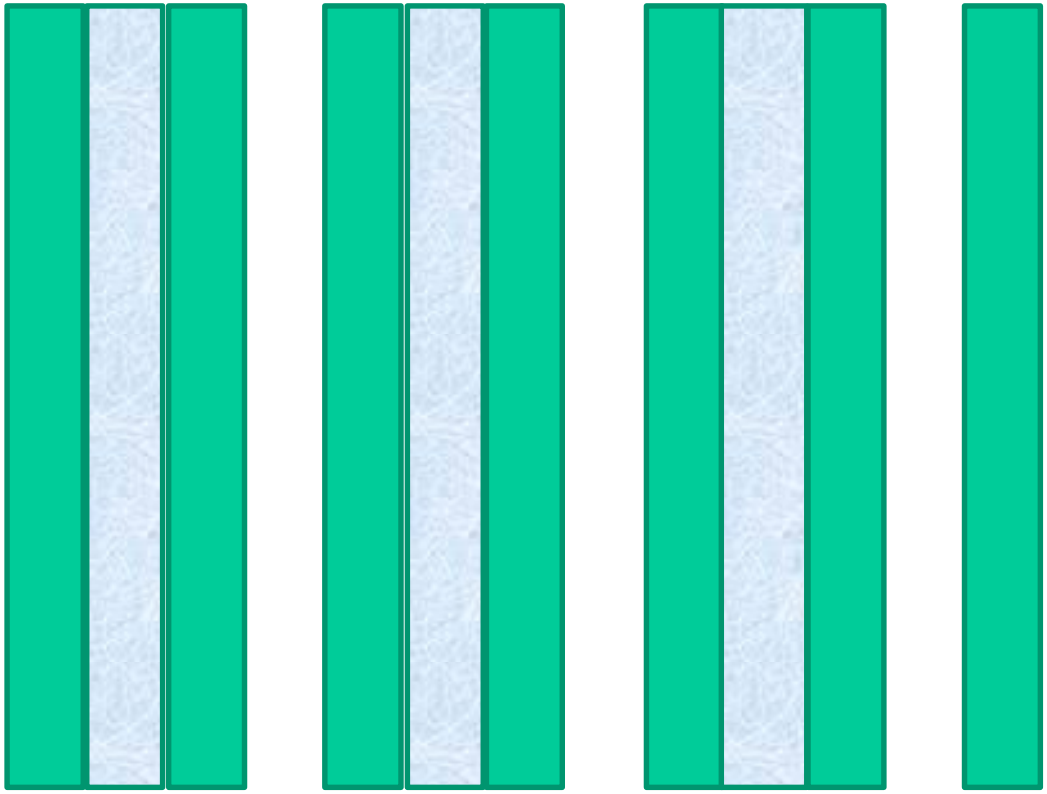
# Phase Shifting Designs




M. Levenson, Microlith. World, 1(1), 6 (1992)

Five means of patterning an isolated dark line. The mask structures are shown at the top with the resulting amplitude profiles in the middle. At the bottom are the in-focus intensity profiles (and the profiles at the end of an out-of-focus k2 =1 exposure window) [red]) plotted versus displacement units of $k_1$. The transmission mask in (a) would print with a zero-bias width corresponding to $k_1 = 0.5$. The chromeless phase edge in (b) and the Levenson-mask in c (phase edge is buried under an opaque line) produce dark lines with $k_1 = 0.25$. The shifter-shield design in (d) projects a dark line of width $k_1 = 0.6$ while the rimshifter mask in (e) produces a line with $k_1 = 0.8$. Except for the transmission mask,in (a), each of these values is near the optimum for that mask structure.

# Laying out Levenson Masks



# Laying out Levenson Masks

FIG. 1

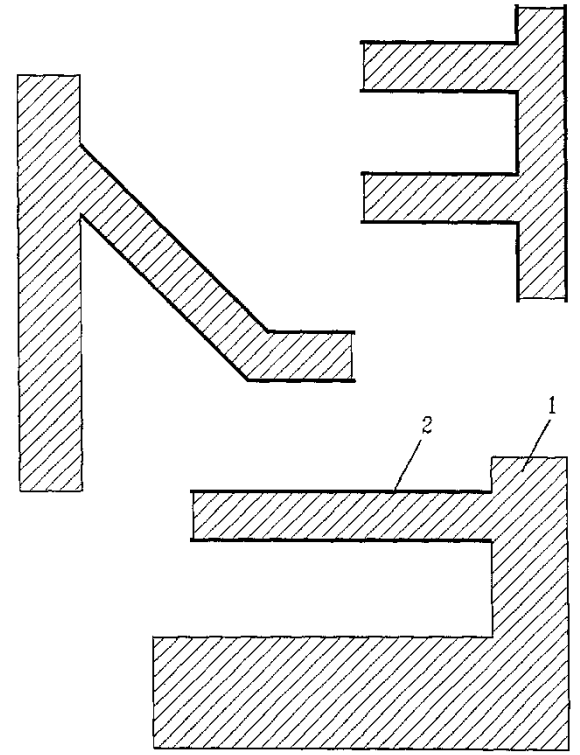
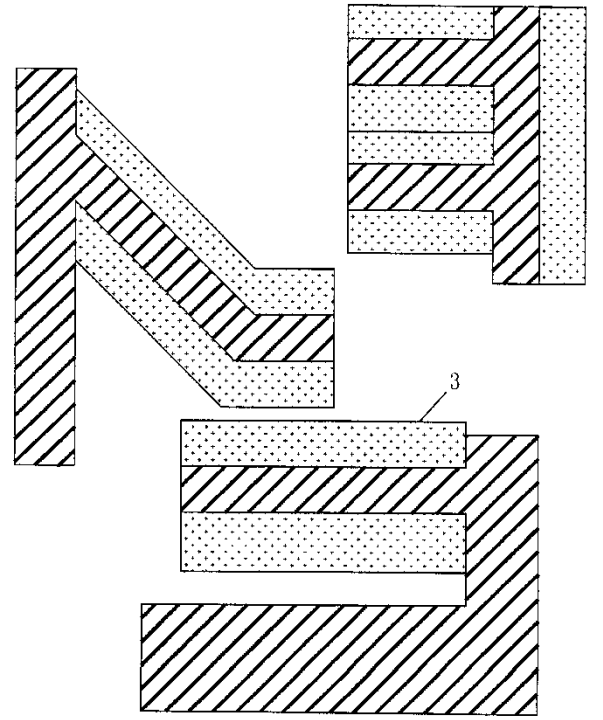



FIG. 2

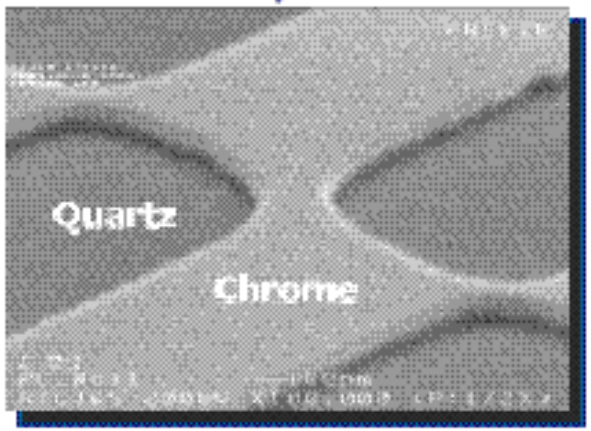


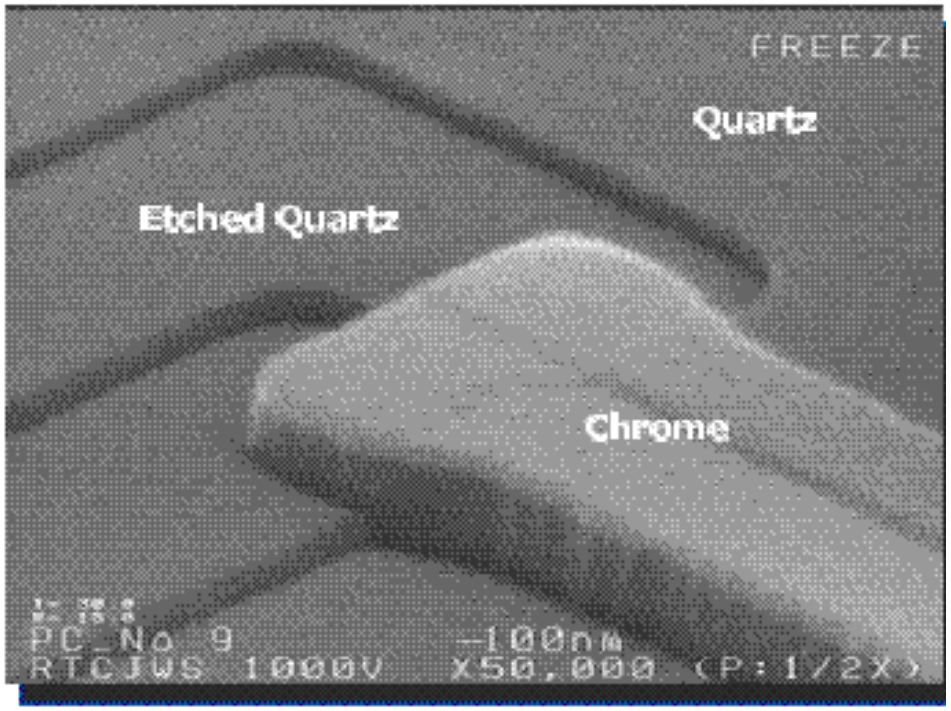
# Reticles

## Phase Shifting Masks

DuPont

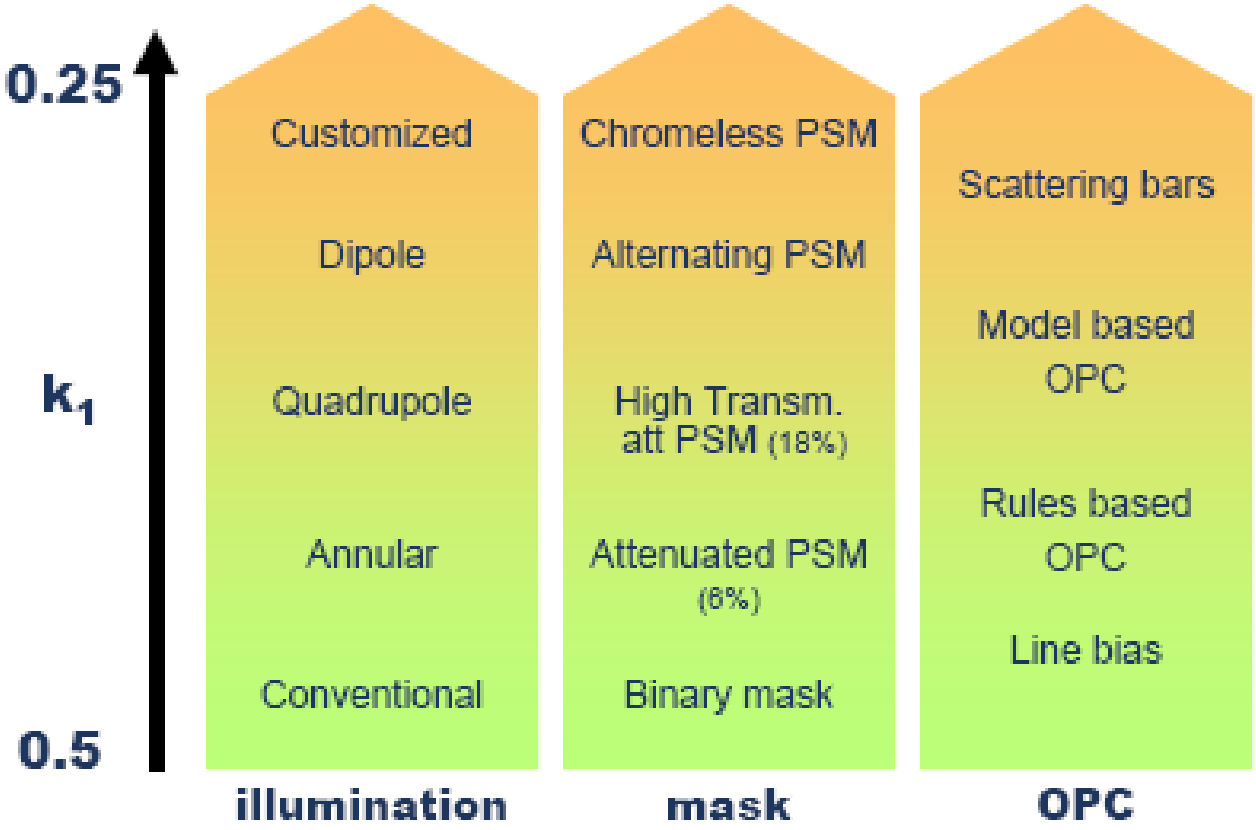
Binary Mask




Multi-Phase Shift Mask

# Myriad of optical extensions

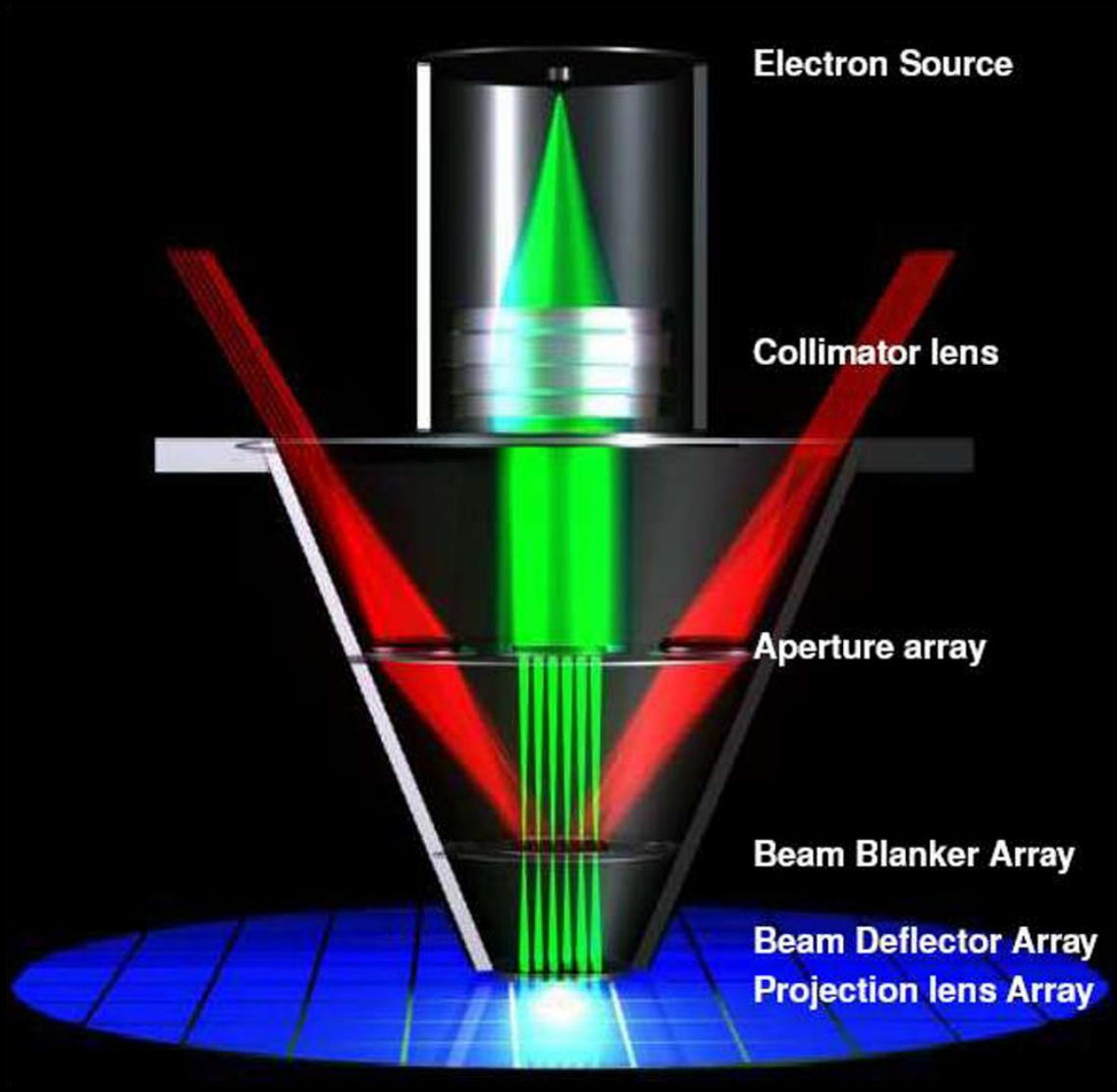






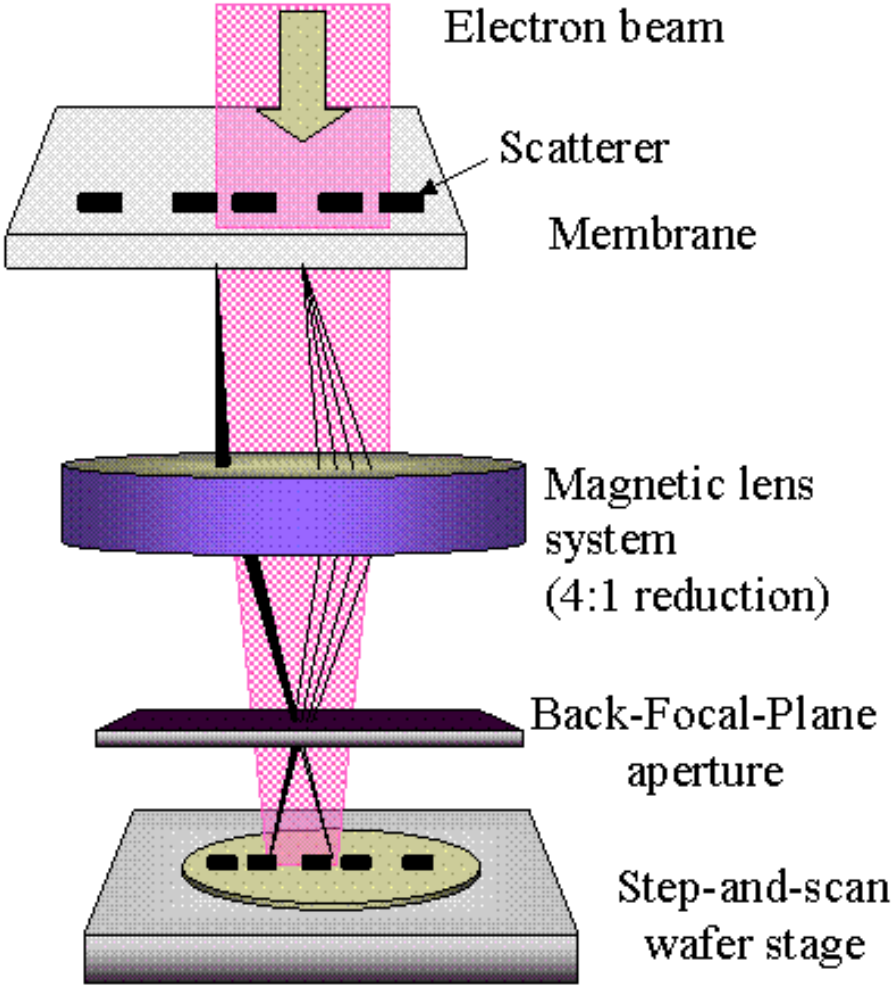
Courtesy: K. Ronse

# IMS eMET Mask Writer Tool

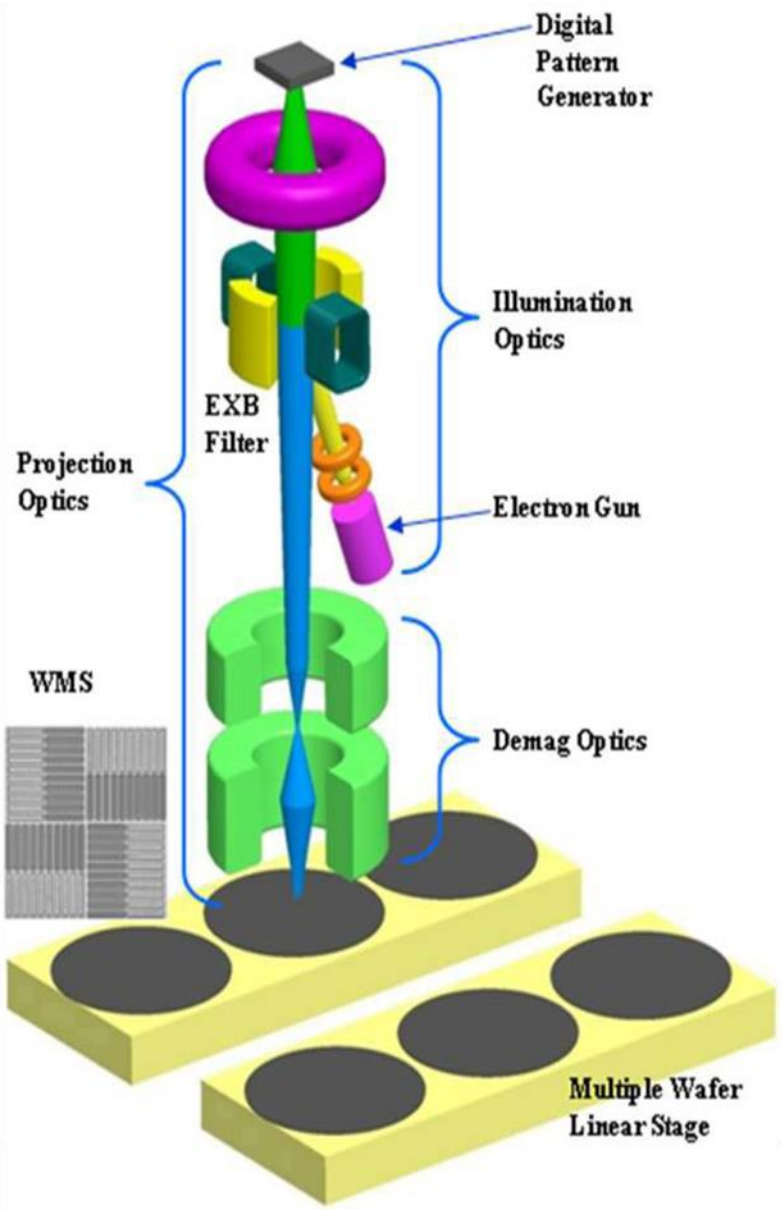


# SCAPEL

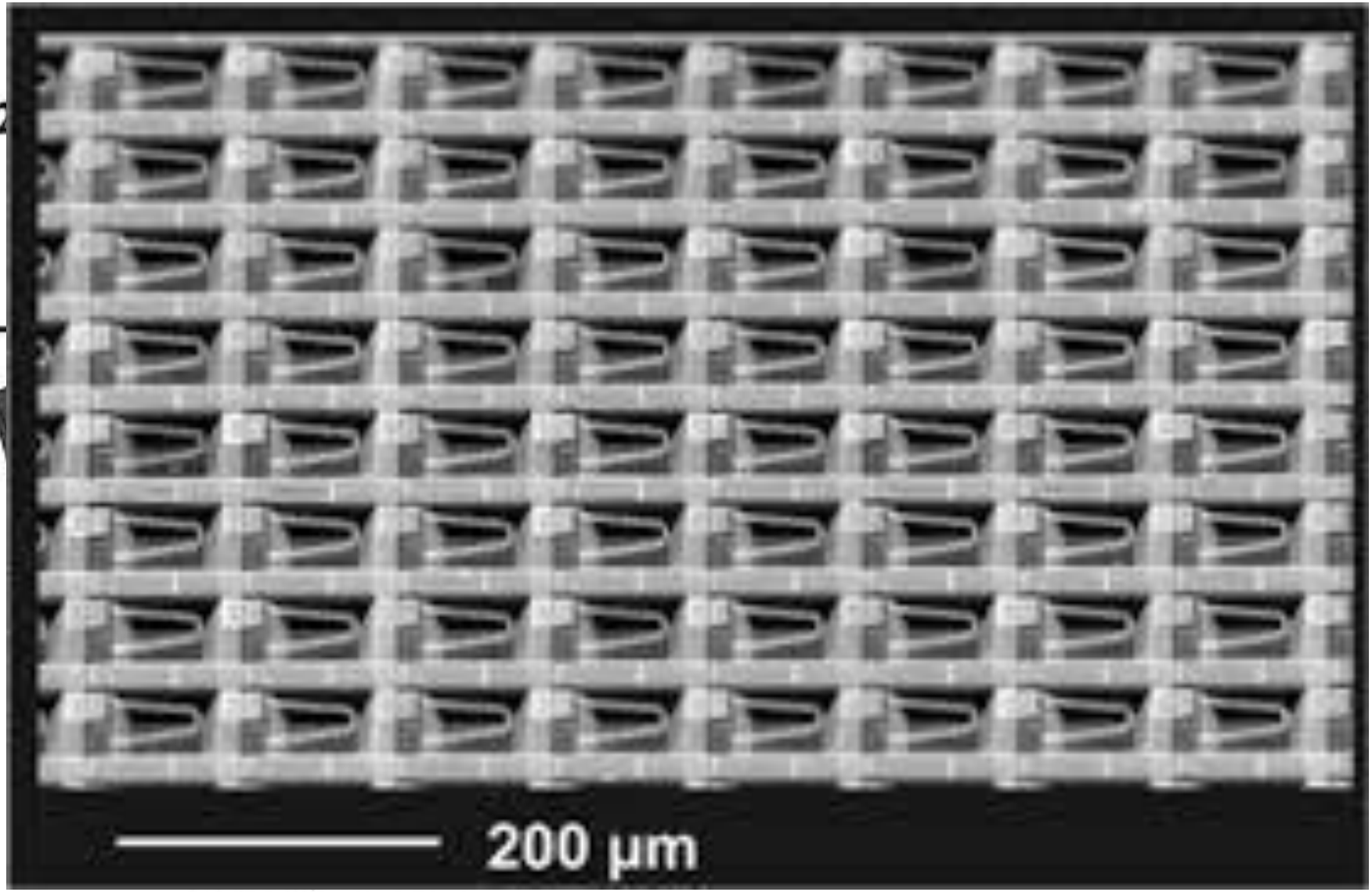
- (SCattering with Angular Limitation Projection Electron-beam Lithography)

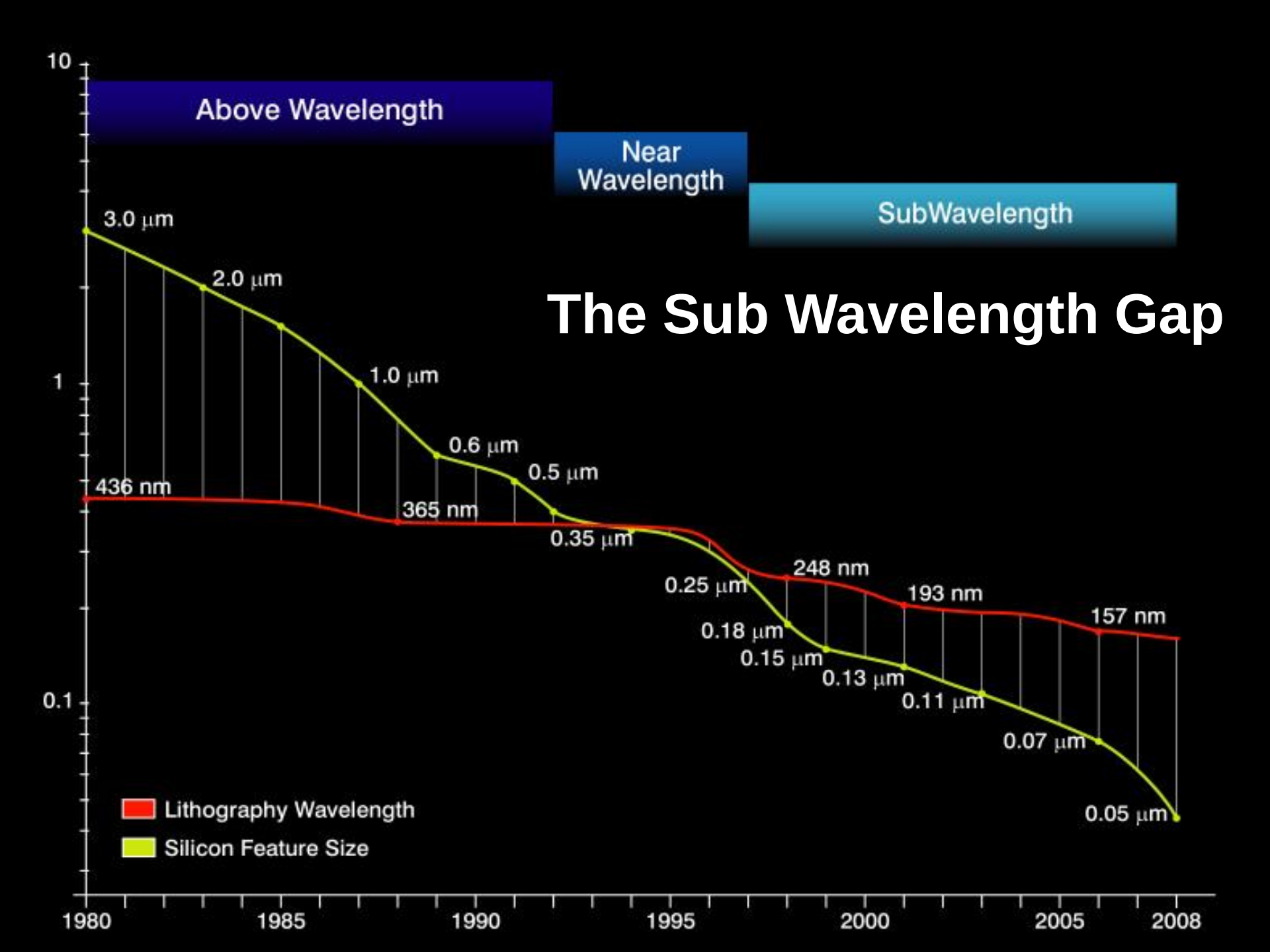


# REBL


Digital
Pattern
Generator
Illumination
Optics
EXB
Filter
Projection
Optics
Electron Gun
WMS
Demag Optics
Multiple Wafer
Linear Stage

# IBM Millipede




Above Wavelength
Near Wavelength
SubWavelength
The Sub Wavelength Gap
10
1
0.1
3.0 μm
2.0 μm
1.0 μm
0.6 μm
0.5 μm
0.35 μm
0.25 μm
0.18 μm
0.15 μm
0.13 μm
0.11 μm
0.07 μm
0.05 μm
436 nm
365 nm
248 nm
193 nm
157 nm
Lithography Wavelength
Silicon Feature Size
1980
1985
1990
1995
2000
2005
2008

# 157 nm Lithography

- **$F_2$ Excimer Laser output 157 nm**
- **157 nm light**
  - Air, water, polyethylene…almost everything is opaque
  - $CaF_2$ is transparent but crystalline, birefringent
  - There is no resist, no Mask material, no Pellicle, immersion Fluid, etc.
- **Requires a New Infrastructure**
  - Glass, purge gas. Mask…. Long lead times and EUV is coming ☺



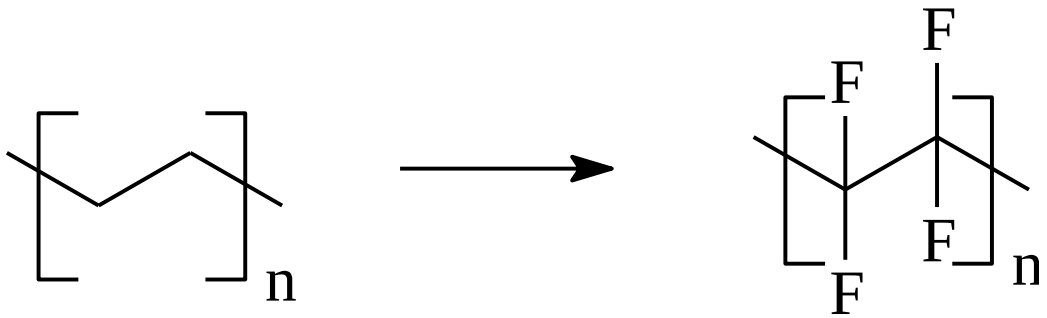
# Absorption ($\mu m^{-1}$) of Common Polymers

| **Transmission 0.00001%!!!** | Wavelength (nm) | | |
|---|---|---|---|
| | **157.6** | **193** | **248** |
| 248 resist | 6.84 | | **0.37** |
| 193 resist | 6.86 | **0.47** | |
| Polystyrene* | 6.20 | | |
| Polynorbornene* | 6.10 | | |
| PMMA* | 5.69 | | |
| Fluorocarbon* | 0.70 | | |

- Vacuum UV
- $O_2$, $H_2O$ absorbs at this wavelength
- Even hydrocarbons like butane and polyethylene absorb strongly

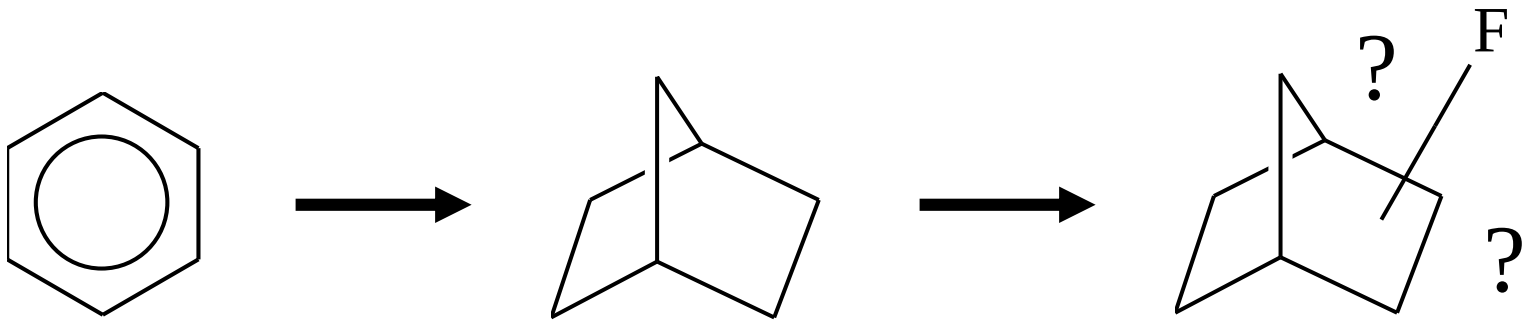
* R.R.Kunz,et al., Proc. SPIE 3678, 13 (1999).

# Fluorination of Norbornane Skeleton




Opaque

Transparent



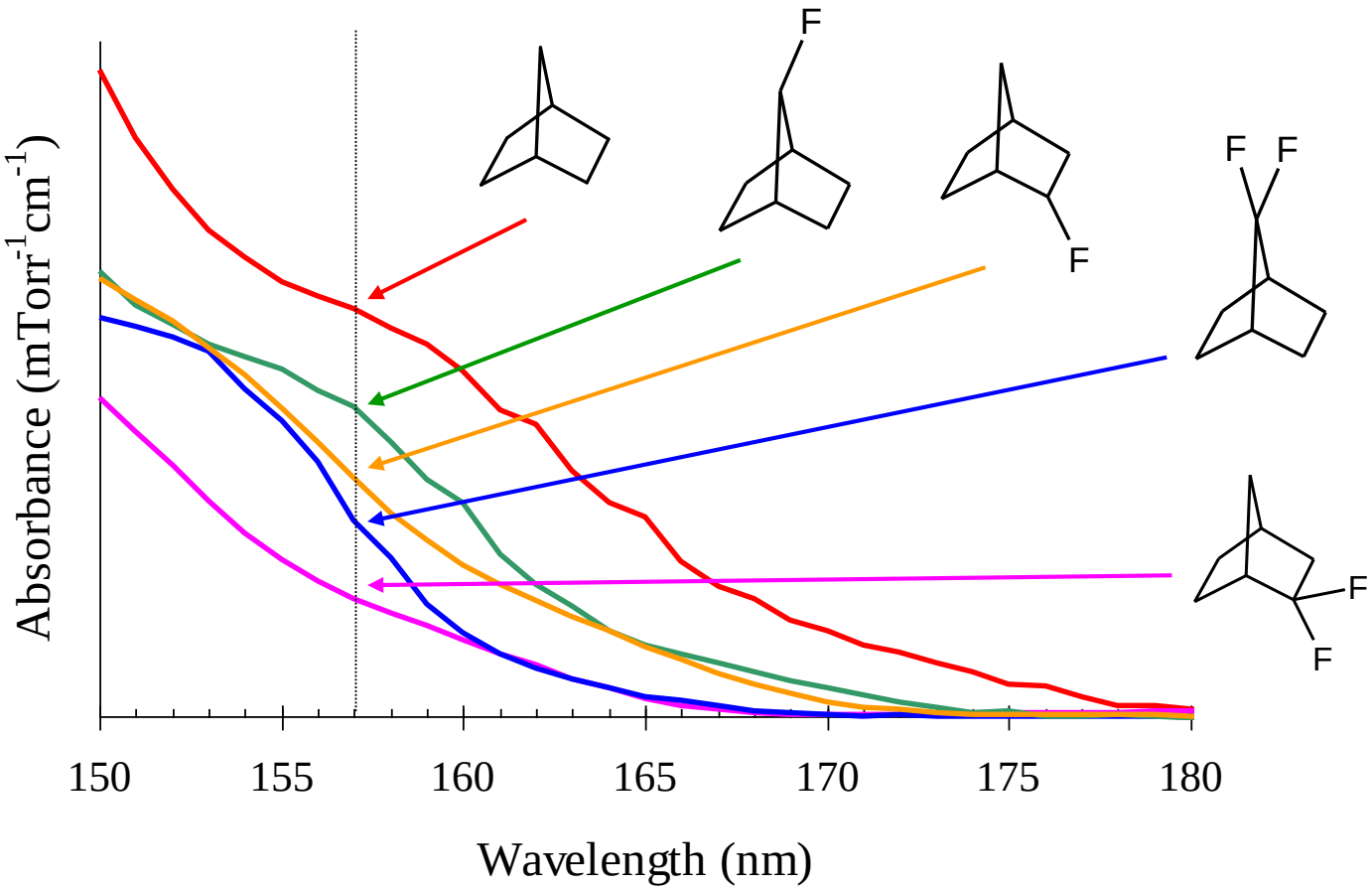

248 nm

193 nm

157 nm

How many fluorines and where to fluorinate?

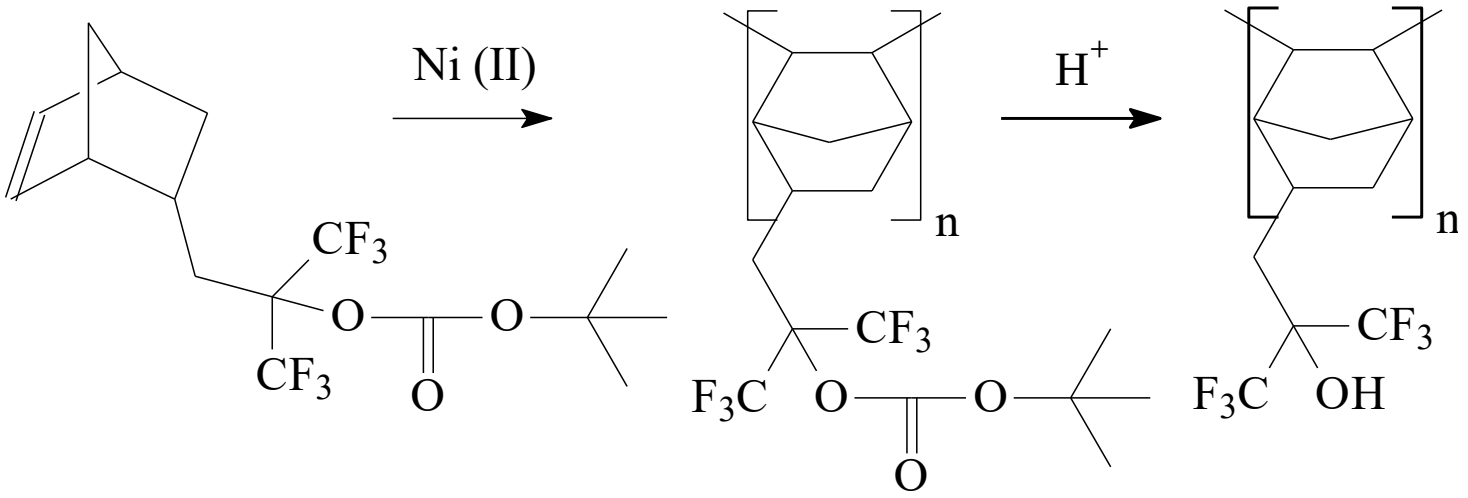
# Selective Fluorination of Norbornane




Geminal substitution at the two carbon bridge is the most effective fluorination pattern → $\alpha$-$CF_3$ acrylates

# Surprising Serendipitous Discovery

Originally for Top Surface Imaging Project



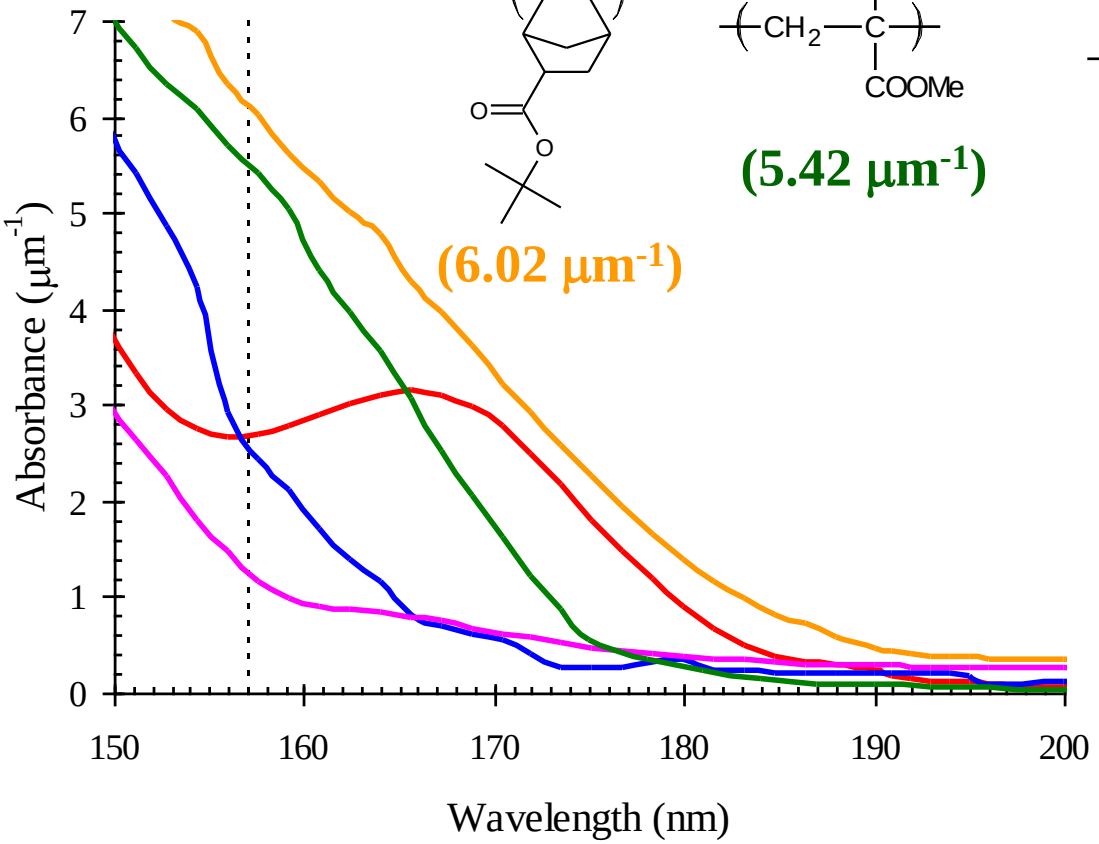

$A_{157} = 2.57\ \mu m^{-1}$

$A_{157} = 1.15\ \mu m^{-1}$

NBHFABOC and NBHFA are surprisingly transparent

*T. Chiba, et. al., J. Photopolym. Sci. Technol* **,** *13 (2000) 657-664*

# Absorbance of Fluorinated Polymers

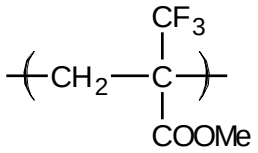




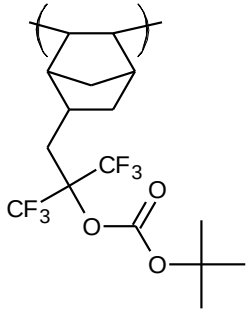

(6.02 μm-1)



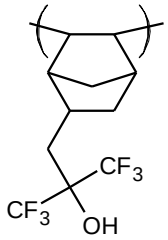

(5.42 μm-1)




(2.68 μm-1)



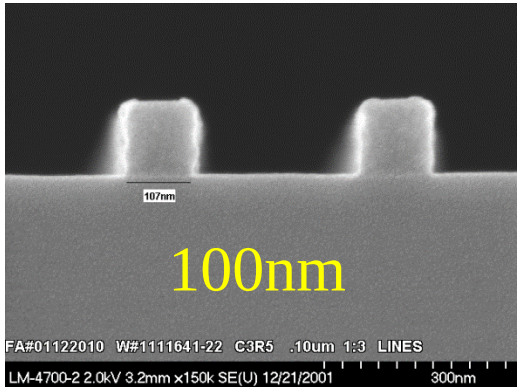

(2.44 μm-1)

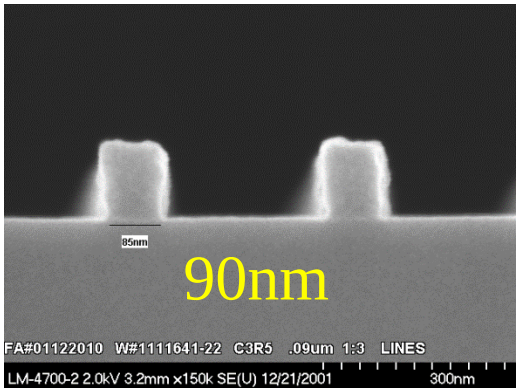


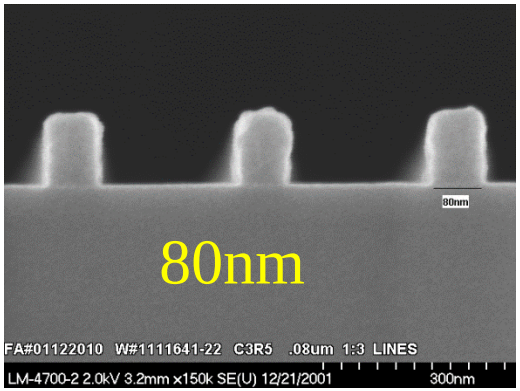

(1.15 μm-1)

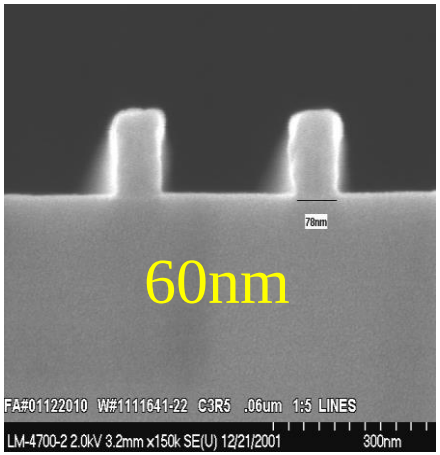
Hexafluoroisopropyl and α-trifluoromethylcarboxylic acid are groups surprisingly transparent!

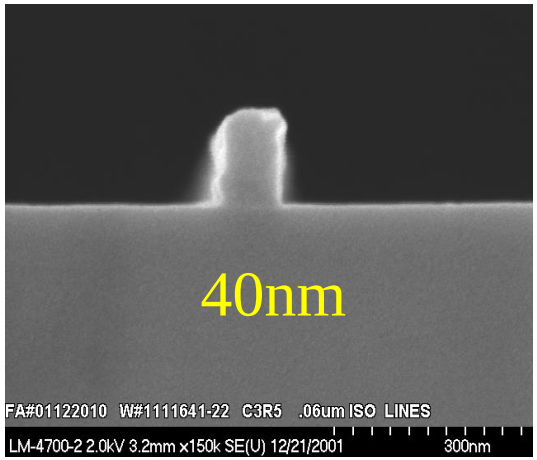
# Recent Imaging Results



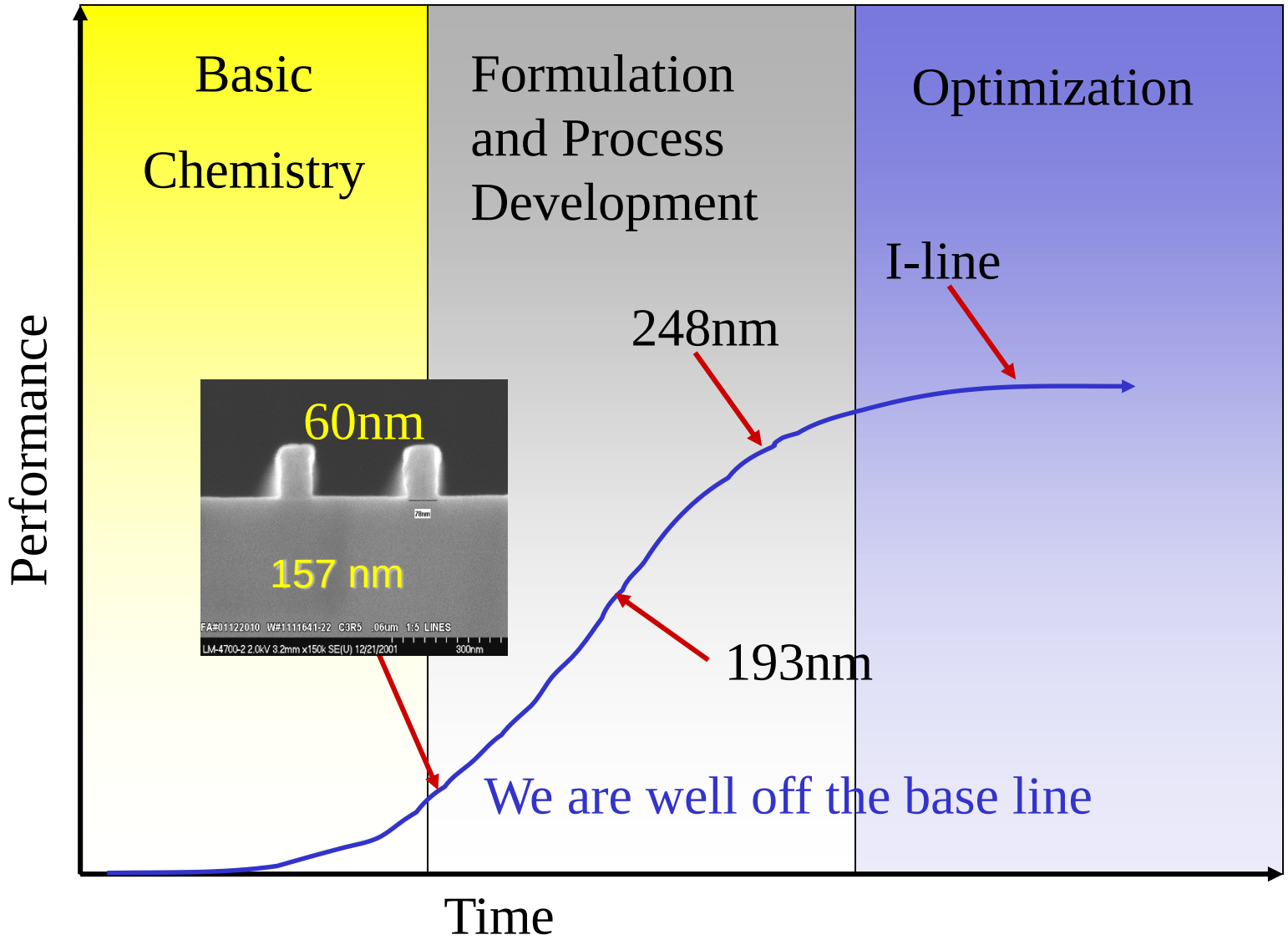



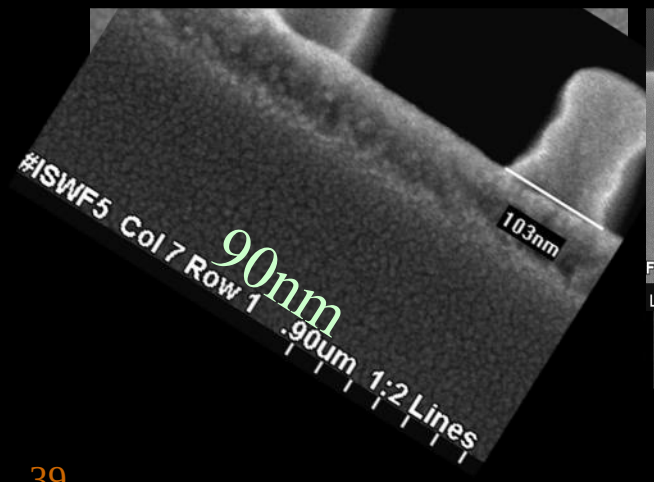



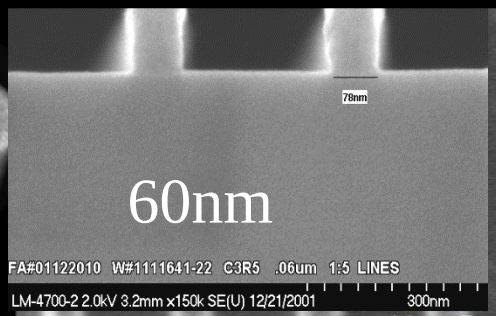



# Resist and Process Development



# Images in UT 157nm Resists



# intel drops 157-nm tools from lithography roadmap

**Mark LaPedus**

5/23/2003 01:40 AM EDT

SANTA CLARA, Calif. -- Intel Corp. has revised its lithography strategy for the second time in the recent months, disclosing it has dropped 157-nm tools from its roadmap and is not pursuing the scanner technology for IC production. The move is expected to impact fab-tool and material vendors developing 157-nm products for Intel.

## The Kiss of Death

El beso de la muerte, by an unknown sculptor.
Barcelona, Spain ca. 1930

# The Landscape is littered with NGL's

- **Electron Beam direct write**
- **Write with many electron beams**
- **Project electron beams**
- **All of the above with ions**
- **Shadow printing with Synchrotron X-rays**

- ***Now here lies 157nm …rest in peace!***

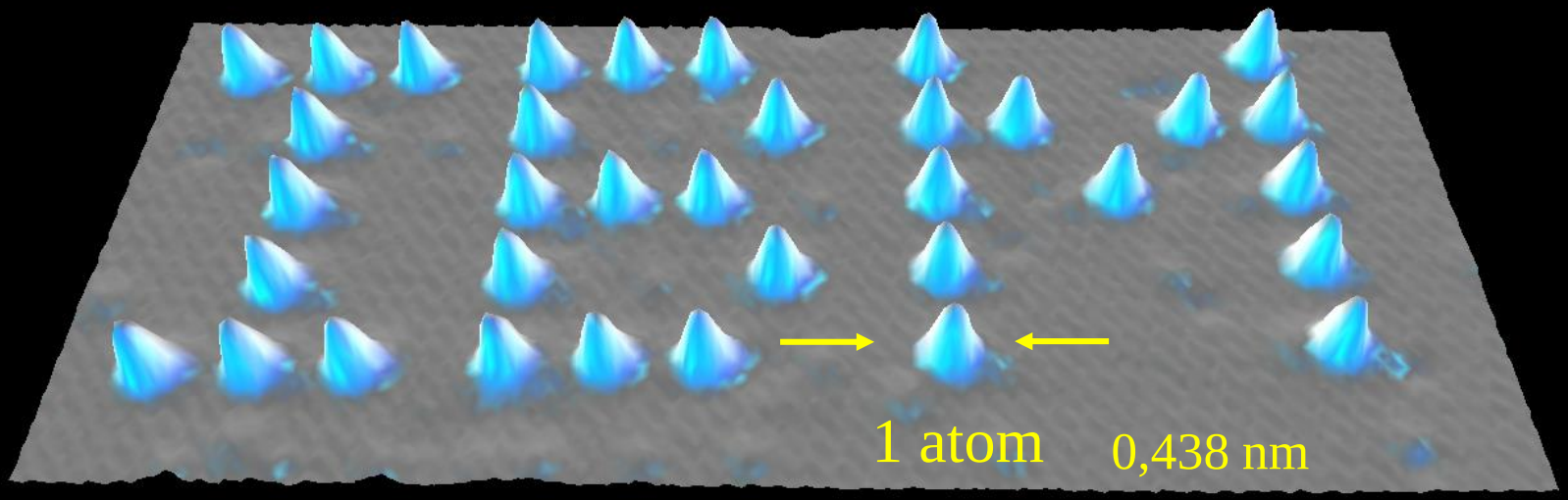
# Let's look more closely in the graveyard

# A "Sixth Sense"





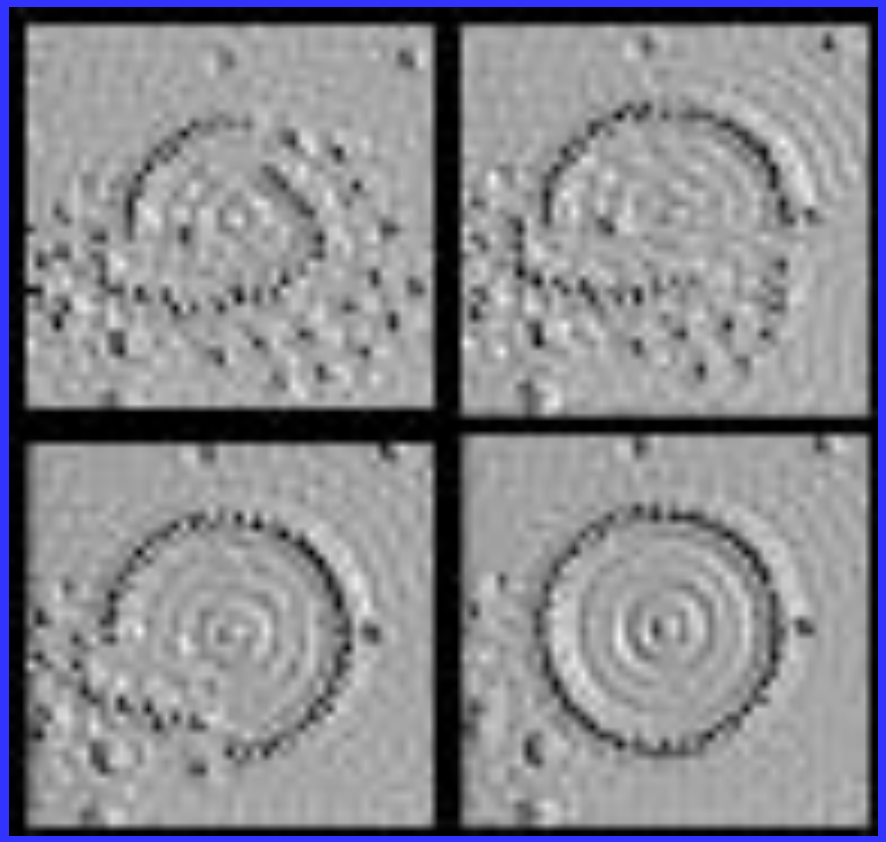
# *Ultimate limit of high resolution patterning!!*




*Eigler, et al IBM Almaden*

*Xe on Nickel*

# Atomic Resolution…atom by atom



Don Eigler

IBM Almaden Research Center

Resolution:

1 atom ~ 0.3–0.5nm

Throughput:

one atom per minute

~ 0.02 pixels/second

*Great Science but not yet practical*

# Production Lithography


- 193nm step and scan exposure
- Chemically Amplified Resist
- Water immersion lithograpy
- Cost > $60 million/tool

Resolution: 40 nm ≈ λ/5

Throughput: 100 wafers/hr

*>300 gigapixels/sec!!!*

*OK…Serial Processes are Simply too Slow*

# Resolution vs. Throughput