3.155J/6.152J Lecture 10: Lithography – Part 1

Prof. Martin A. Schmidt

Massachusetts Institute of Technology

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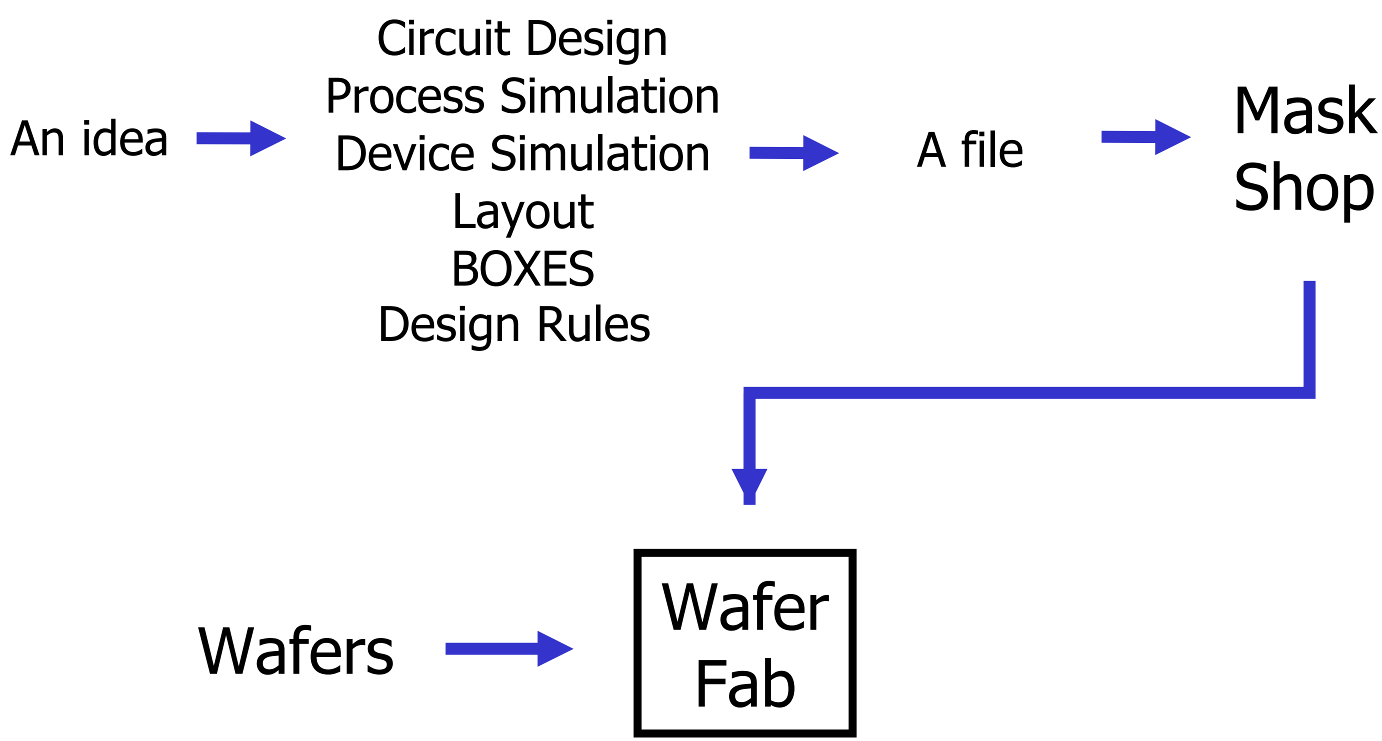
Outline

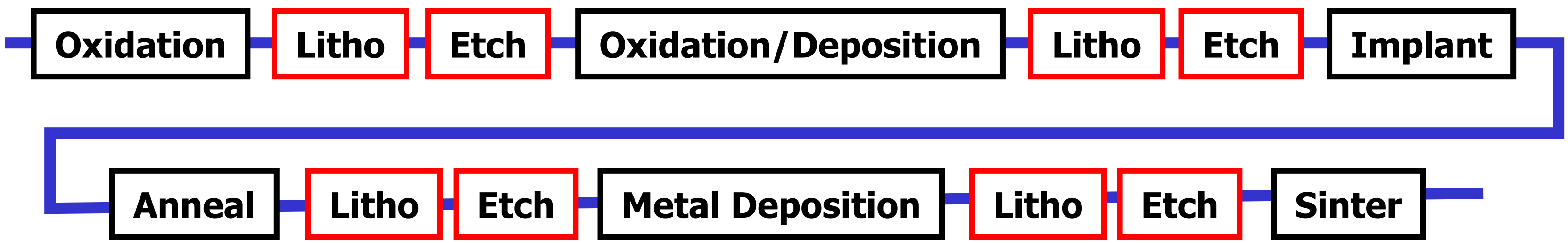
- The Lithographic Process
  - Basic Process
  - Definitions
- Fundamentals of Exposure
- Exposure Systems
- Resists
- Advanced Lithography
- Recommended reading
  - Plummer, Chapter 5
  - Other: Campbell, Chapter 7,8,9

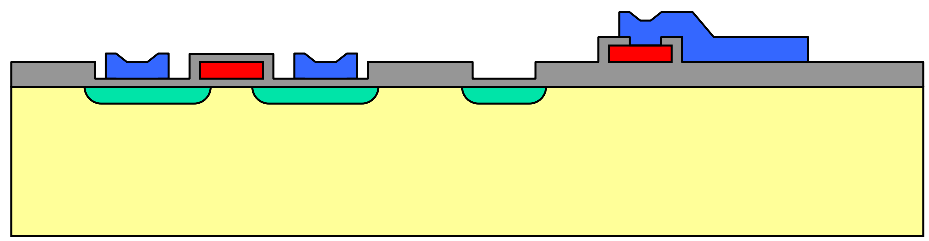
IC Process


An idea
Circuit Design
Process Simulation
Device Simulation
Layout
BOXES
Design Rules
A file
Mask Shop
Wafers
Wafer Fab

Wafer Fab - Lithography

- Most Common Measure of Complexity
  - # of Masks, Minimum Feature (examples)
- Approximately 50% of the Process Steps





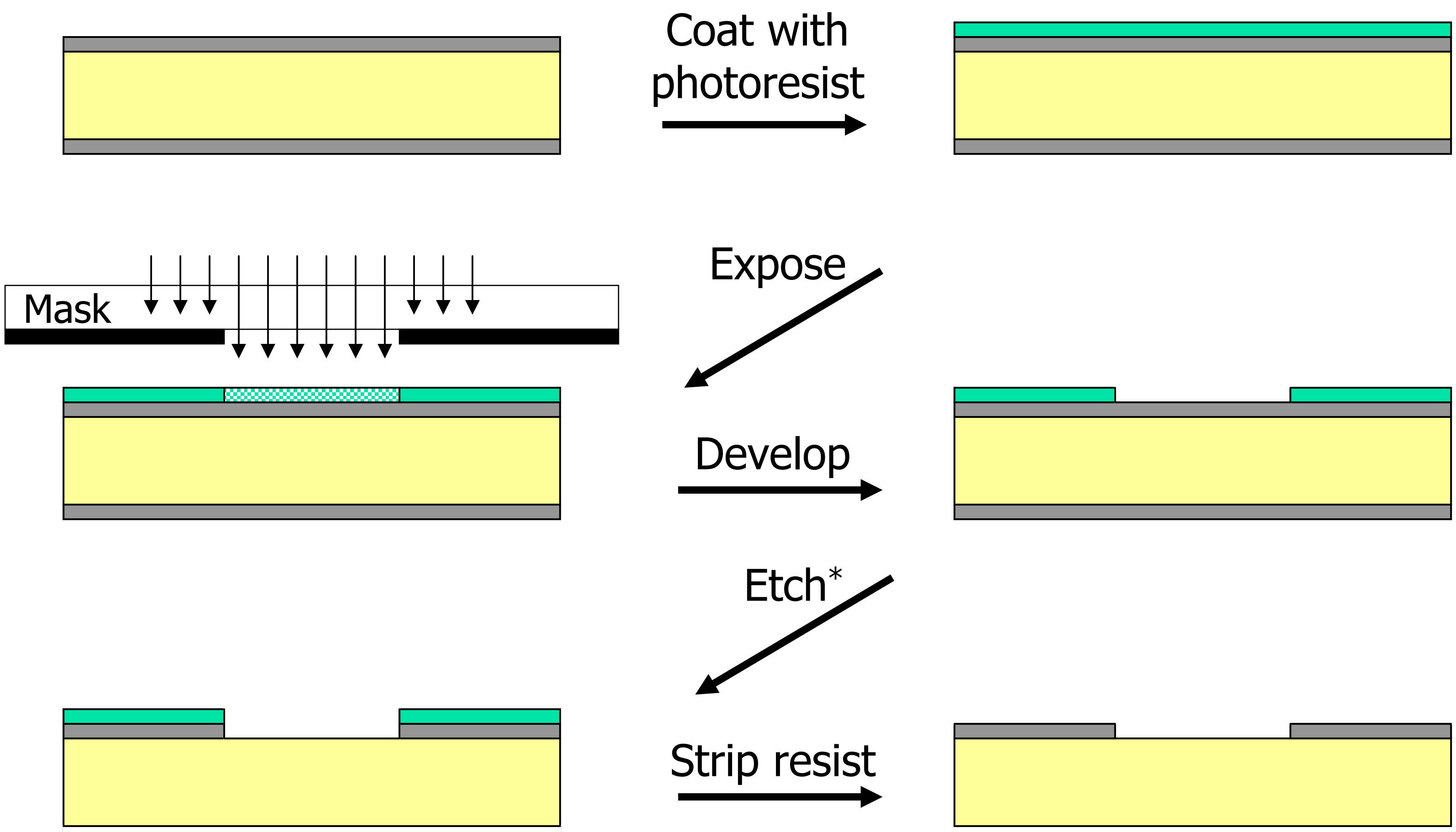
- Drives Infrastructure
  - Cleanliness
  - Vibration
  - Temperature and Humidity

Semiconductor Roadmap

Lithography requirements for future generations of silicon technology

Year of first DRAM Shipment	1997	1999	2003	2006	2009	2012
DRAM Bits/Chip	256M	1G	4G	16G	64G	256G
Minimum Feature Size nm						
Isolated Lines (MPU)	200	140	100	70	50	35
Dense Lines (DRAM)	**250**	**180**	**130**	**100**	**70**	**50**
Contacts	280	200	140	110	80	60
Gate CD Control 3σ (nm)	20	14	10	7	5	4
Alignment (mean + 3σ) (nm)	85	65	45	35	25	20
Depth of Focus (μm)	0.8	0.7	0.6	0.5	0.5	0.5
Defect Density (per layer/m^2)	100	80	60	50	40	30
@ Defect Size (nm)	@ 80	@ 60	@ 40	@ 30	@ 20	@ 15
DRAM Chip Size (mm^2)	280	400	560	790	1120	1580
MPU Chip Size (mm^2)	300	360	430	520	620	750
Field Size (mm)	22x22	25x32	25x36	25x40	25x44	25x52
Exposure Technology	248 nm DUV	248 nm DUV	248 nm or 193 nm DUV	193 nm DUV or ?	193 nm DUV or ?	?
Minimum Mask Count	22	22/24	24	24/26	26/28	28

Pattern Transfer Steps

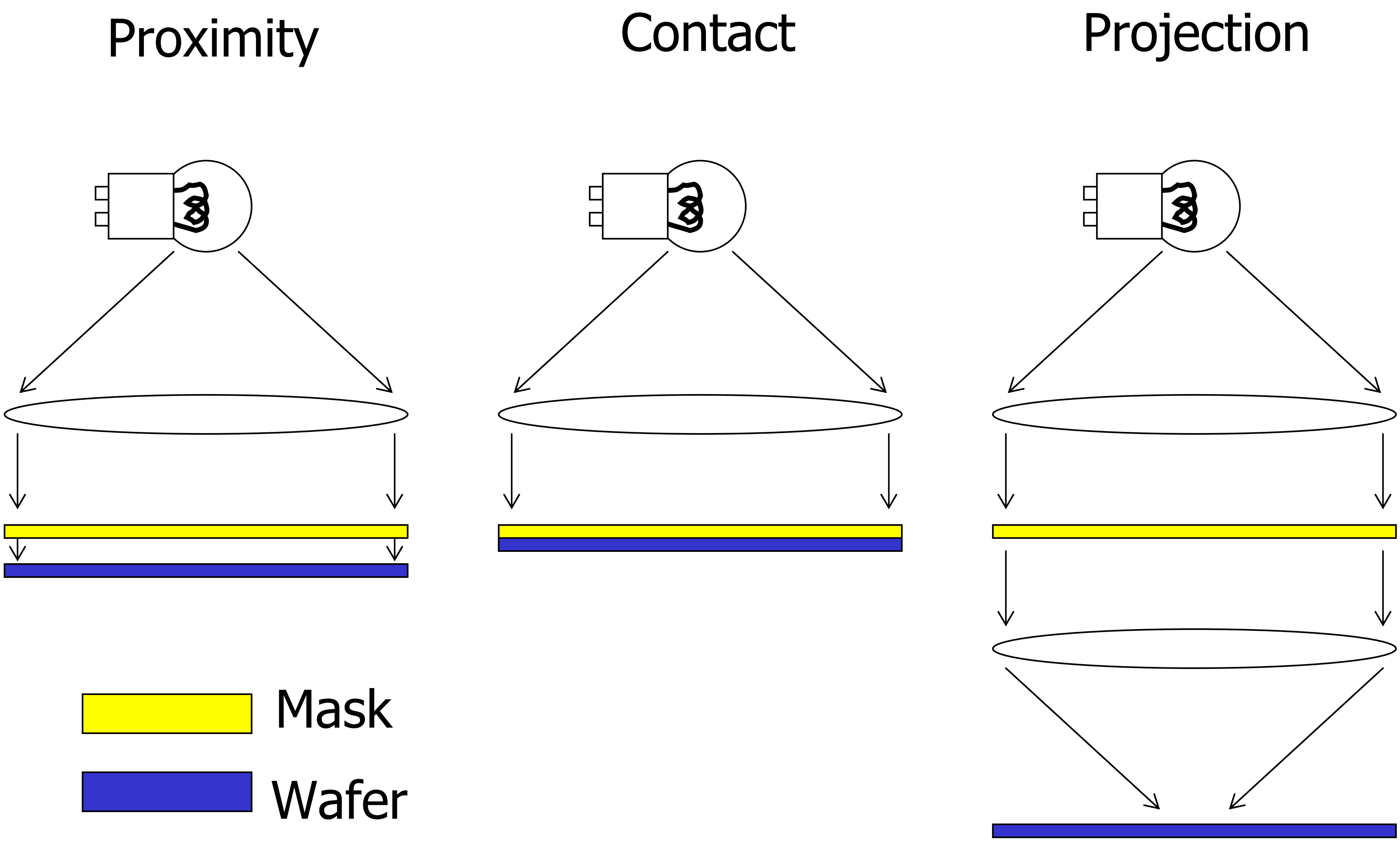


*Wet etch

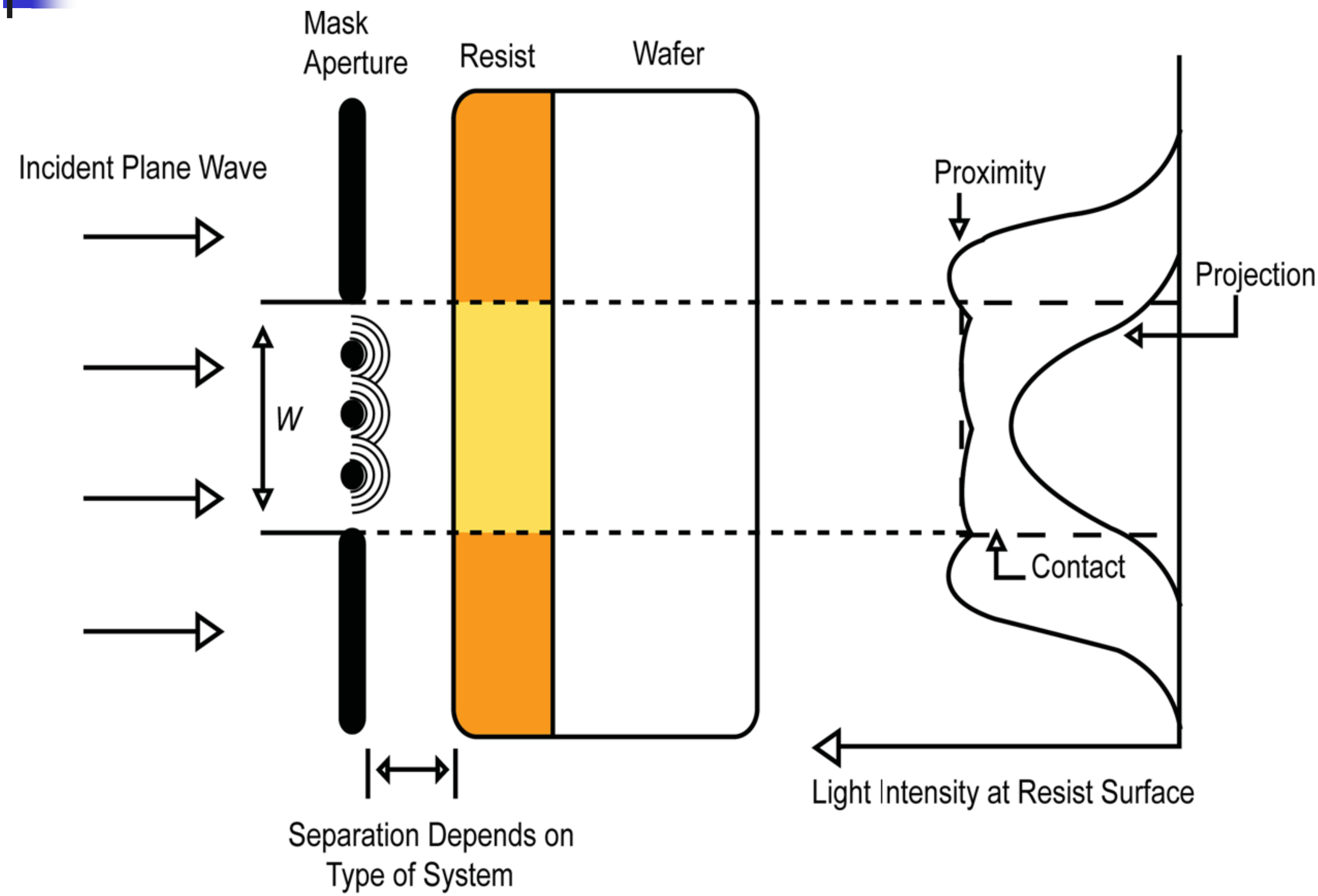
Definitions

- Metrics
  - Resolution
  - Throughtput
  - Registration (Alignment)
- Exposure Systems - UV
  - Projection - Fraunhofer
  - Proximity - Fresnel
  - Contact - Fresnel
  - Advanced
    - DUV, E-Beam, X-Ray, Nano-imprint
- Resists
  - Positive/Negative
  - Contrast
  - CMTF

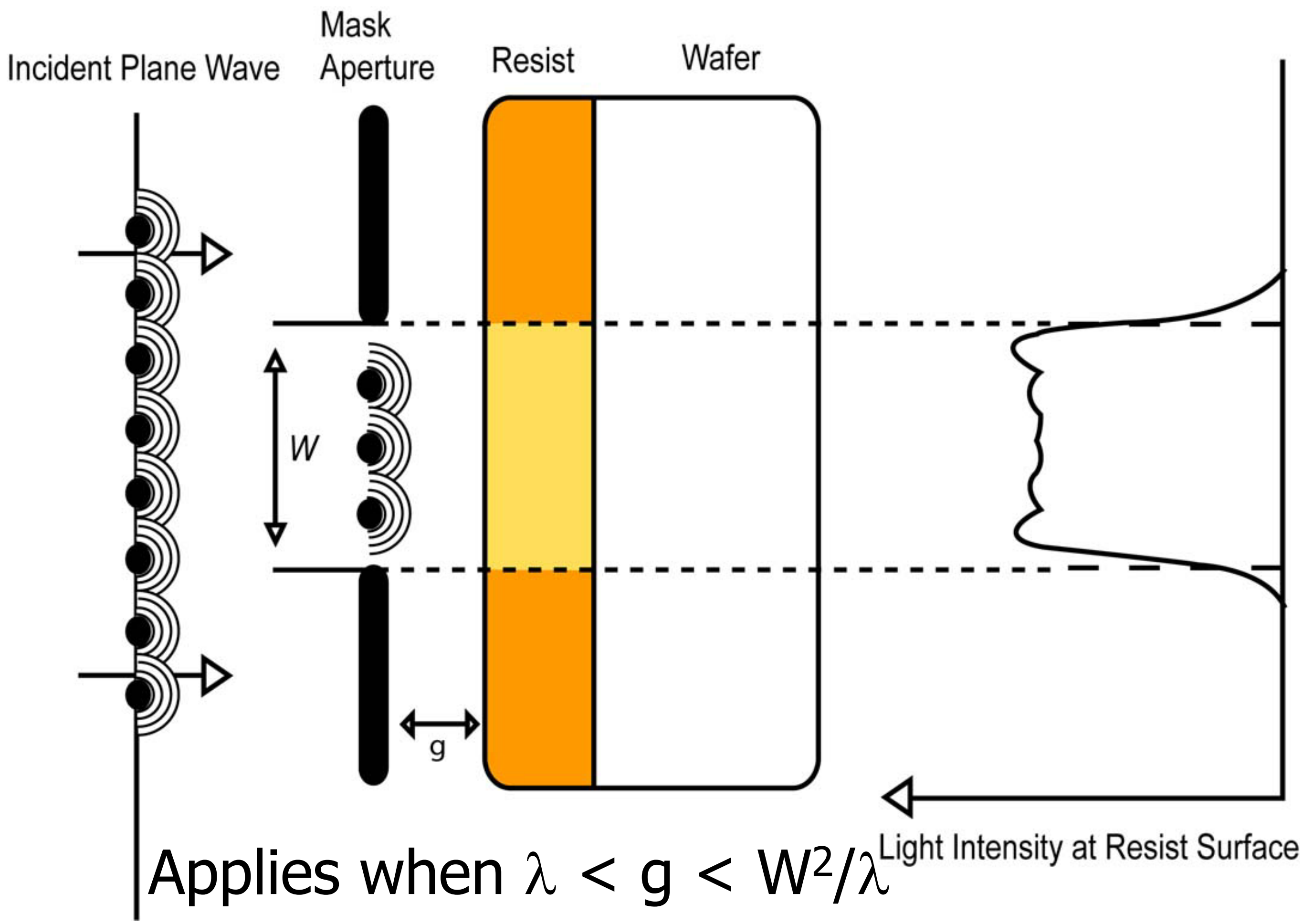
Lithography Systems



Contact/Proximity Printing



Contact/Proximity Printing



Applies when $\lambda < g < W^2/\lambda$

Minimum resolvable feature = $(\lambda g)^{1/2}$

Proximity Printing Limits

Minimum resolvable feature = $(\lambda g)^{1/2}$

Gap = 20 μm and Source = 436 nm

$\Rightarrow$ 3.0 μm

Maximum allowable proximity gap for near and deep UV sources as a function of the feature size normalized to the gap required for 2.5 μm resolution with a deep UV source

Feature Size (μm)	Maximum Gap for Near UV Source	Maximum Gap for Deep UV Source
2.5	0.63	1.0
2.0	0.37	0.61
1.0	0.08	0.24
0.5	0.05	0.07

Projection Printing

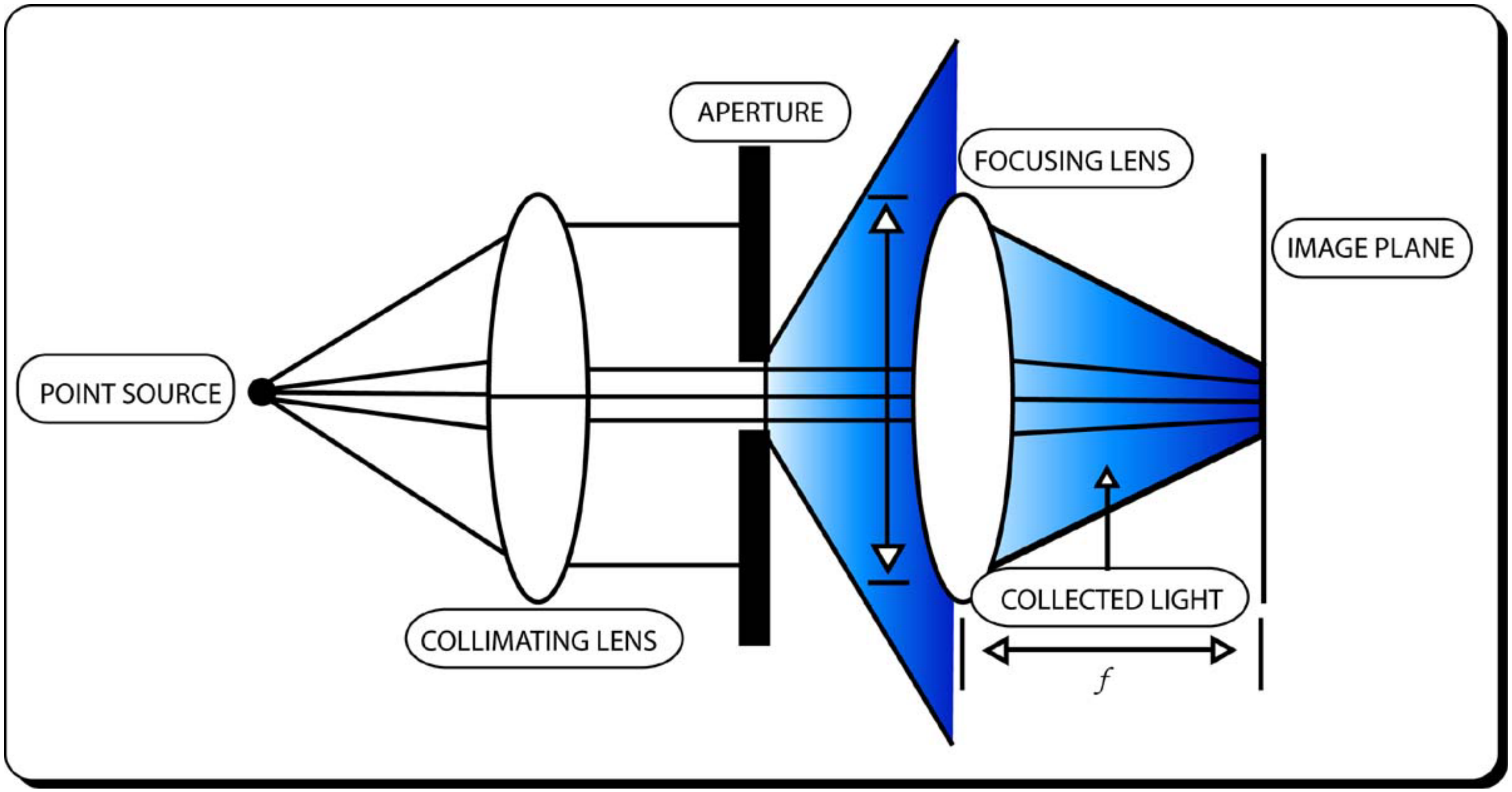
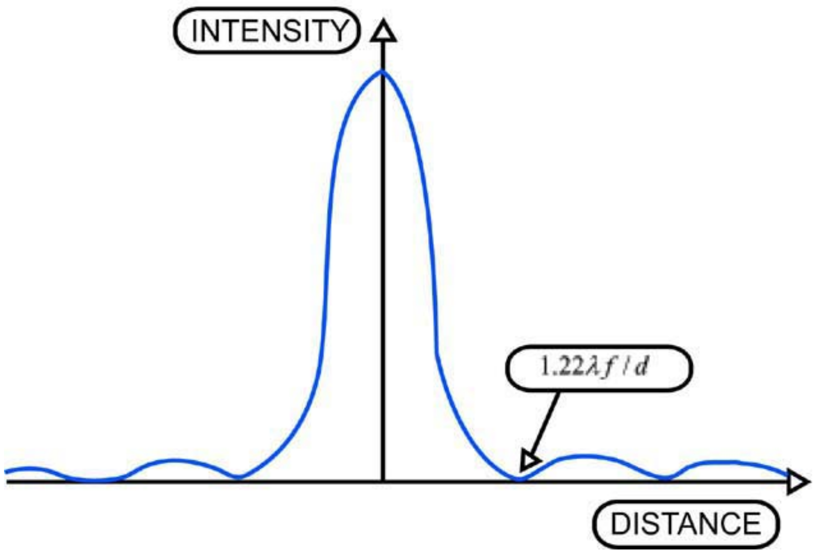
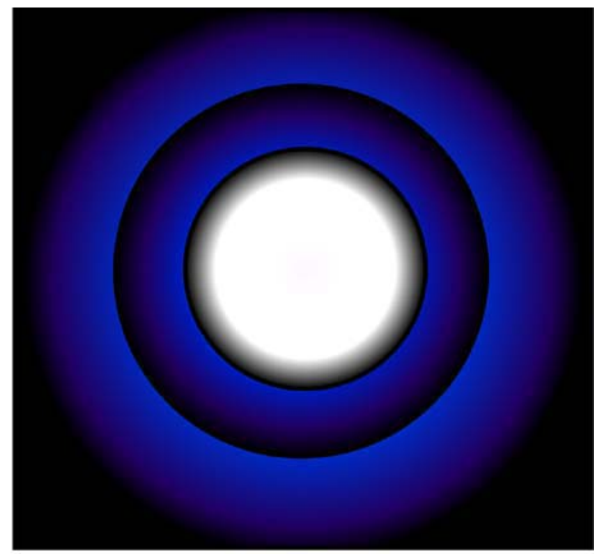


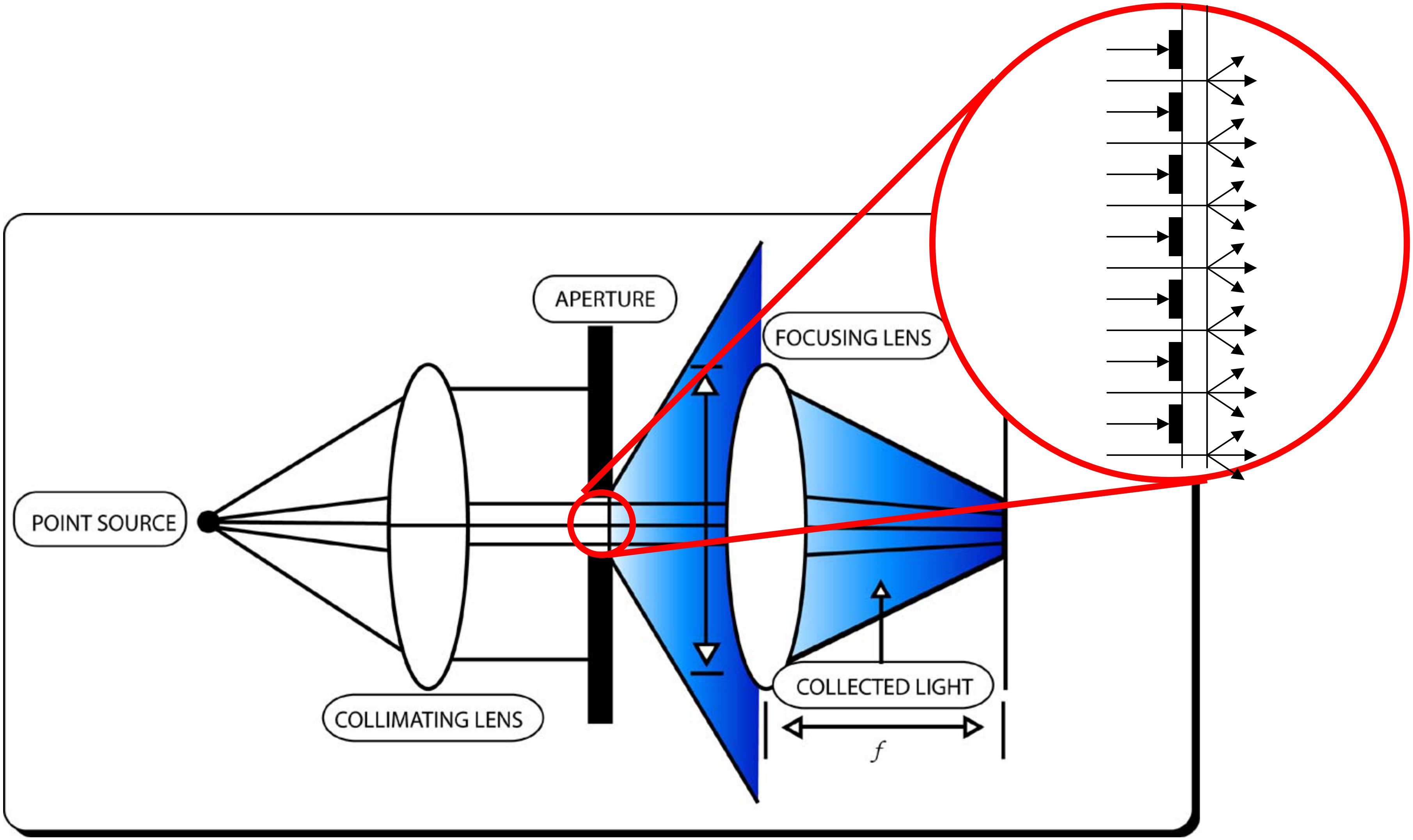
Image from a Circular Opening





Note limit of d

Resolving Features

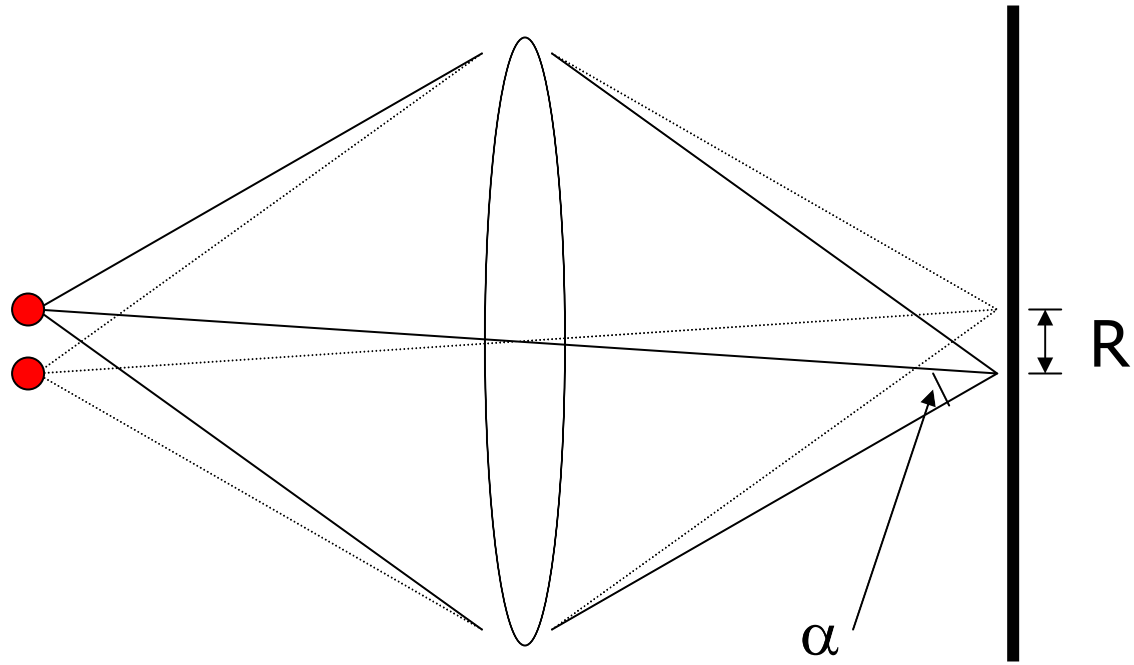


Rayleigh Limit

Rayleigh Criterion: When the peak of one projection lands on the first zero of the other.

S. Wolf, Microchip Manufacturing, Lattice Press

The Rayleigh Criterion



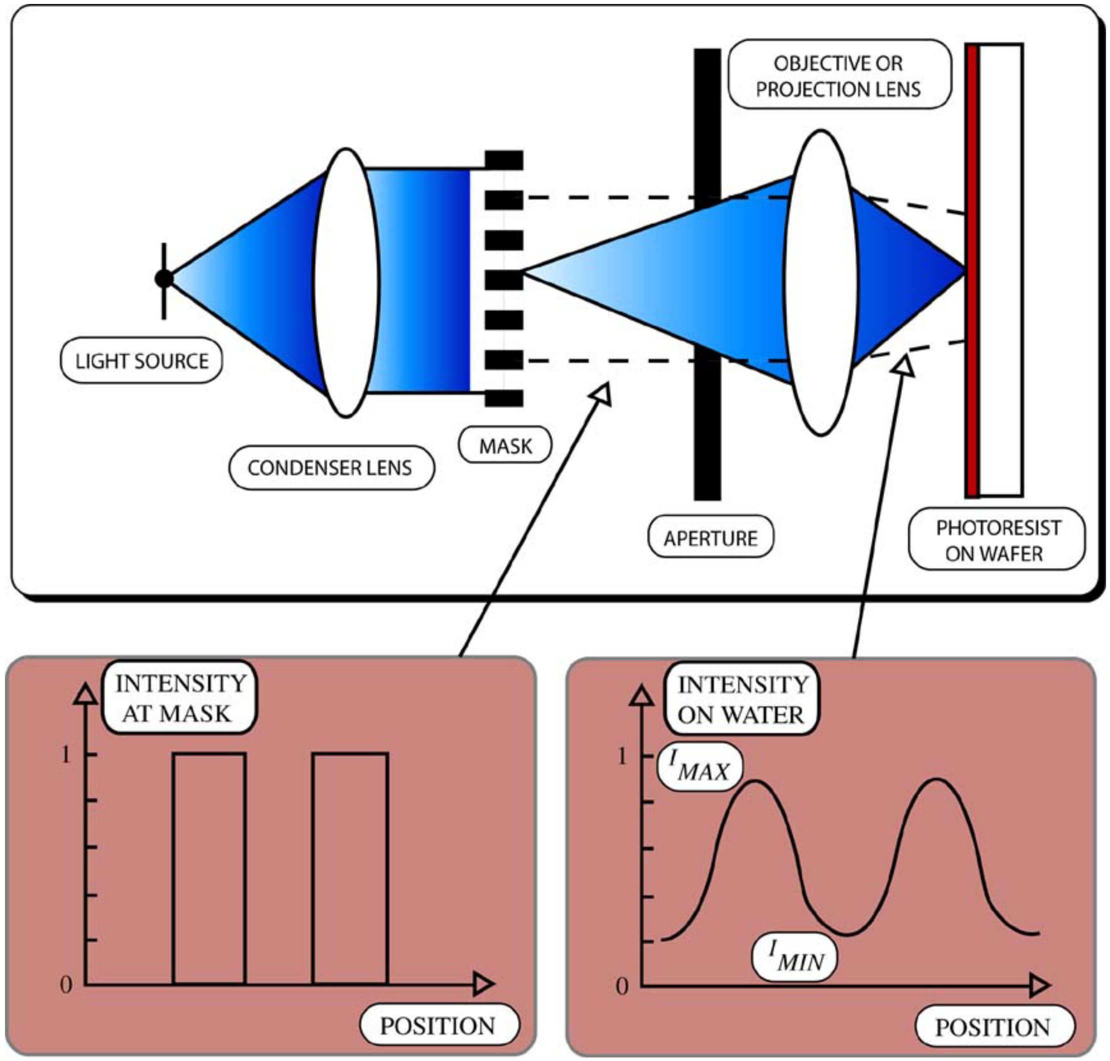
n=1 (air)

$$R = 1.22\lambda f/d = 1.22\lambda f/n(2f\sin\alpha) = 0.61\lambda/n\sin\alpha$$

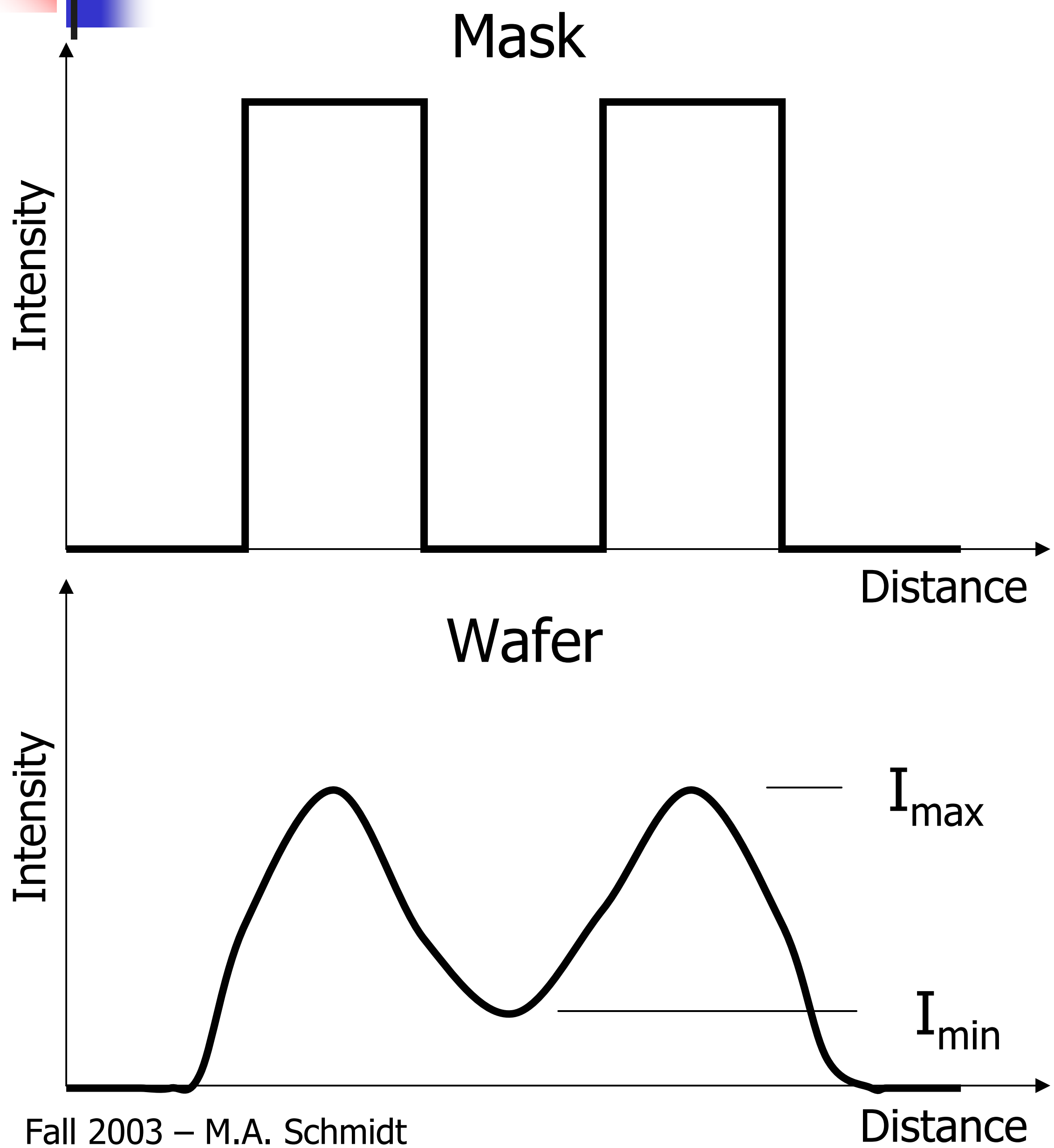
$NA = n\sin\alpha$ (Range from 0.16-0.76)

$R = 0.61\lambda/NA = k_1\lambda/NA$
(practical k_1 = 0.6-0.8)

Modulation Transfer Function (MTF)

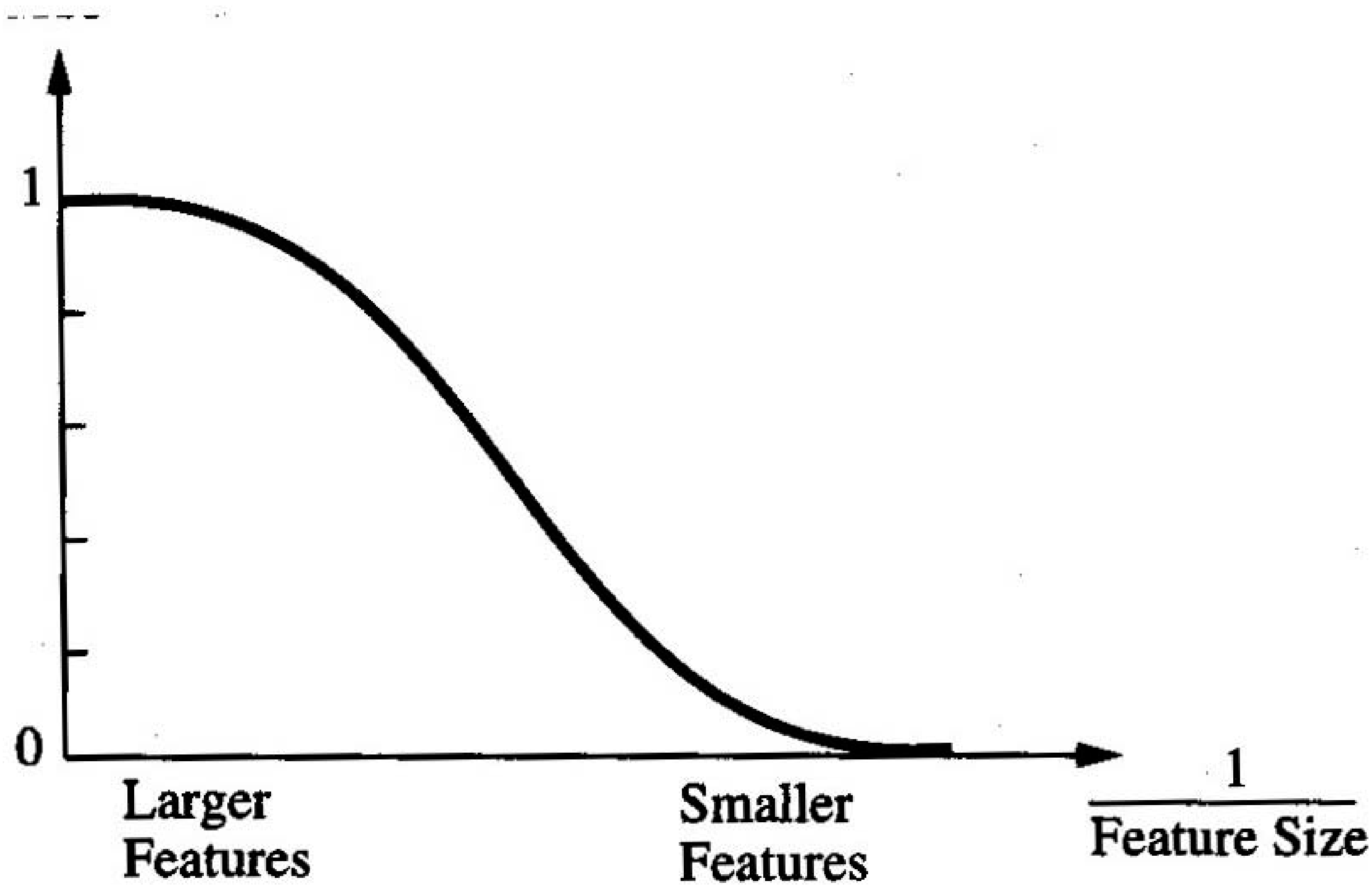


Modulation Transfer Function (MTF)

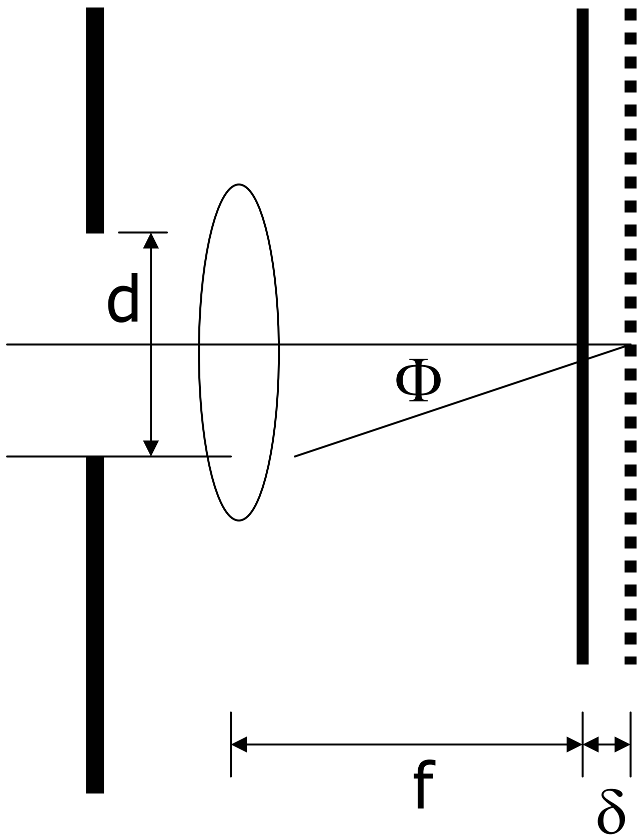


$$\text{MTF} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

MTF vs Feature Size



Depth of Focus



$$\lambda/4 = \delta - \delta\cos\Phi$$

Small Φ:

$$\lambda/4 = \delta\Phi^2/2$$

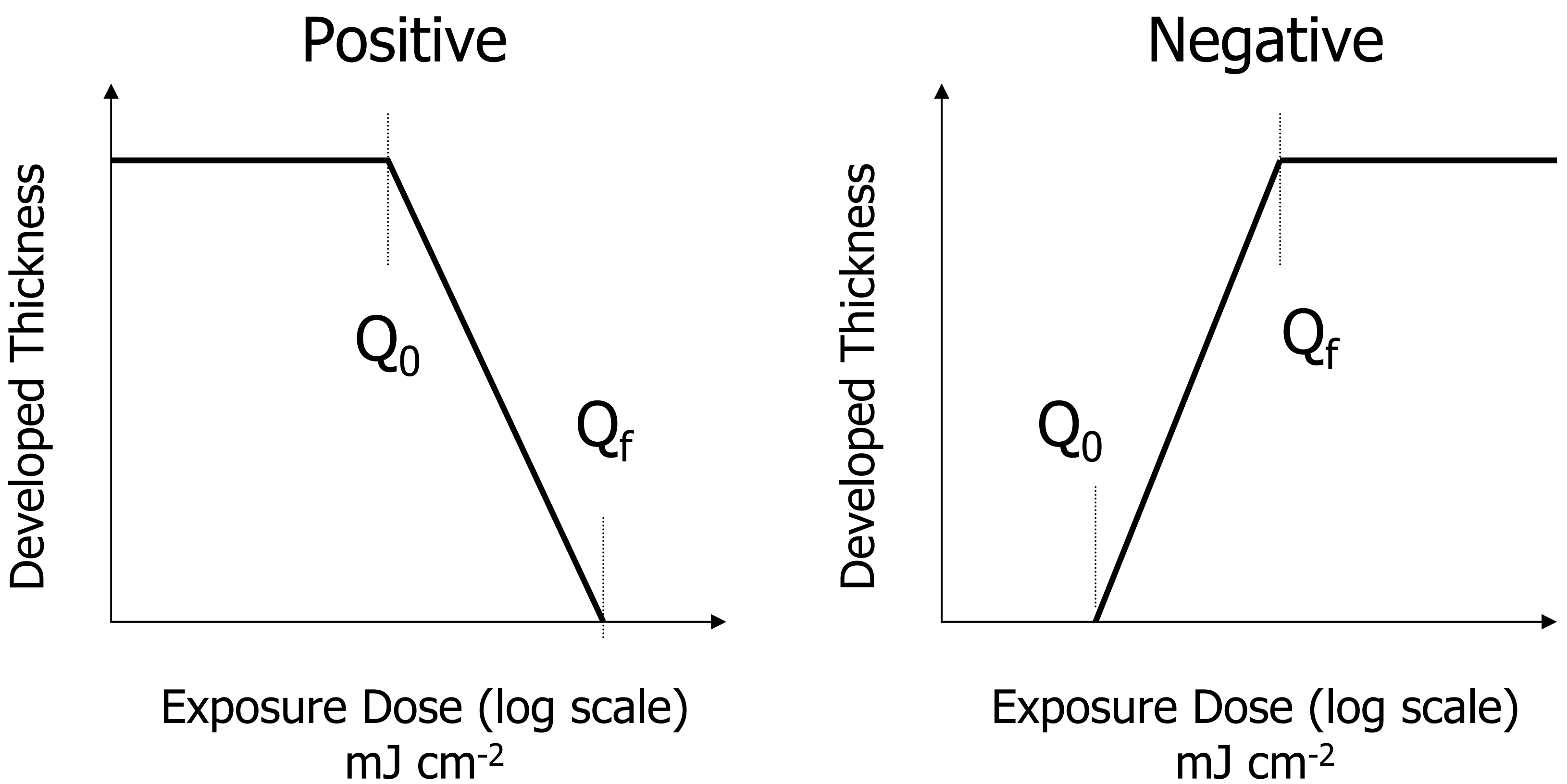
$$\Phi = \sin\Phi = d/2f = NA$$

$$\text{Depth of Focus} = \delta = \lambda/2(NA)^2$$
$$= k_2\,\lambda/(NA)^2$$

$$R = 0.61\lambda/NA = k_1\lambda/NA$$

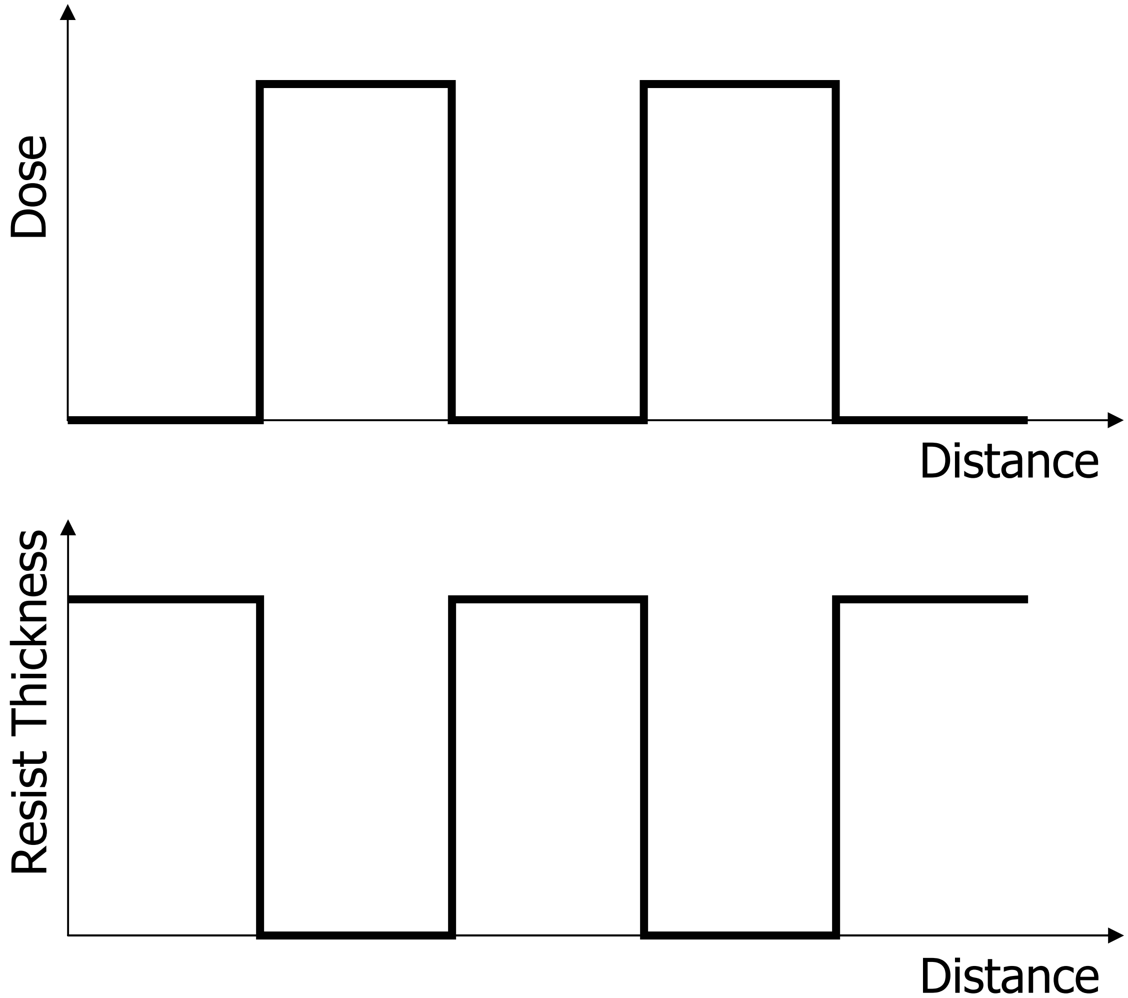
Resist Contrast

Dose = Intensity (W/cm^{-2}) x time (s)

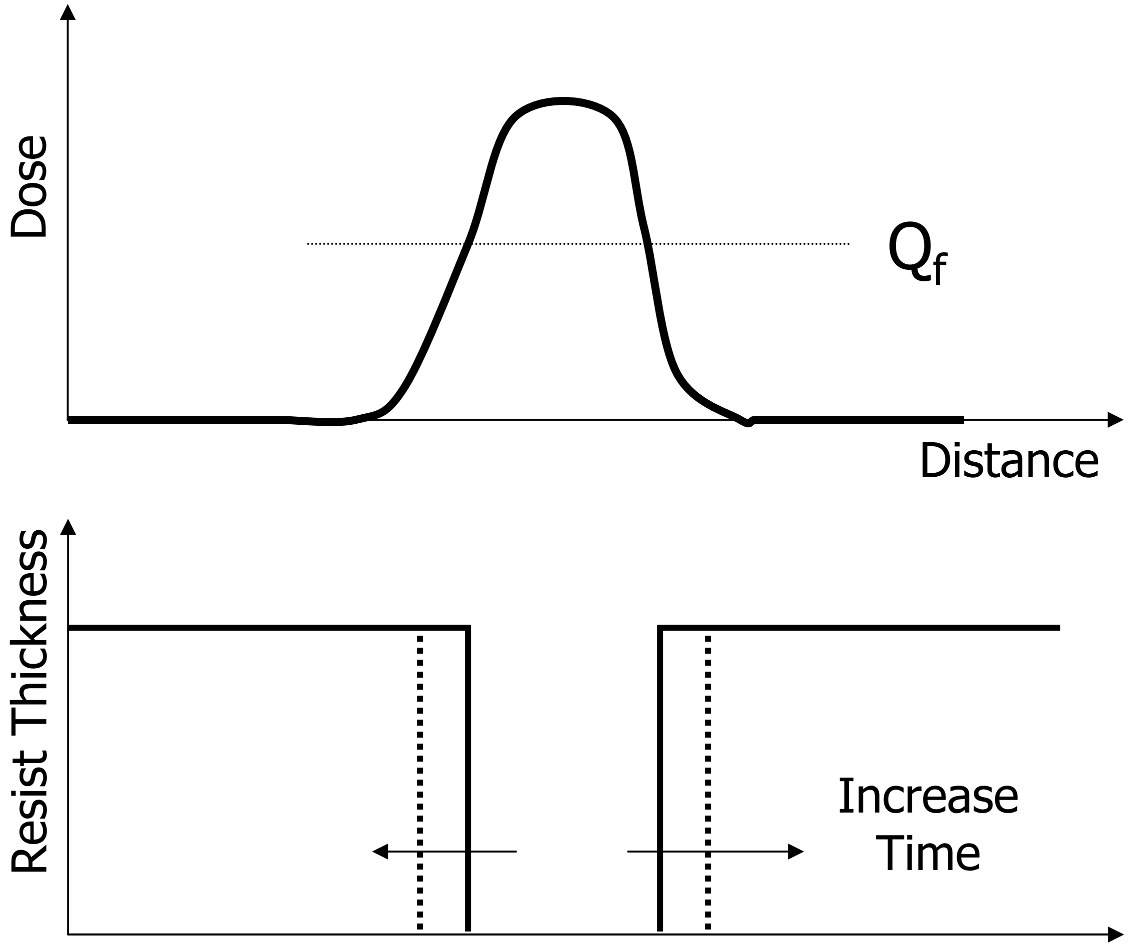


$$\gamma = 1 / \log_{10}(Q_f/Q_0)$$

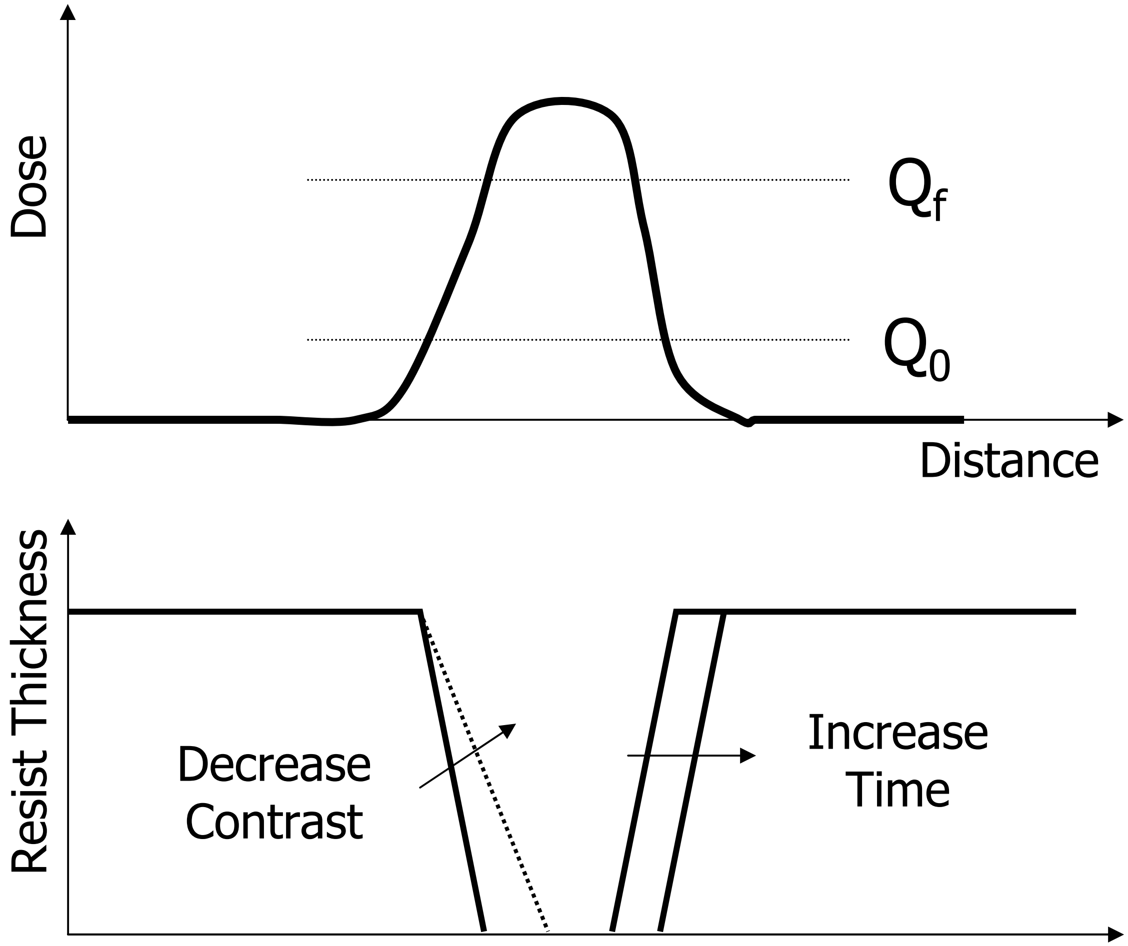
Ideal Exposure – Ideal Resist



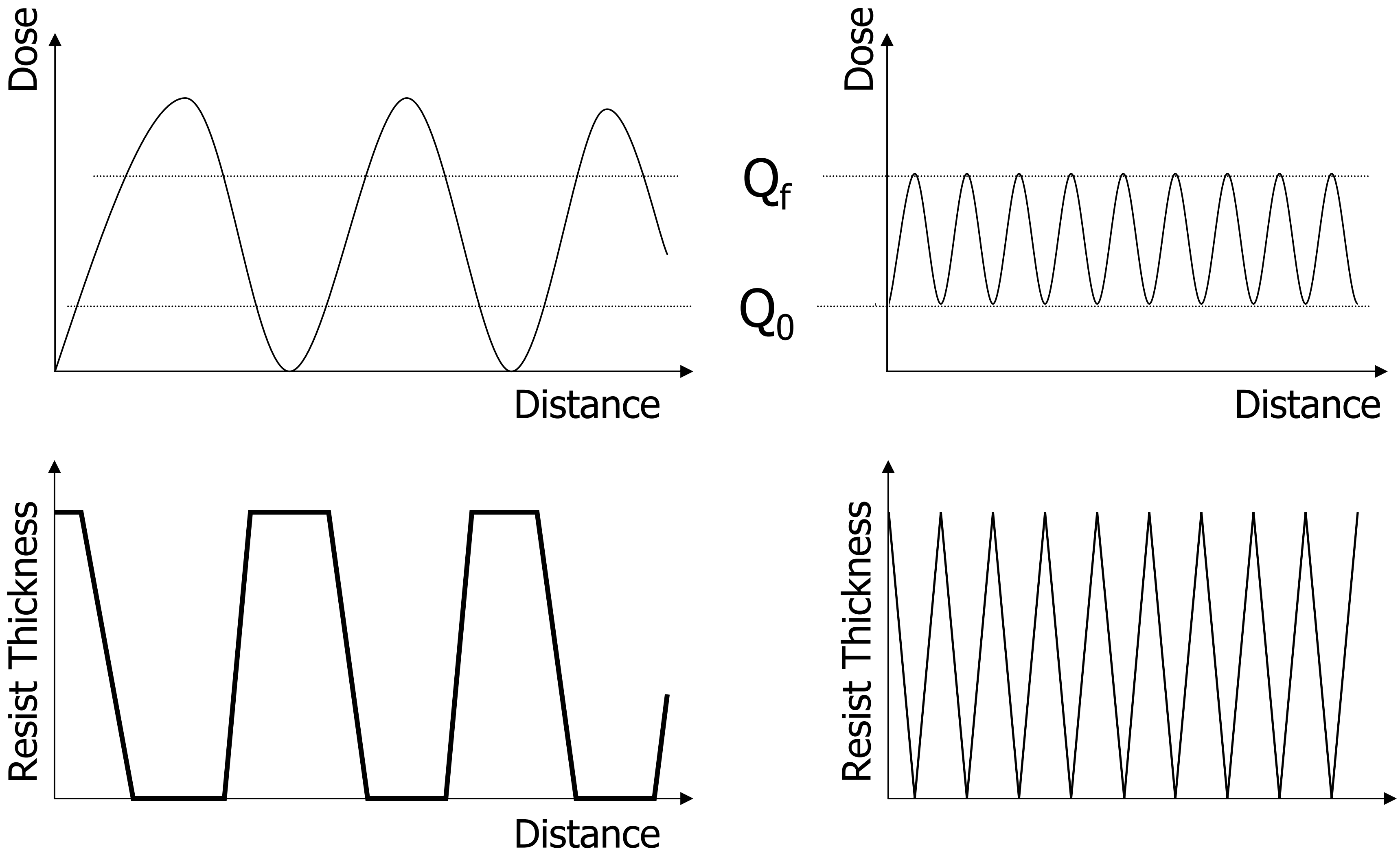
Real Exposure – Ideal Resist



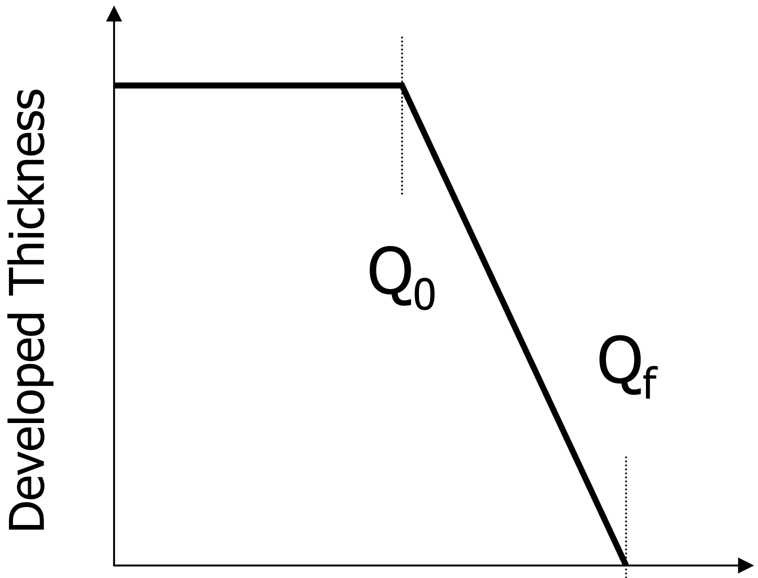
Real Exposure – Real Resist



Decreasing 'Pitch'



Critical Modulation Transfer Function (CMTF)



$$\gamma = 1 / \log_{10}(Q_f/Q_0)$$

$$\text{CMTF} = \frac{Q_f - Q_0}{Q_f + Q_0} = \frac{10^{1/\gamma} - 1}{10^{1/\gamma} + 1}$$

If $\gamma = 3$, CMTF = 0.37
If $\gamma = 2$, CMTF = 0.52

Effect of Coherence on MTF