Modeling of Microlithographic Processes

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OUTLINE

Modeling
Numerical Aperture, Magnification
Diffraction, Single Slit, Double Slit, Grating
Rayleigh’s Criterion
Fourier Optics
Modulation Transfer Function
Coherency
Reflections
Exposure, Bleaching, A,B,C Parameters
Development
Prolith

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MODELING

Modeling means to obtain mathematical expressions
For the following:

AERIAL IMAGE - which depends on the parameters of the optical system, numerical aperture, coherency, wavelength

REFLECTIONS - local irradiance depends on reflections from the multilayer substrate

RESIST BLEACHING- resist bleaches during exposure which in turn changes parameters used in the reflection of the degree.

RESIST DEVELOPMENT- is a function of inhibitor concentration remaining after exposure.

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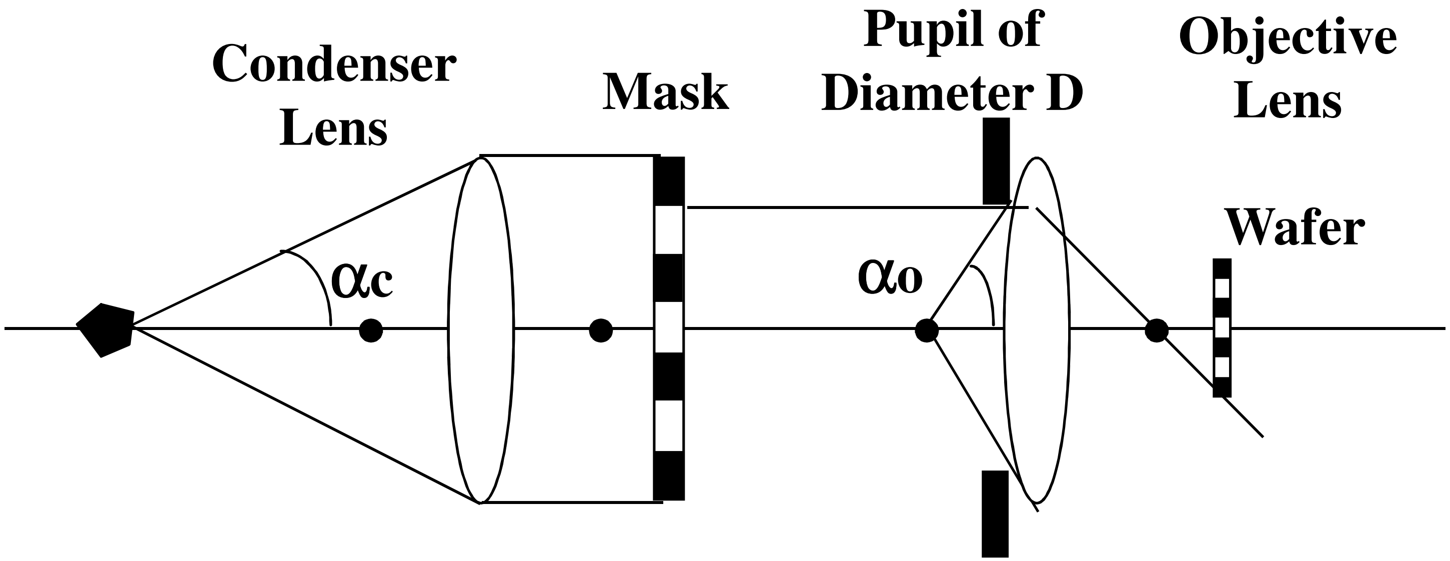
NUMERICAL APERTURE

The numerical aperture is a quantitative measure of the acceptance angle of a lens, and is important in predicting resolution and depth of focus.



NA = n sin (α)

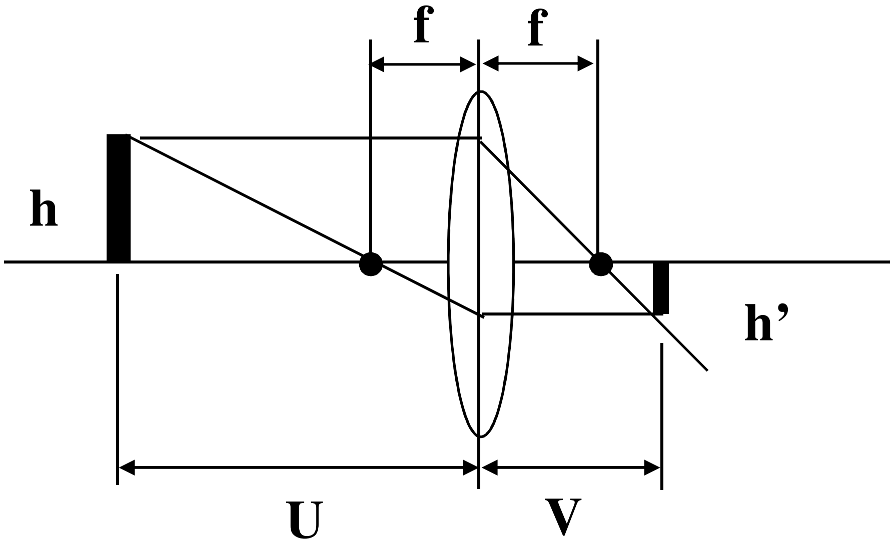
where n = index of refraction of medium

$NA = n \sin(\tan^{-1}(D/2f))$

$NA = D/2f$

MAGNIFICATION

Simple Lens:



M = Magnification

$U = f\,(1+1/M)$

$V = f\,(1+M)$

$h' = M\,h$

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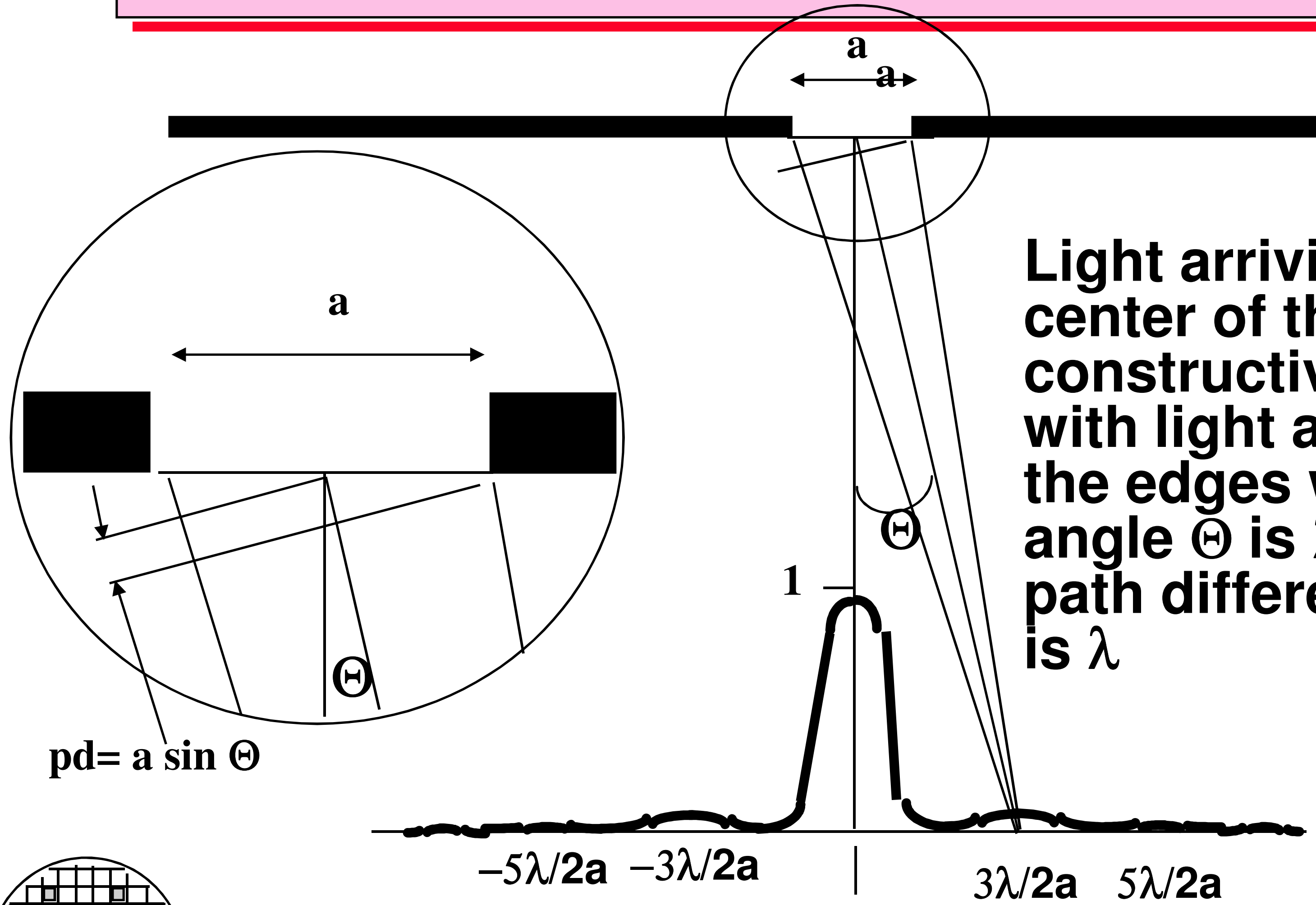
SINGLE SLIT DIFFRACTION



Light arriving from the center of the slit constructively interferes with light arriving from the edges when the angle Θ is λ/a and the path difference (pd) is λ

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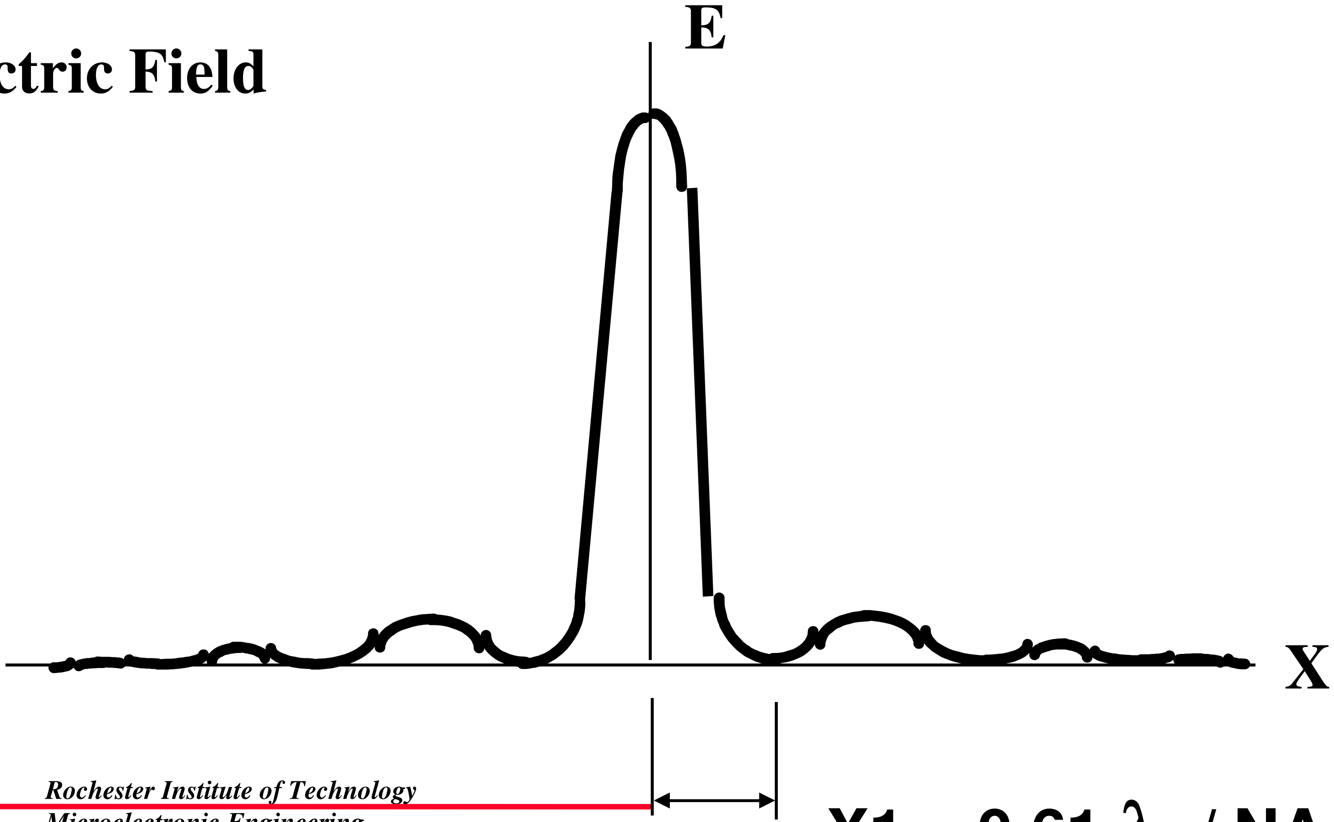
AIRY DISK

Image of a point source of wavelength λ formed by a system with numerical aperture NA

Electric Field



$X1 = 0.61\ \lambda\ /\ NA$

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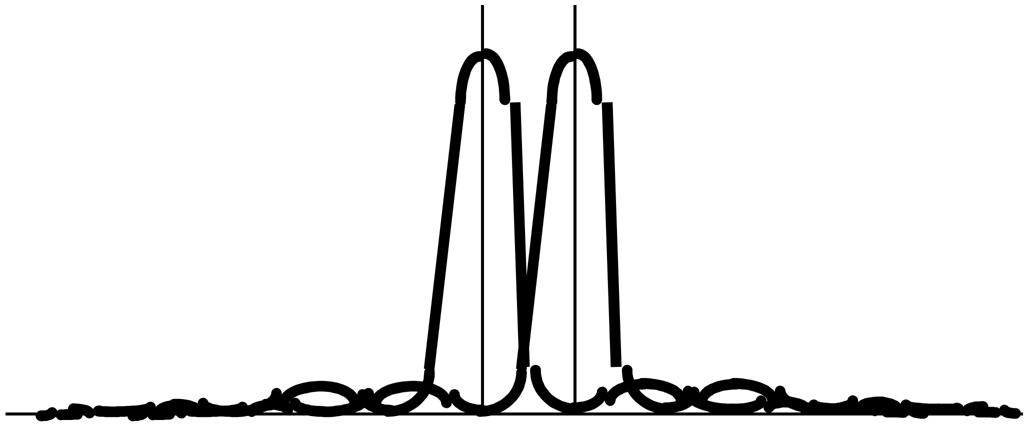
LORD RAYLEIGH'S CRITERION



When looking at two stars (point sources): two stars are just resolved when the peak of one Airy disk falls on the minimum of the second airy disk

$$L_{min} = 0.61\ \lambda\ /\ NA$$

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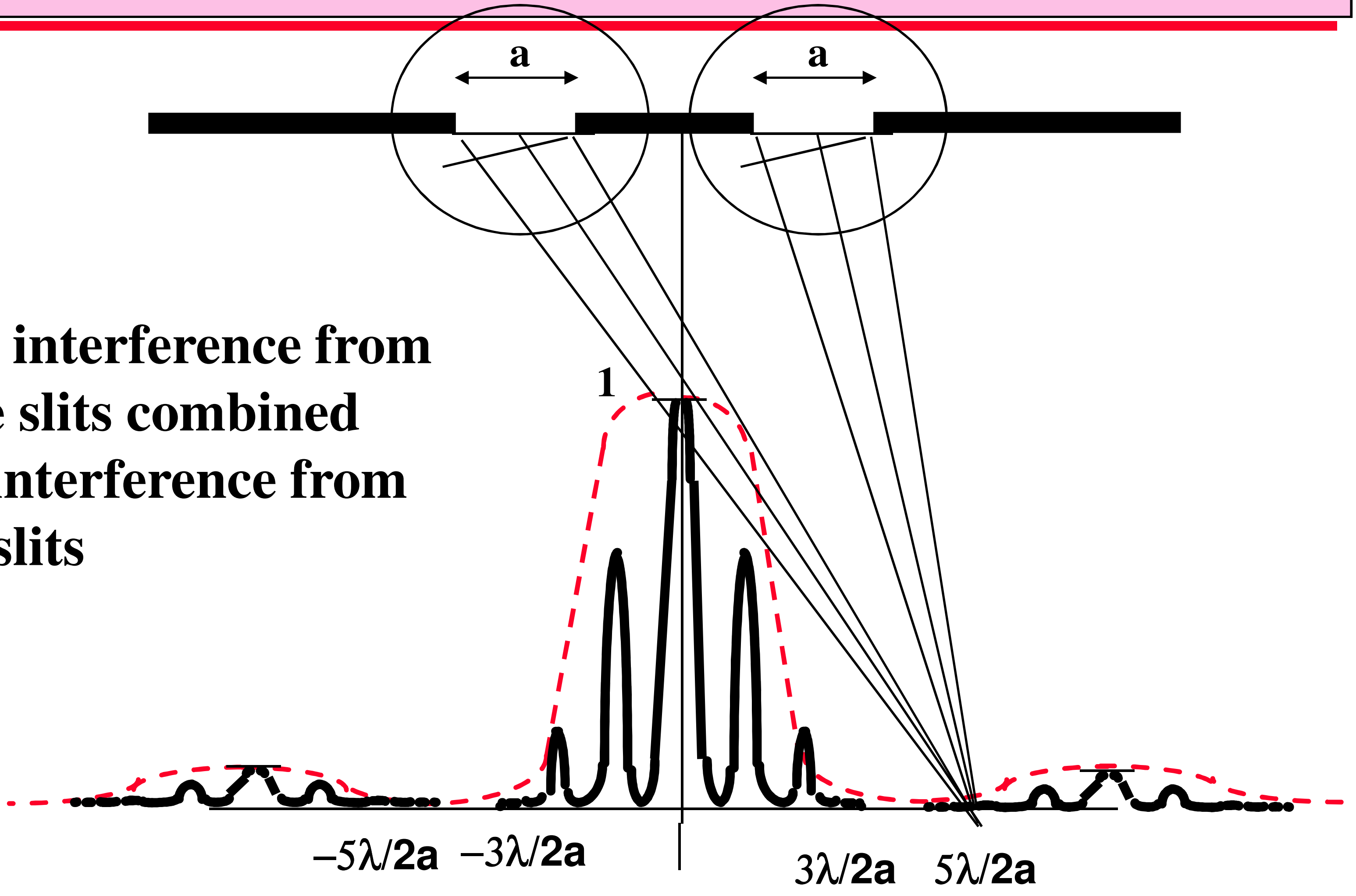
RESOLUTION AND DOF ESTIMATE FROM RAYLEIGH CRITERION

$$L_{min} = 0.61\,\lambda\ /\ NA$$

$$DOF = \lambda\ /\ (2(NA)^2)$$

	g-line	i-line	i-line	KrF	ArF
λ	436 nm	365nm	365nm	248nm	193nm
NA	0.28	0.28	0.52	0.52	0.60
Lmin	0.95µm	0.80µm	0.50µm	0.35µm	0.22µm
DOF	2.78µm	2.33µm	0.8µm	0.64µm	0.268µm

DOUBLE SLIT DIFFRACTION



Light interference from single slits combined with interference from both slits

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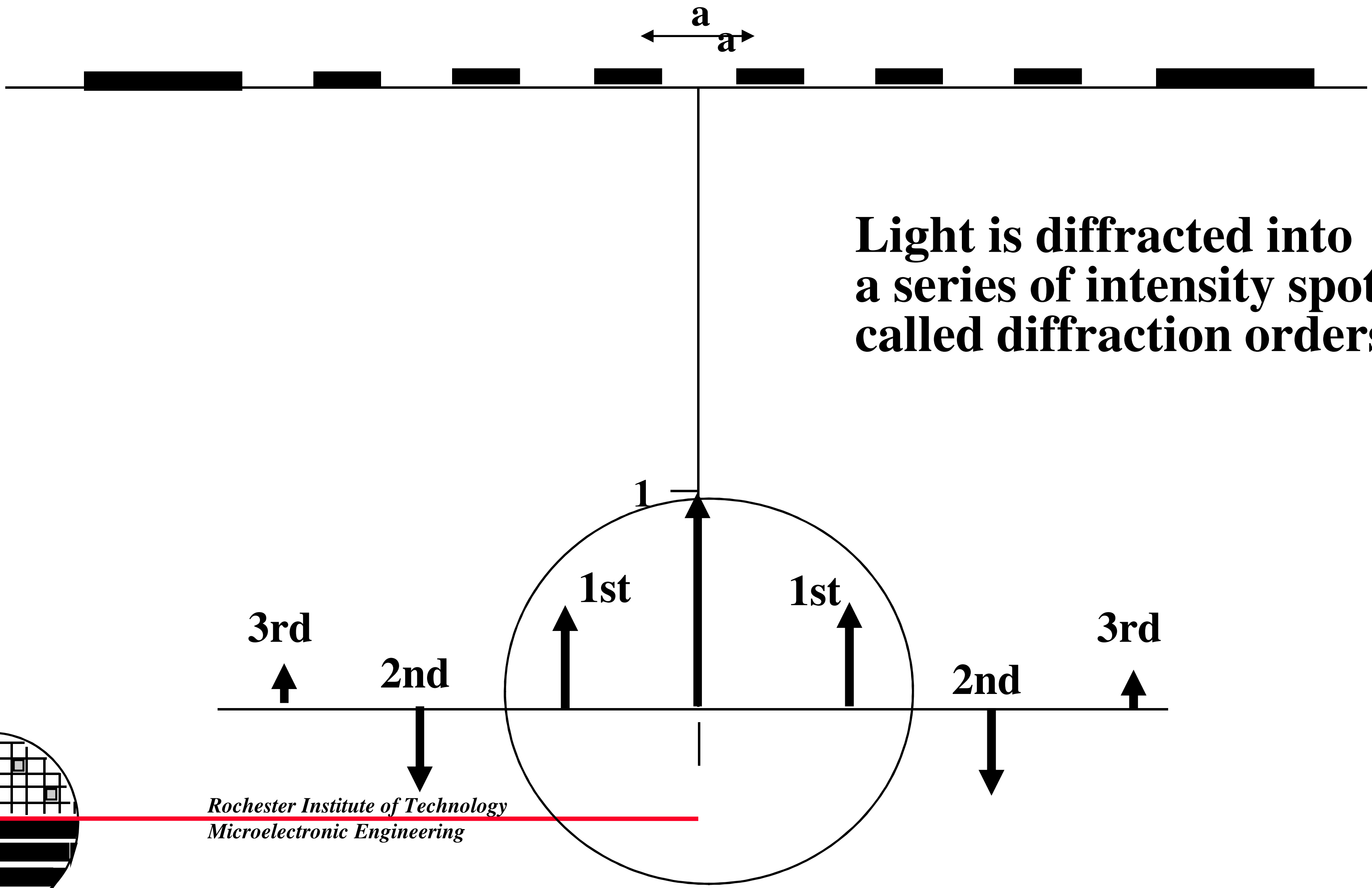
DIFFRACTION GRATING



Light is diffracted into a series of intensity spots called diffraction orders

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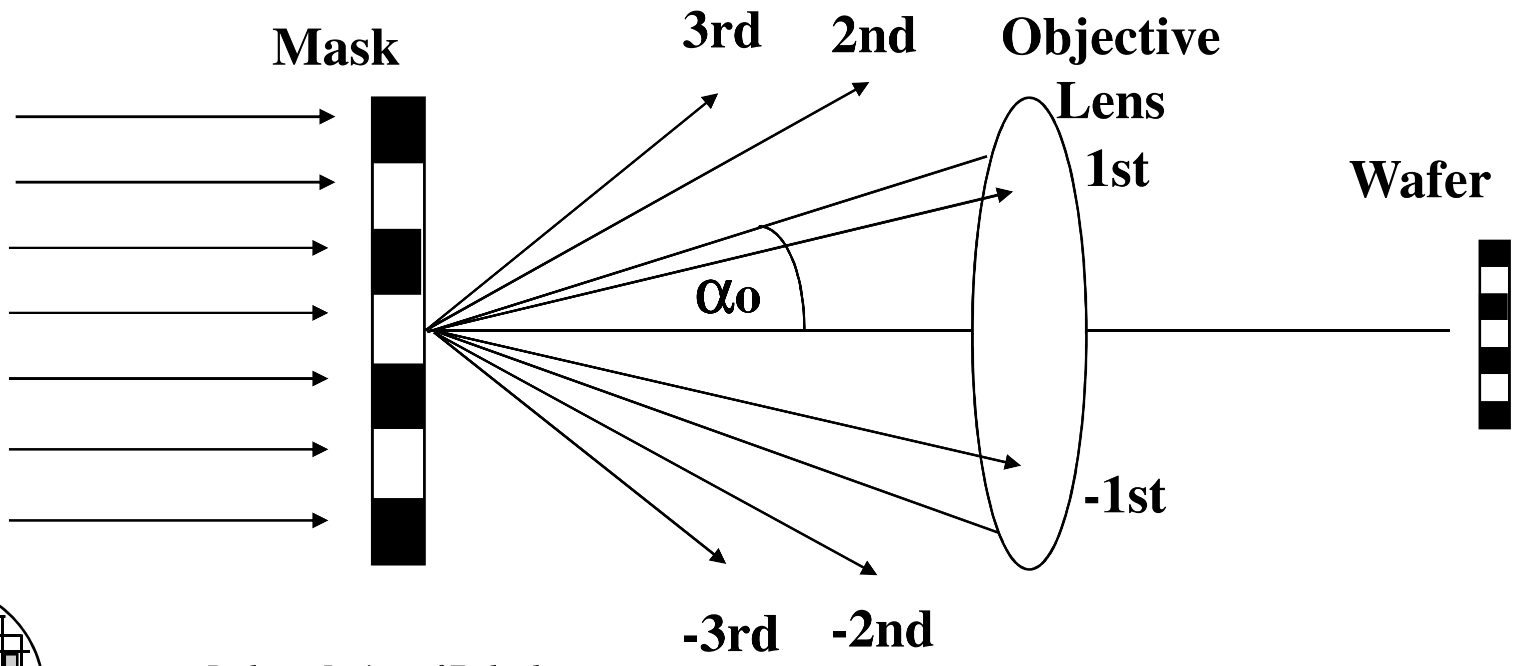
LENS COLLECTION OF DIFFRACTED IMAGE

If we think of a mask as a diffraction grating, we see that the lens is able to collect only the 1st diffraction order, thus the aerial image on the wafer is sinusoidal with amplitude determined by the system modulation transfer function at that spatial frequency



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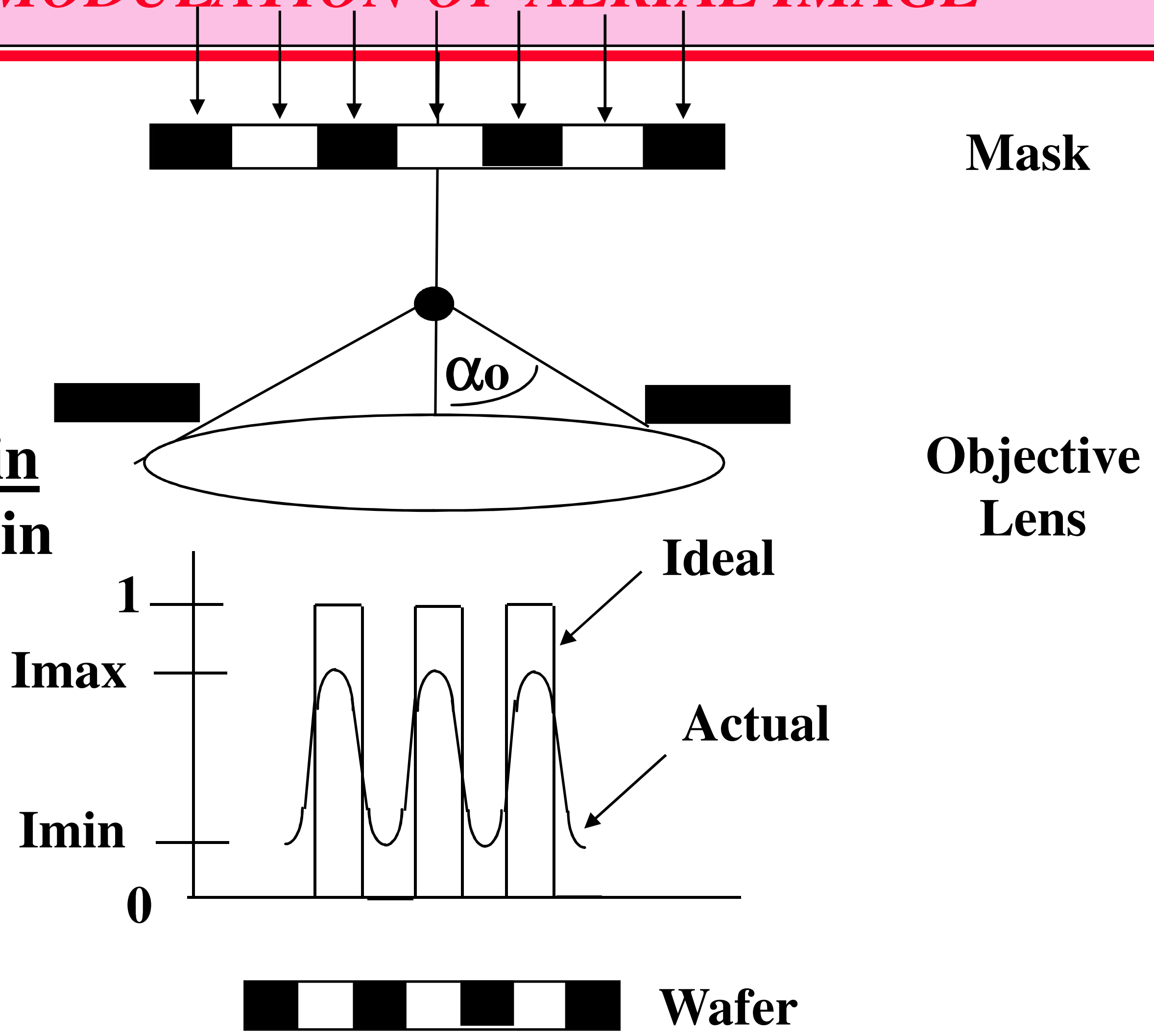
MODULATION OF AERIAL IMAGE

Modulation:

$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$



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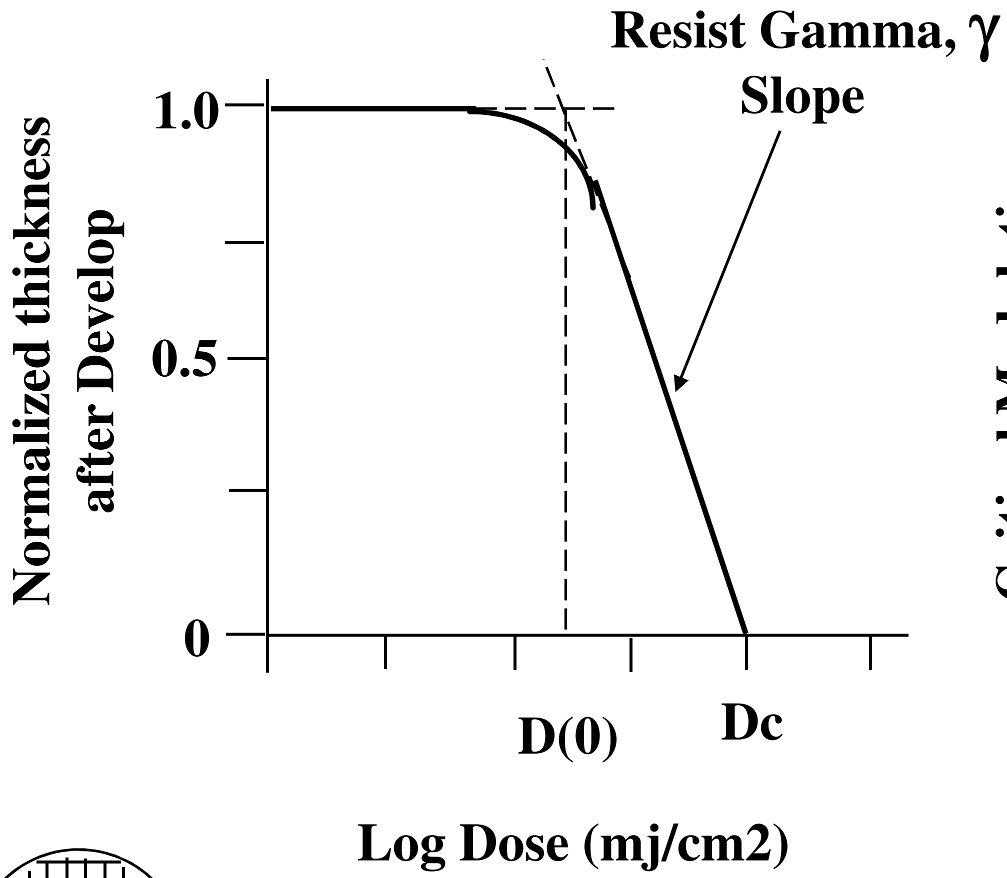
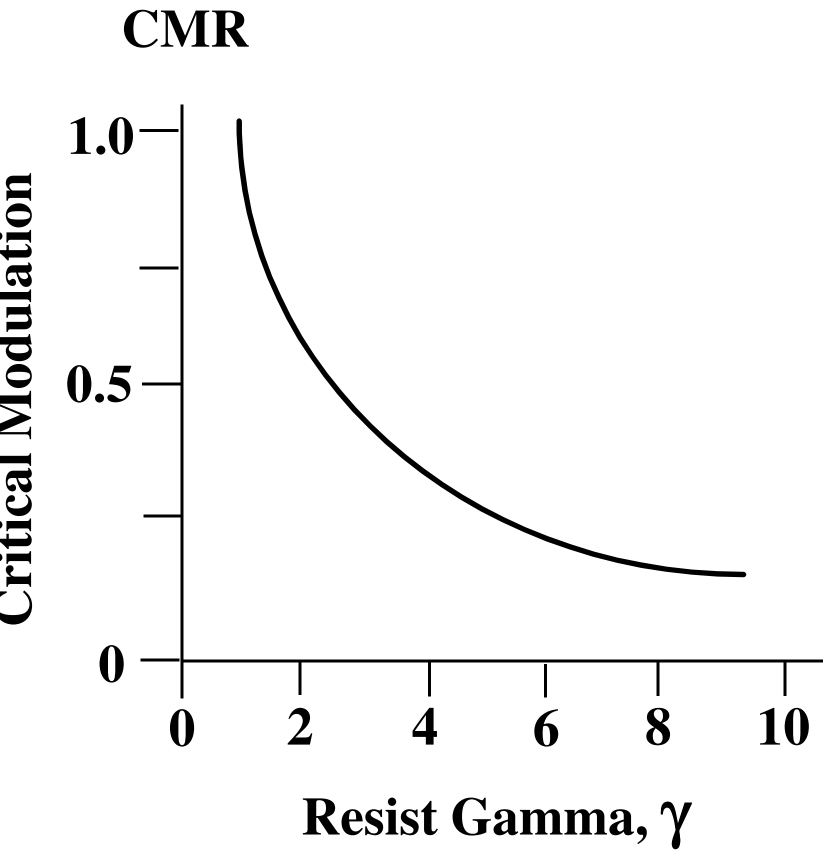
CRITICAL MODULATION FOR RESIST (CMR)





$$CMR = (10^{1/\gamma} - 1)/(10^{1/\gamma} + 1)$$

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FOURIER SERIES REPRESENTATION OF A PERIODIC FUNCTION

Mask Pattern (x) = $A_0/2 + \sum_{m=1}^{\infty}$ Bm Sin (mkx)

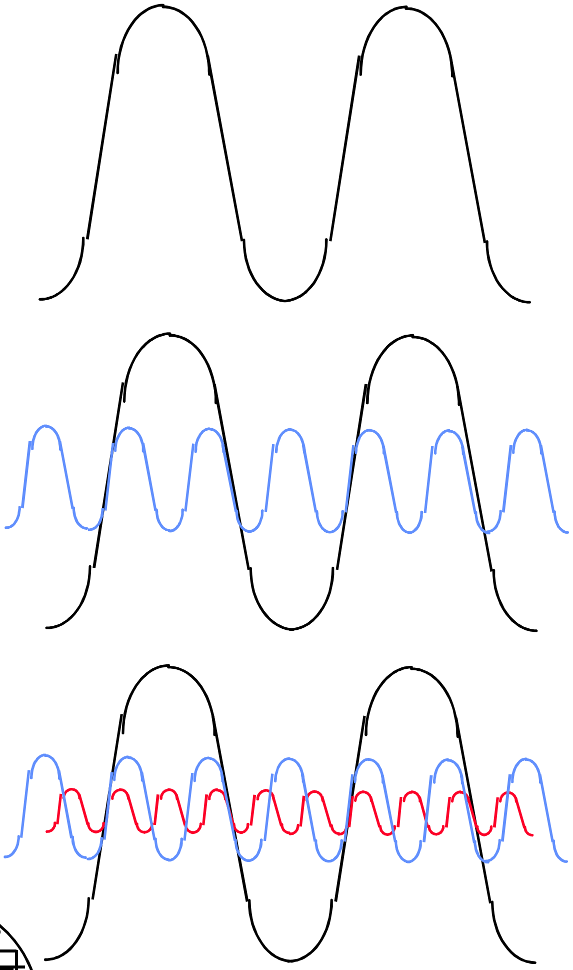
where k = $2\pi / \lambda$

and λ = spatial wavelength

and Bm = $2/\lambda \int_{0}^{\infty} f(x) \sin(mkx)\, dx$

Any periodic function can be created from an infinite summation of harmonically related sinusoids

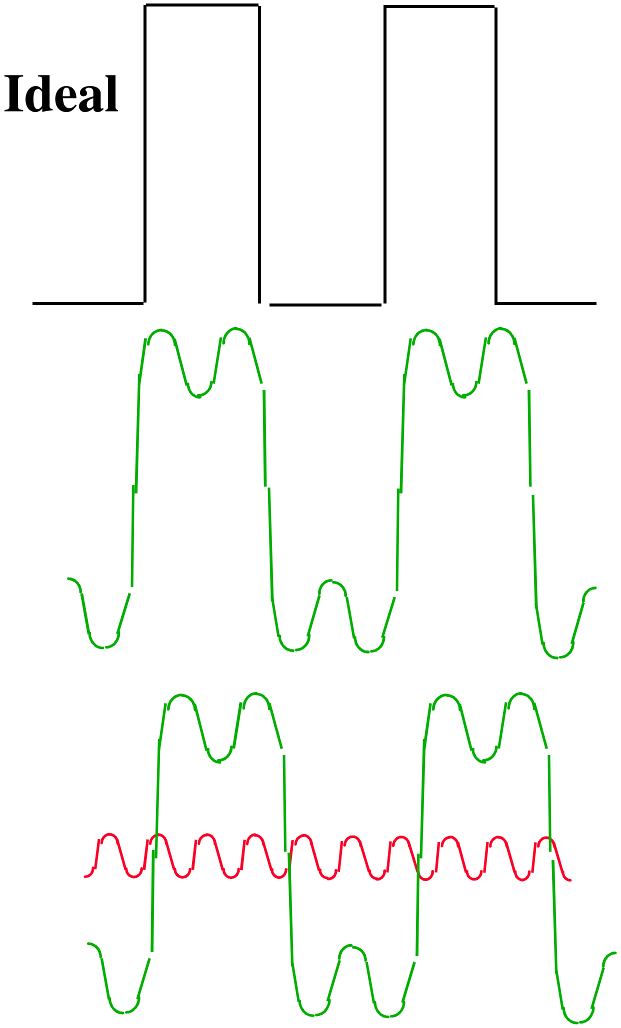
FOURIER SERIES



First

First
+
third

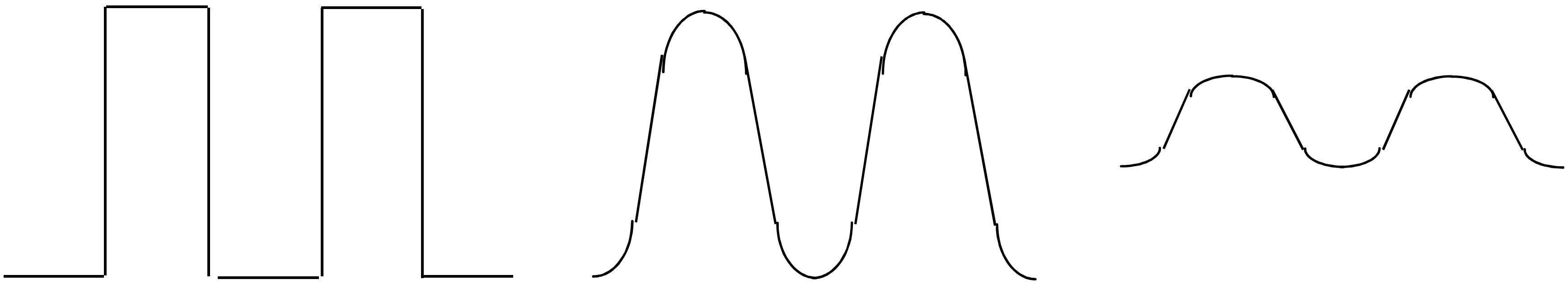
First
+
third
+
fifth



CALCULATION OF AERIAL IMAGE

$$\text{Wafer Pattern}(x) = A_0/2 + \sum_{m=1}^{\infty} \text{MTF}(mk/2\pi) A_0/2 \,\text{Sin}\,(mkx)$$

where MTF($mk/2\pi$) is the value of the modulation transfer function at spatial frequency $\nu = mk/2\pi$



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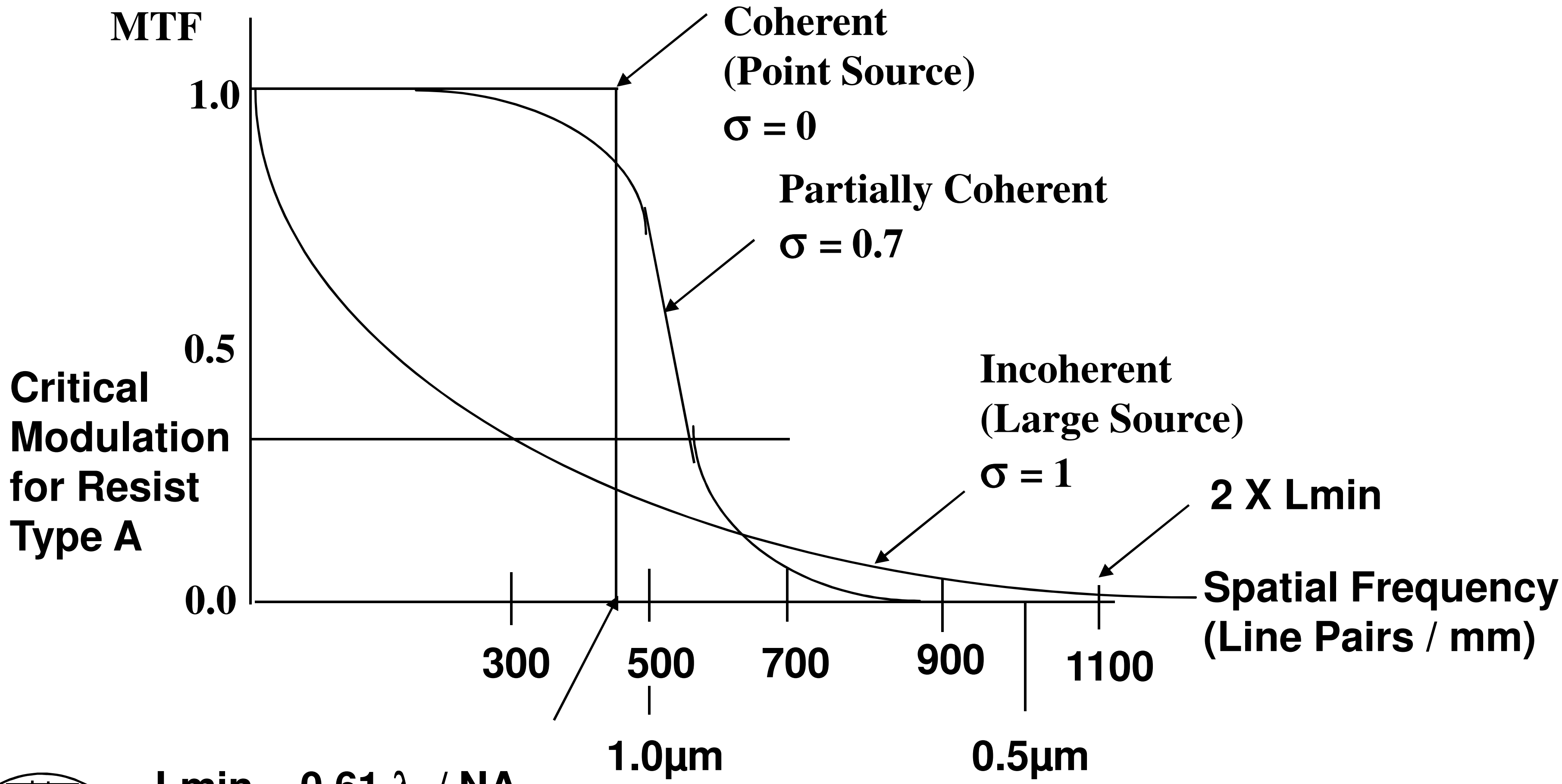
MODULATION TRANSFER FUNCTION (MTF)



Lmin = 0.61 λ / NA

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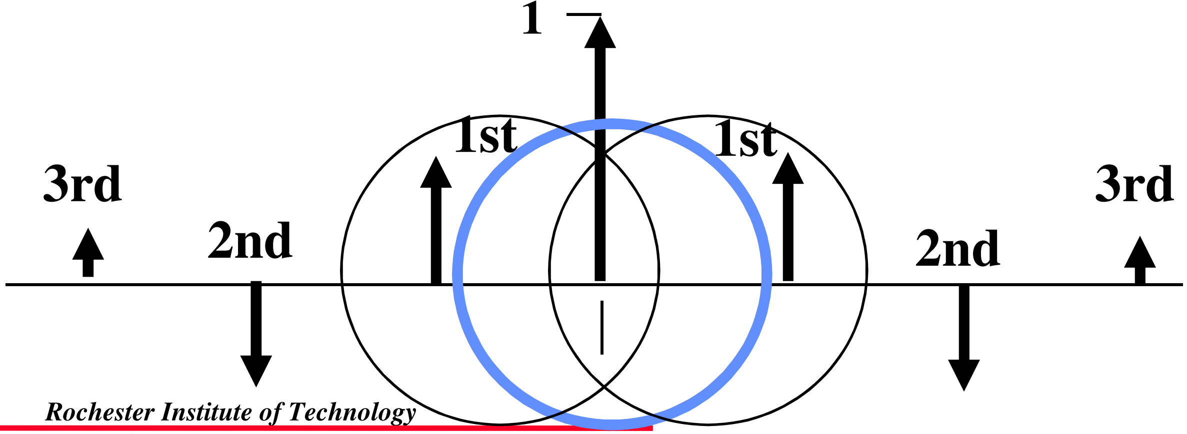
COHERENCY

Coherent - Normally incident plane wave illumination (point source)
Incoherent - a continuous spectrum of plane waves with incident angles ranging from +/- 90 degrees (infinite size source)
Partially Coherent - A finite range of incident Angles of the plane waves

σ = NAc/NAo Numerical Aperture of Condenser Lens divided by Numerical Aperture of the Objective Lens.

Off Axis illumination allows images to be formed from the + or - 1st diffraction order techniques include **ring illumination**, **quadrapole illumination**, **variable pupil, and gaussian illumination**

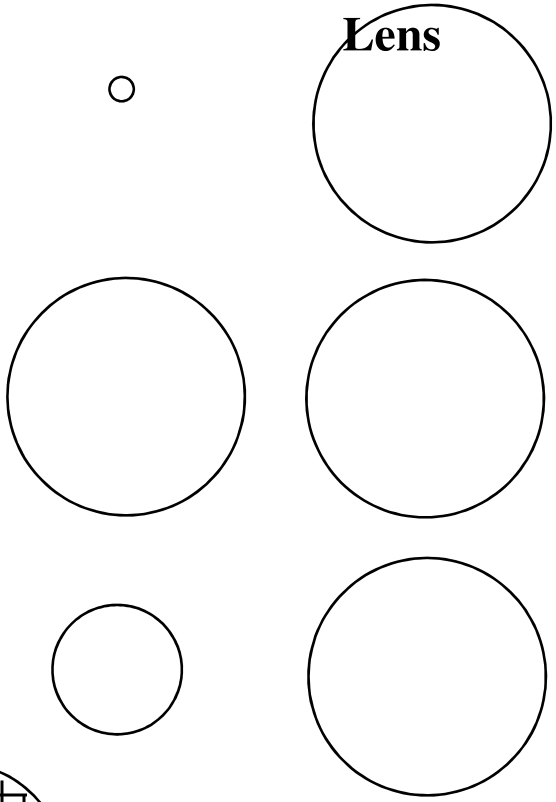


MTF AND COHERENCY

Illumination Source

Objective Lens

Convolution of source pupil with the lens entrance pupil gives the shape of the MTF.



Coherent (Point Source)

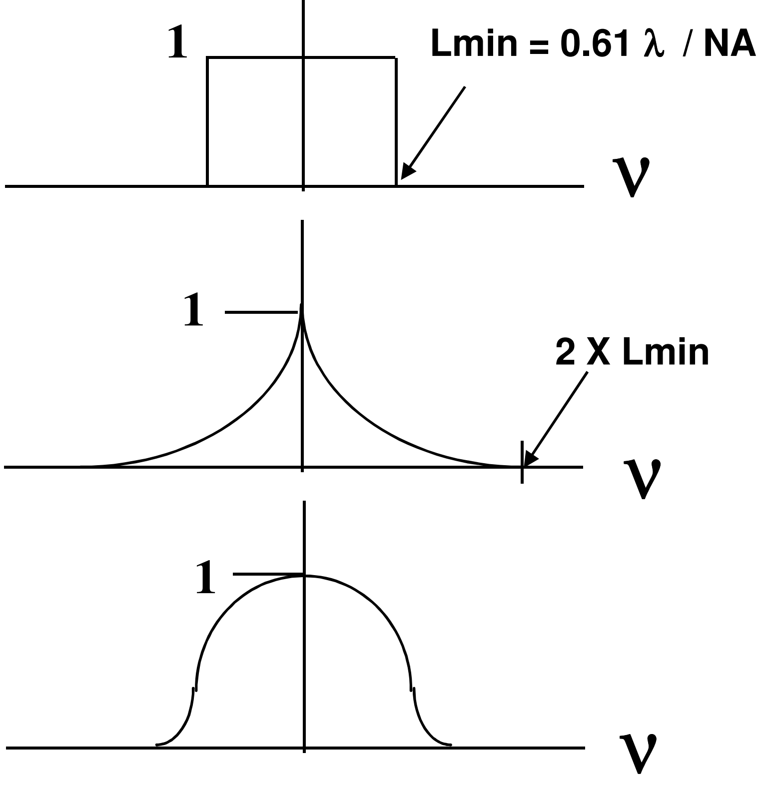
$\sigma = 0$

Incoherent (Large Source)

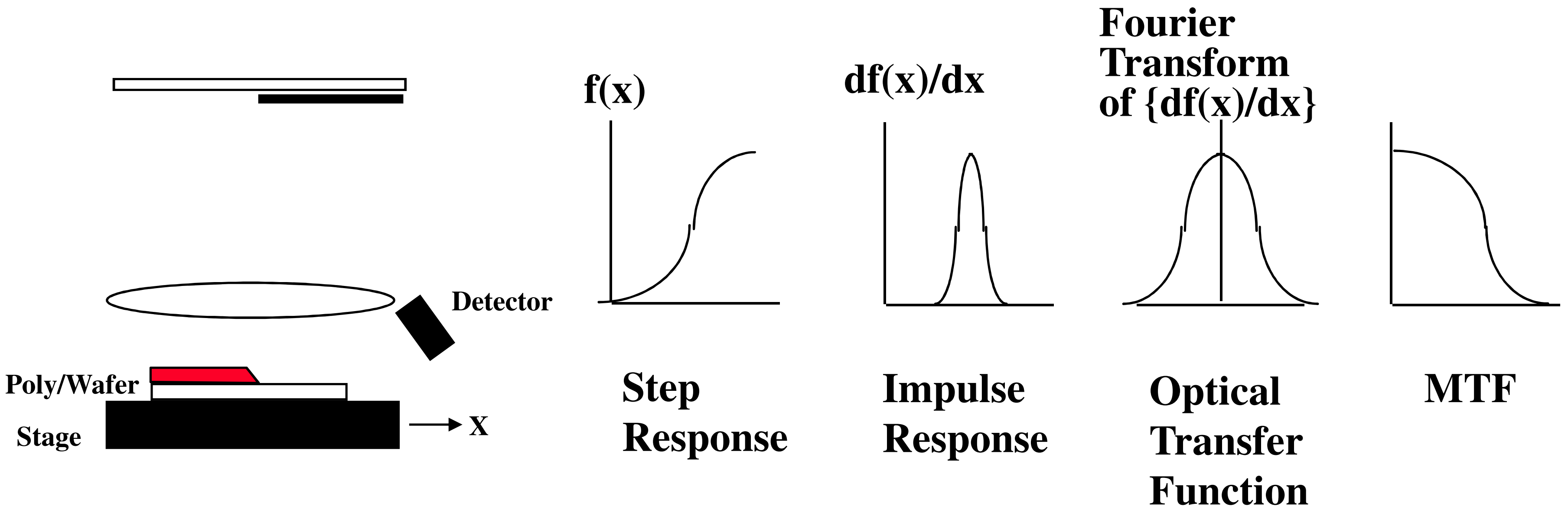
$\sigma = 1$

Partially Coherent

$\sigma = 0.7$

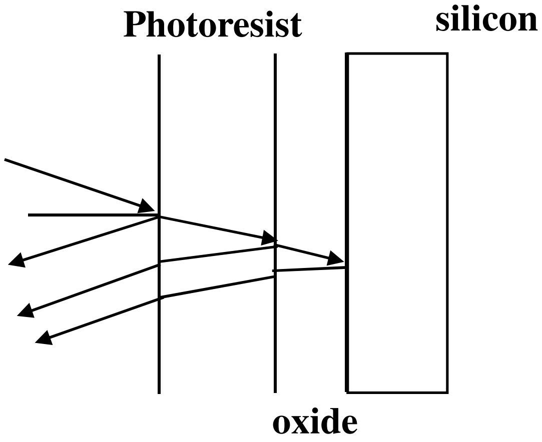


EXPERIMENTAL DETERMINATION OF MTF



The edge of the poly line acts like a mirror to reflect light toward the detector. The stage is programmed to move in small increments and the x-y plotter records the reflected intensity versus stage position. The recorded signal is the step response. The differentiated step response is the impulse response and the Fourier Transform of the impulse response is the optical transfer function (OTF). MTF is the magnitude part of the OTF.

CALCULATION OF IRRADIANCE IN A SYSTEM WHERE THERE ARE MULTIPLE REFLECTING LAYERS



Light is an electromagnetic wave. The electric field is calculated from the irradiance value at the surface of the photoresist. Using the reflection and transmission coefficients for the boundary of two dielectrics a system of equations is built for a multi-layer substrate. The dielectric materials are described by their complex index of refraction.

The relationship between Irradiance and electric or magntic field is:

Irradiance = ave Power / unit area

$$I = c\varepsilon_o E^2 / 2 \qquad \text{or} \qquad I = (c / 2\,\mu_o)B^2$$

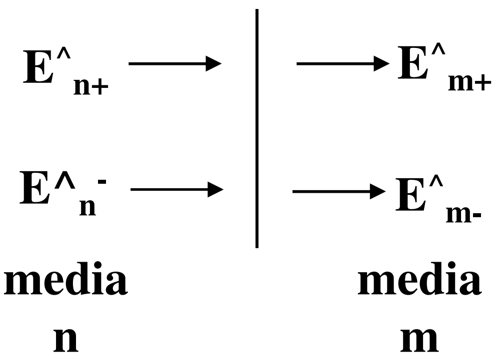
where c is speed of light 3e8m/s

ε_o is permitivitty, μ_o is permeability

REFLECTION CALCULATIONS (CONT.)

$rn = (Nn - Nm)/(Nn+Nm)$

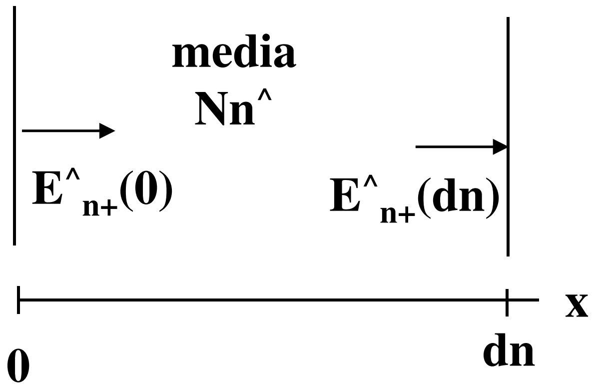
$tn = (2Nn)/(Nn+Nm)$



$$E^\wedge_{m+} = tn\, E^\wedge_{n+} + rn\, E^\wedge_{m-}$$

$$E^\wedge_{n-} = rn\, E^\wedge_{n+} + tn\, E^\wedge_{m-}$$

As light traverses a dielectric material there is a phase shift, δn



$$E^\wedge_{n+}(dn) = E^\wedge_{n+}(0)\, e^{\,j\delta n}$$

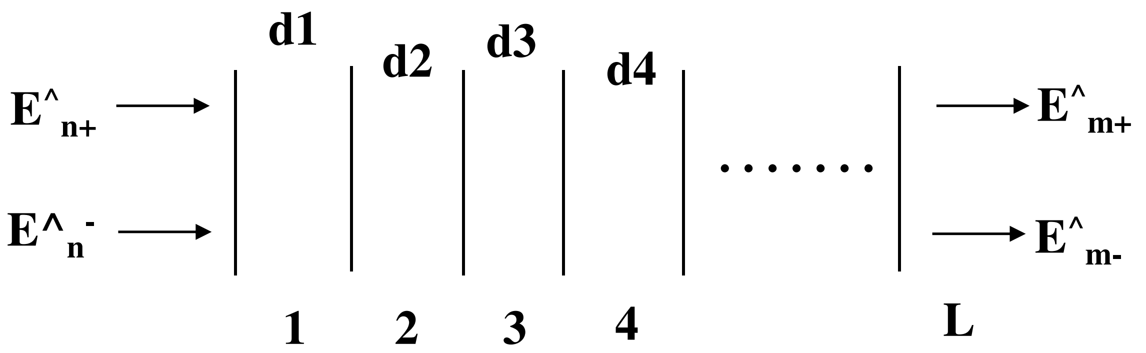
where $\delta n = 2\,\pi\, Nn^\wedge\, dn / \lambda$

$$E^\wedge_{n+}(0) = E^\wedge_{n+}(dn)\, e^{+j\delta n}$$

$$E^\wedge_{n-}(0) = E^\wedge_{n-}(dn)\, e^{-j\delta n}$$

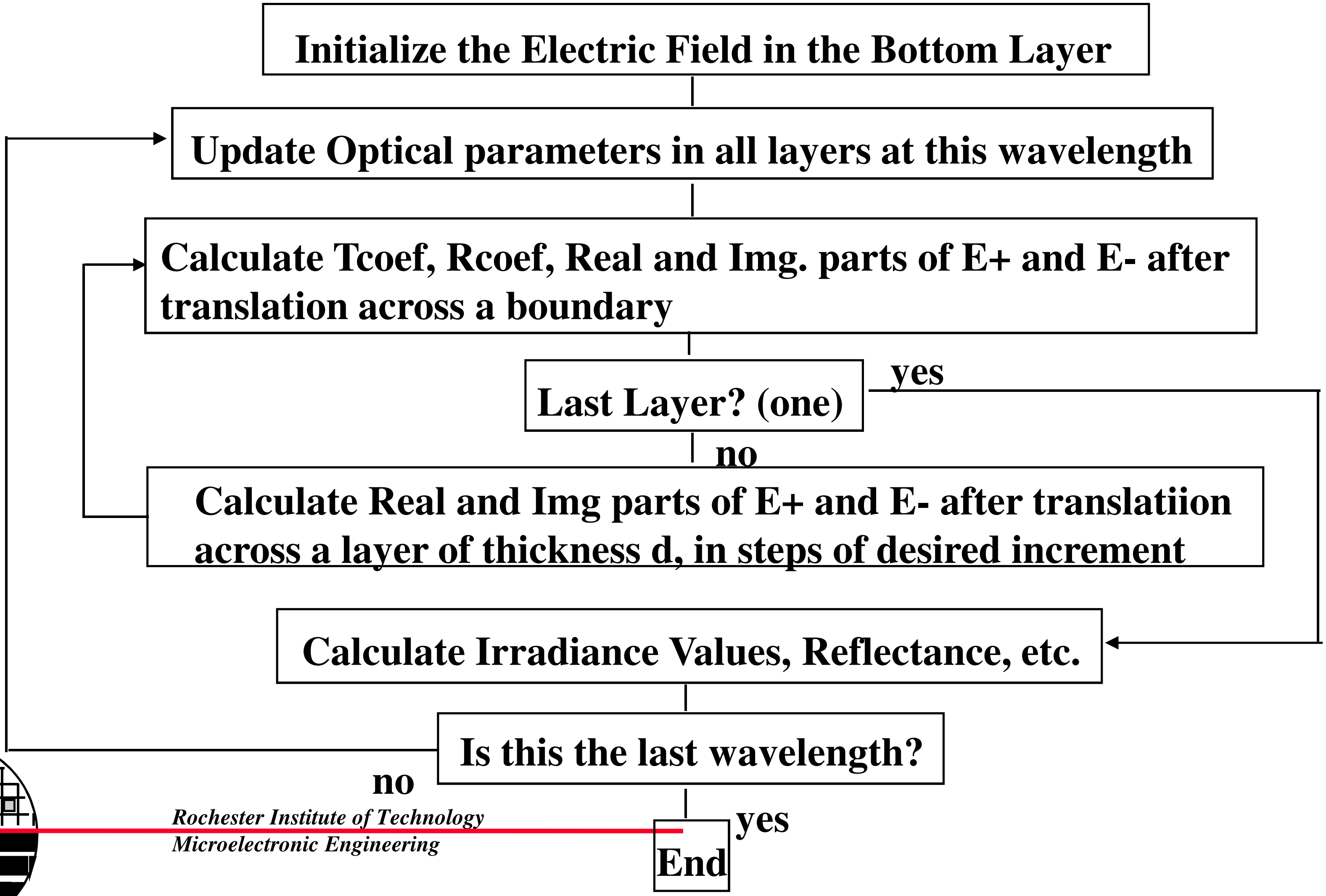
REFLECTION CALCULATIONS

The two equations on the previous page are rearrange so input quantities are on the left and output quantities are on the right. The equations are converted to matrix format for simplicity. This allows for concise a representation of a system of any number of layers.



$$\begin{vmatrix} E1+ \\ E1- \end{vmatrix} = \begin{vmatrix} R & R \\ R & R \end{vmatrix} \begin{vmatrix} T2 & 0 \\ 0 & T2 \end{vmatrix} \begin{vmatrix} R & R \\ R & R \end{vmatrix} \begin{vmatrix} T3 & 0 \\ 0 & T3 \end{vmatrix} \circ\circ\circ\circ \begin{vmatrix} TL & 0 \\ 0 & TL \end{vmatrix} \begin{vmatrix} R & R \\ R & R \end{vmatrix} \begin{vmatrix} EL+ \\ EL- \end{vmatrix}$$

FLOW CHART FOR CALCULATIONS



Initialize the Electric Field in the Bottom Layer

Update Optical parameters in all layers at this wavelength

Calculate Tcoef, Rcoef, Real and Img. parts of E+ and E- after translation across a boundary

Last Layer? (one)

yes

no

Calculate Real and Img parts of E+ and E- after translatiion across a layer of thickness d, in steps of desired increment

Calculate Irradiance Values, Reflectance, etc.

Is this the last wavelength?

no

yes

End

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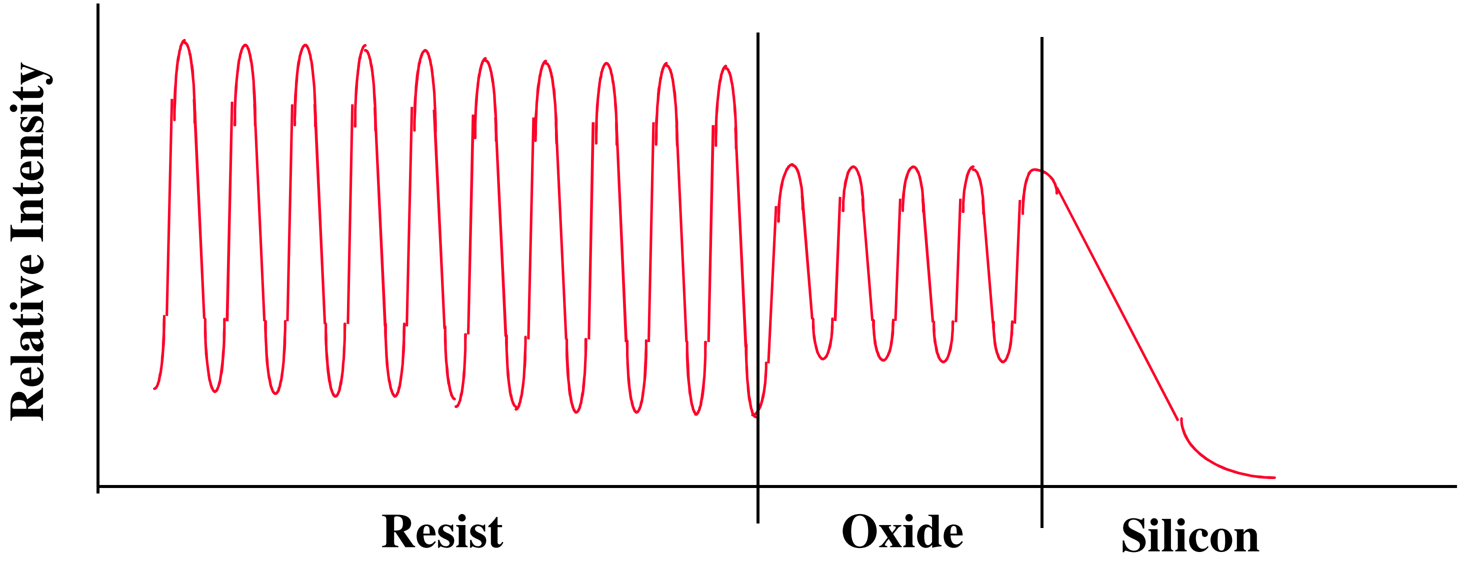
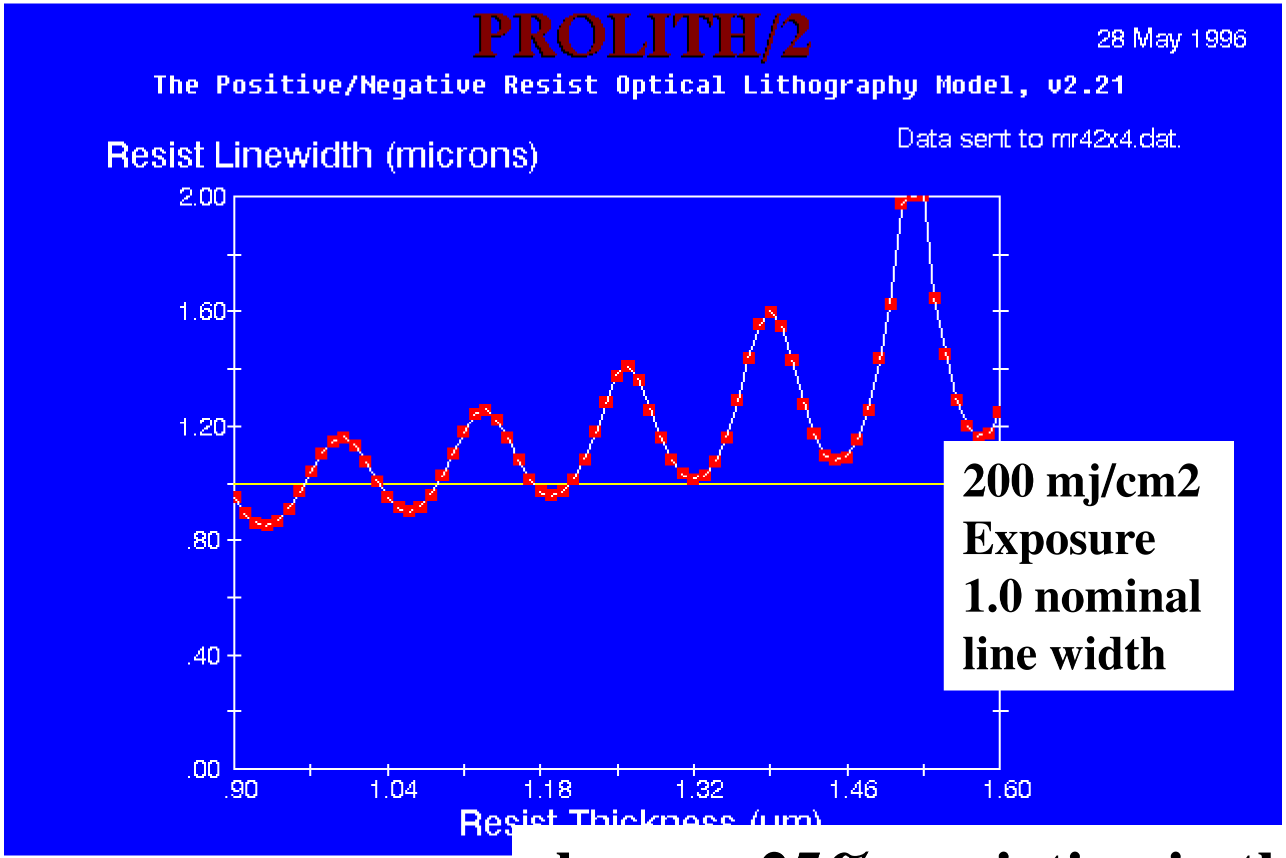
STANDING WAVES



Photoresist line width depends on exposure level at the bottom of the resist layer. If the reflections are such as to create a localized minima at the bottom of the resist the line widths may be large or there may be difficulty in "clearing out" (scum). On the other hand a localized maxima may cause line widths to be small.

This effect can be large.

SWING CURVES FOR CD



200 mj/cm2
Exposure
1.0 nominal
line width

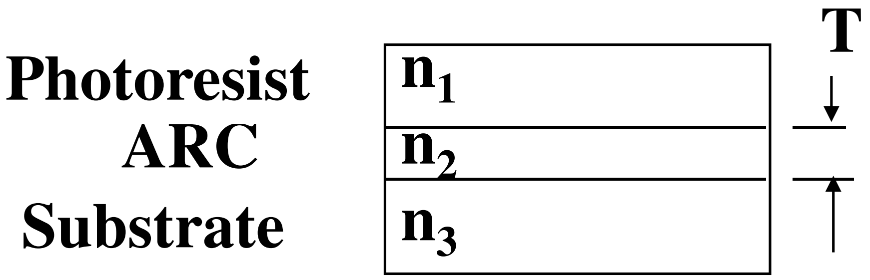
shows a 25% variation in thickness results in 100% variation in linewidth

ANTI REFLECTIVE COATINGS

To give minimum reflection:

Thickness, $T = \text{Lambda} / 4\, n_2$

$$n_2 = \sqrt{n_1 n_3}$$



MODELING OF EXPOSURE IN PHOTORESIST

Complex Index of Refraction of Photoresist $\hat{n} = n - jK$

$K = \alpha \lambda / 4\pi$ is the extinction coefficient

n = real part of the index of refraction

λ = wavelength

The absorption constant α

$\alpha = A\,m(z,t) + B$

where m is the relative amount of photoactive inhibitor at position z and time t

A is the exposure dependent parameter

B is the exposure independent parameter

An optical sensitivity parameter C relates the destruction of inhibitor local irradiance, I

$$\frac{dm(z,t)}{dt} = -I(z,t)\,m(z,t)\,C$$

Dr. Fred H. Dill, IBM, IEEE Transactions on Electron Devices vol. ED-22, July 1975

A,B,C PARAMETERS FOR EXPOSURE

A,B,C Exposure Parameters for AZ 1350J

λ	A (μm^{-1})	B (μm^{-1})	C (cm^2/mj)	n
436nm	0.54	0.06	0.014	1.68
405nm	0.86	0.07	0.018	1.70
365nm	0.74	0.20	0.012	1.72

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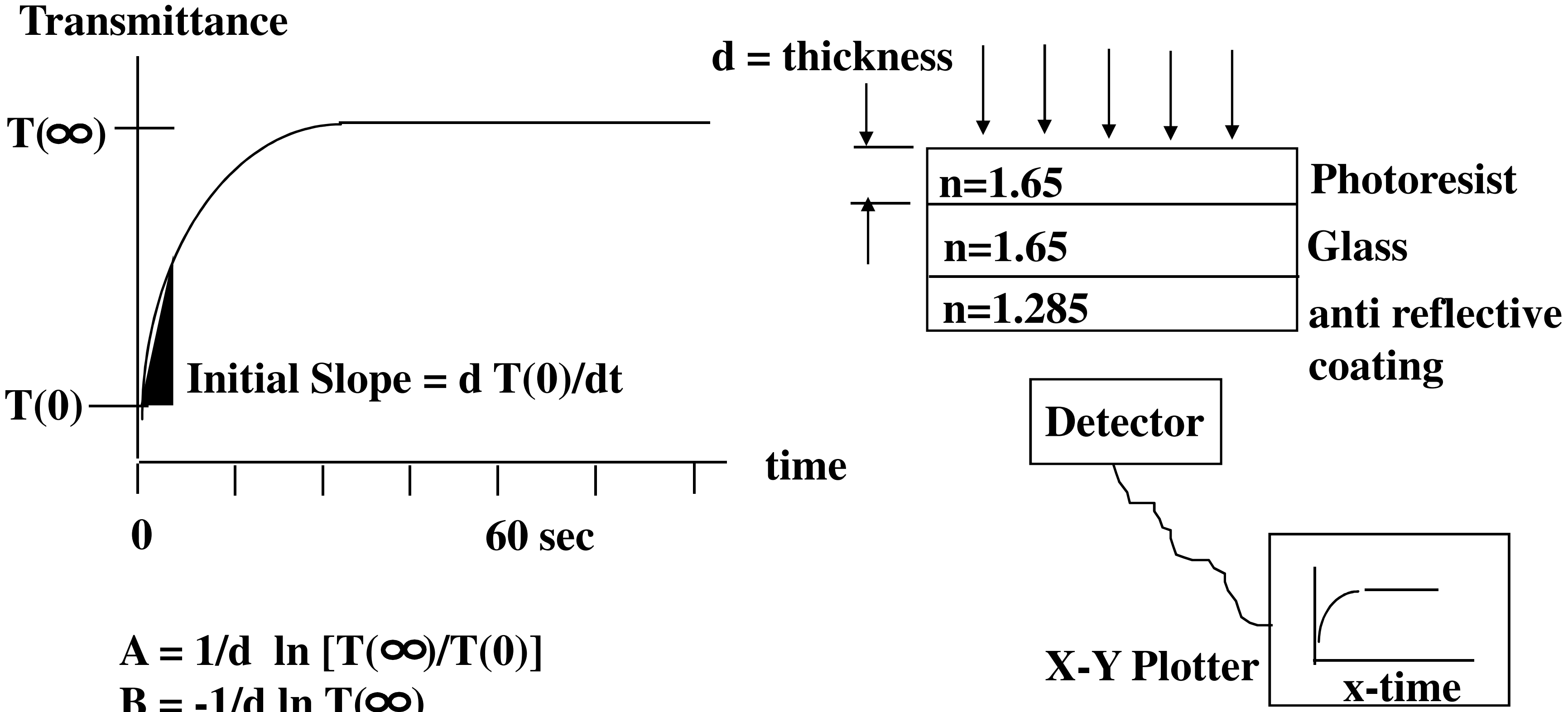
MEASUREMENT OF A,B,C, PARAMETERS



$A = 1/d \ \ln [T(\infty)/T(0)]$
$B = -1/d \ln T(\infty)$
$C = \ \{A+B/AI_0 \ T(0) \ (1-T(0))\} \ dT(0)/dt$

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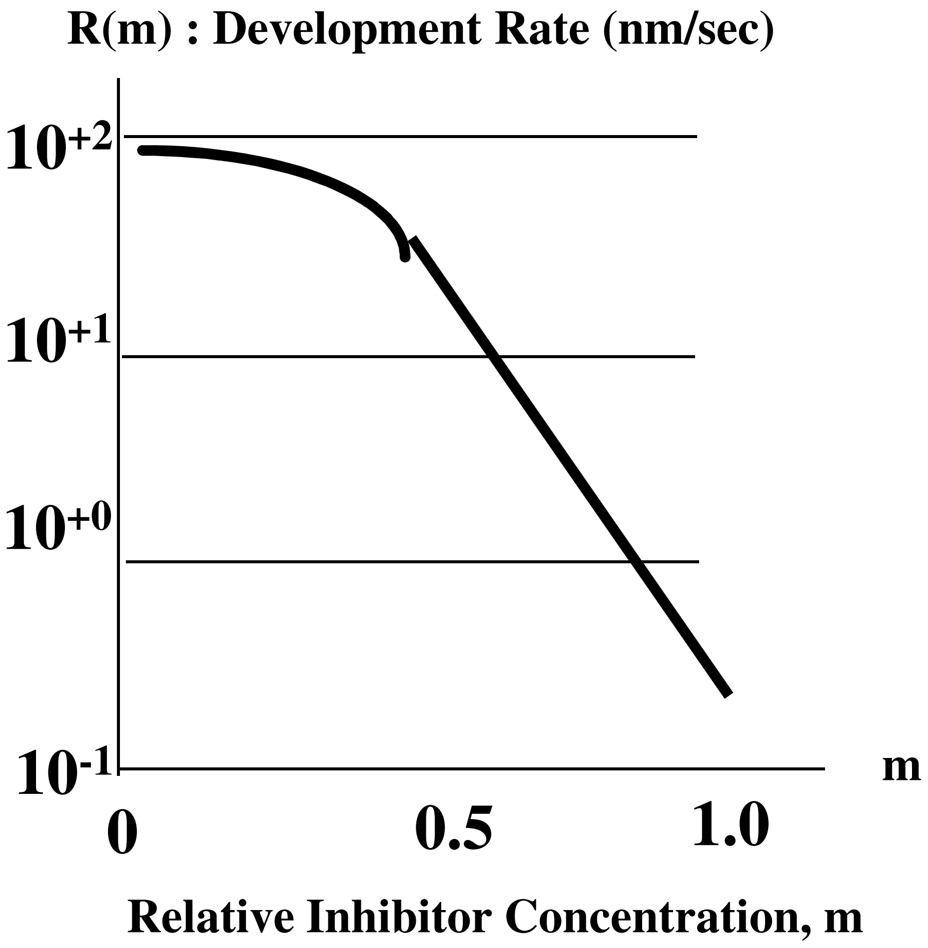
MODELING OF DEVELOPMENT IN POSITIVE RESIST

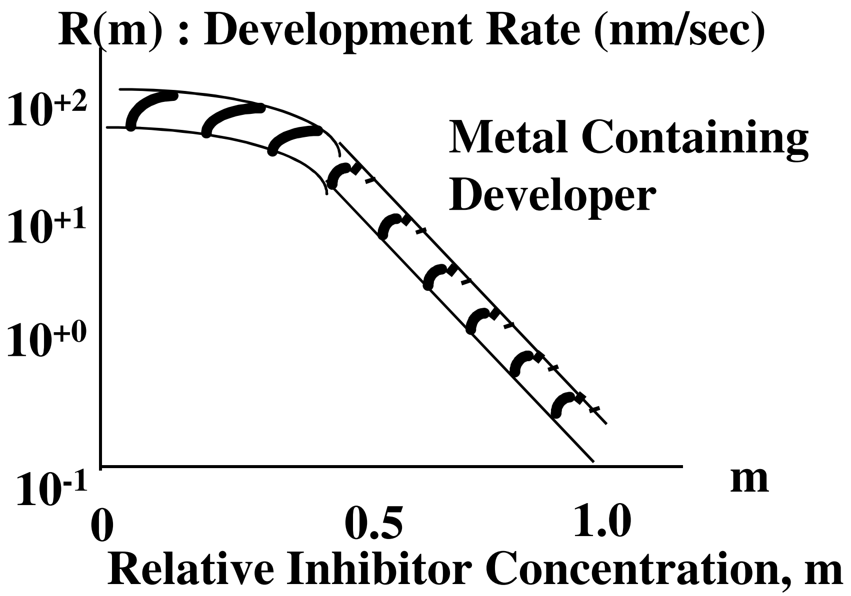
Kim's Model:

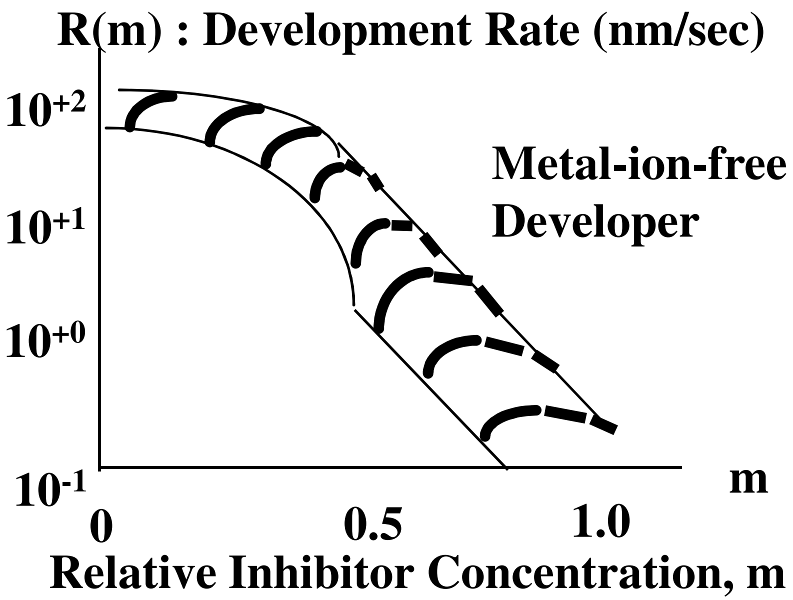
$$R(m) = \frac{1}{\dfrac{1-me^{Rs\,(1-m)}}{R1} + \dfrac{me^{-Rs(1-m)}}{R2}}$$

where R1 is rate of fully exposed resist
R2 is rate of unexposed resist
Rs is sensitivity of development rate to changes in m



SURFACE RATE RETARDATION EFFECT





This retardation may be described by a multiplicative factor which varies linearly with exposure parameter m. The value of the factor with m=0 is called R5 and with m=1 is called R6. The depth dependence factor is exponential with characteristic delay distance R4. Metal-ion-free developer uses additional parameters R7, R8, R, R10.

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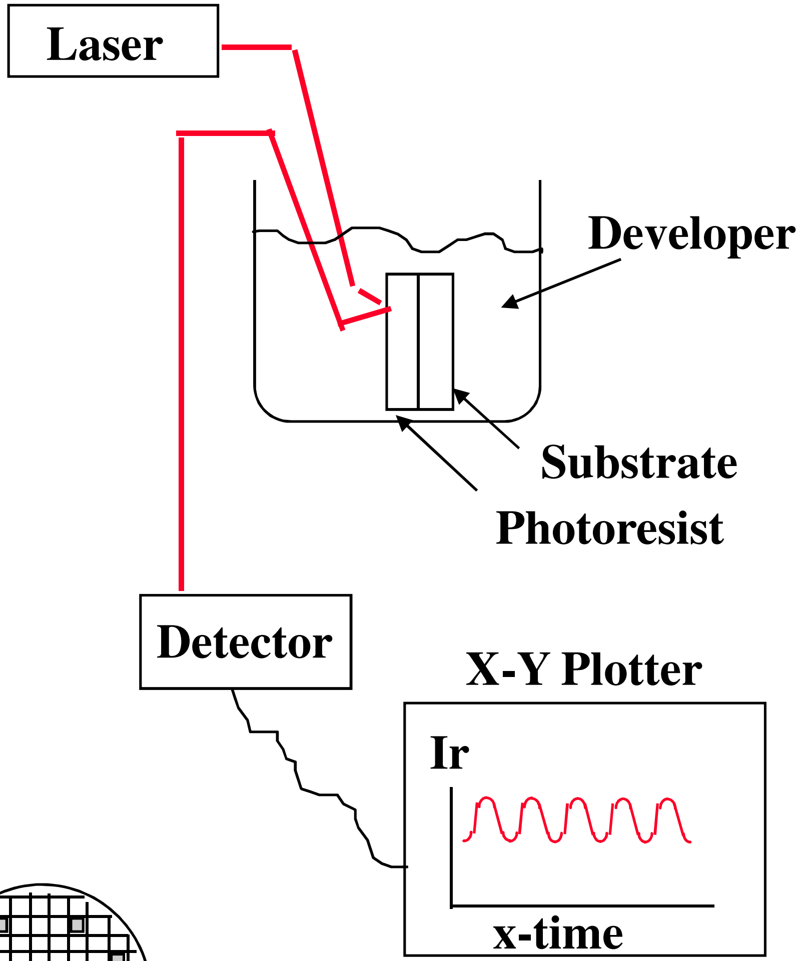
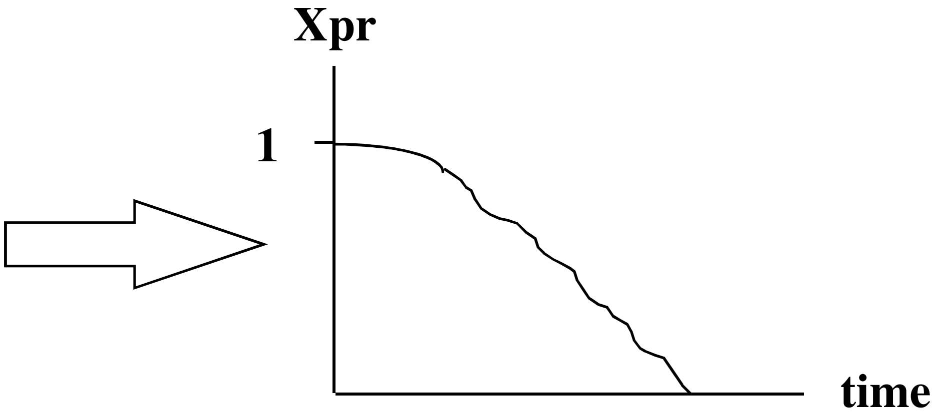
MEASUREMENT OF DEVELOPMENT RATE



Convert the data Ir vs t into Xpr vs t
The slope dXpr/dt
is the development rate.



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PROLITH

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FAX (512) 327-1510
prolith_info@finle.com

PROLITH INPUT PARAMETERS

Projection System:
- **Wavelength = 436 nm**
- **Bandwidth = 0.0 nm**
- **Numerical Aperture = 0.29**
- **Partial Coherence = 0.70**
- **Line width = 1.00 µm**
- **Pitch = 2.00 µm**
- **Mask Bias = 0.0**
- **Focal Position = 0.0**
- **Image Flare = 0.0**

Prebake Conditions: Hotplate
- **Bake Time = 1.0 min**
- **Temperature = 90 C**

Exposure Energy = 300 mJ/cm2

PEB Bake Time = 0.3 min
PEB Temperature = 120 C
Development Time = 120 sec
Resist System: System 8
Thickness = 1.2 µm
Layer #1: Si Dioxide
- **Thickness = 500nm**

Layer #2: Polysilicon
- **Thickness = 600 nm**

Layer #3: Si Dioxide
- **Thickness = 50 nm**

Substrate: Silicon

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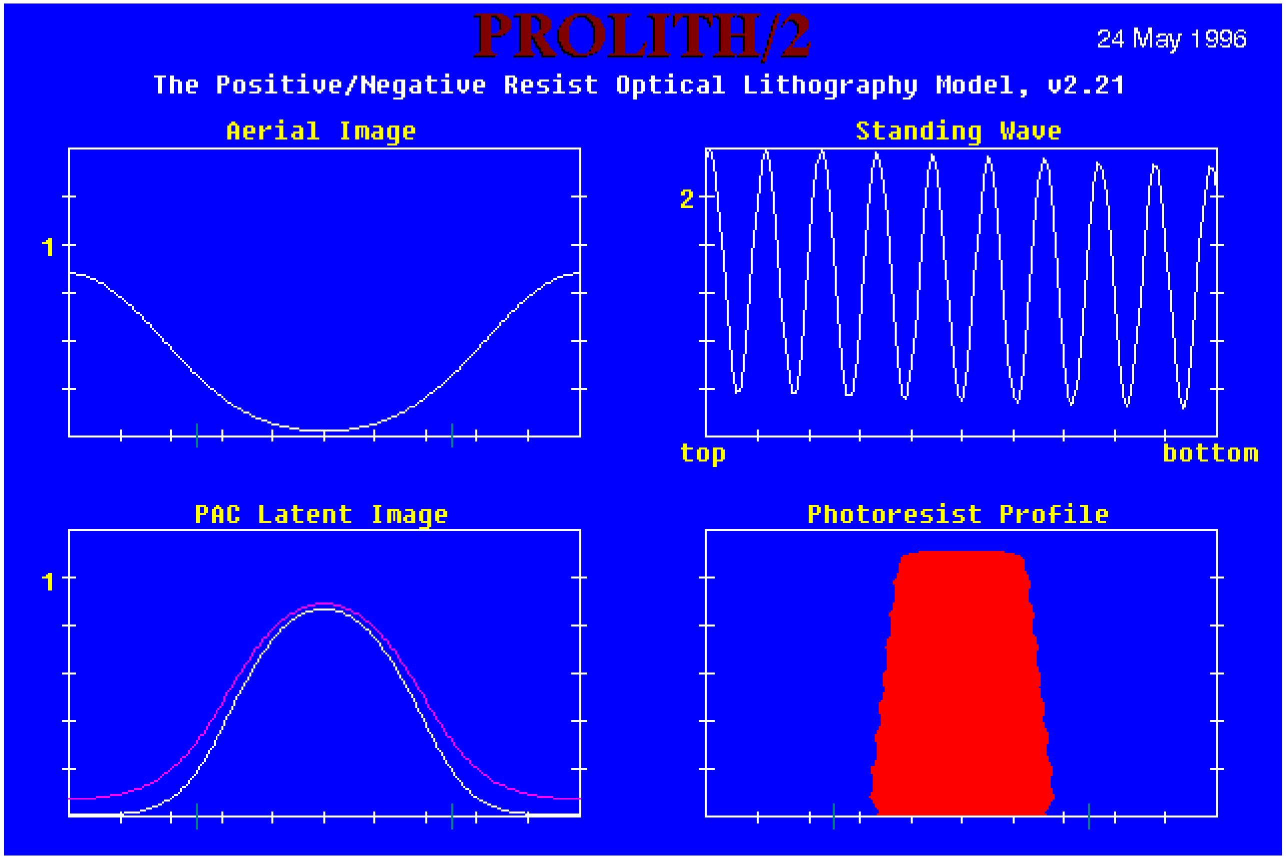
EXAMPLE OUTPUT



PROLITH/2

24 May 1996

The Positive/Negative Resist Optical Lithography Model, v2.21

PRINTED OUTPUT VALUES

PROLITH/2 Single Run Results

Image Log-slope = 4.0095 1/microns
PAC Gradient = 1.6175 1/microns
Resist Line width = 1.7129 microns
Side wall Angle = 83.69 degrees
Time To Clear = 33.09 seconds
Line Resist Loss = 84.23 nm

PROLITH/2 Run Time = 0.18 minutes
with a speed factor of 10

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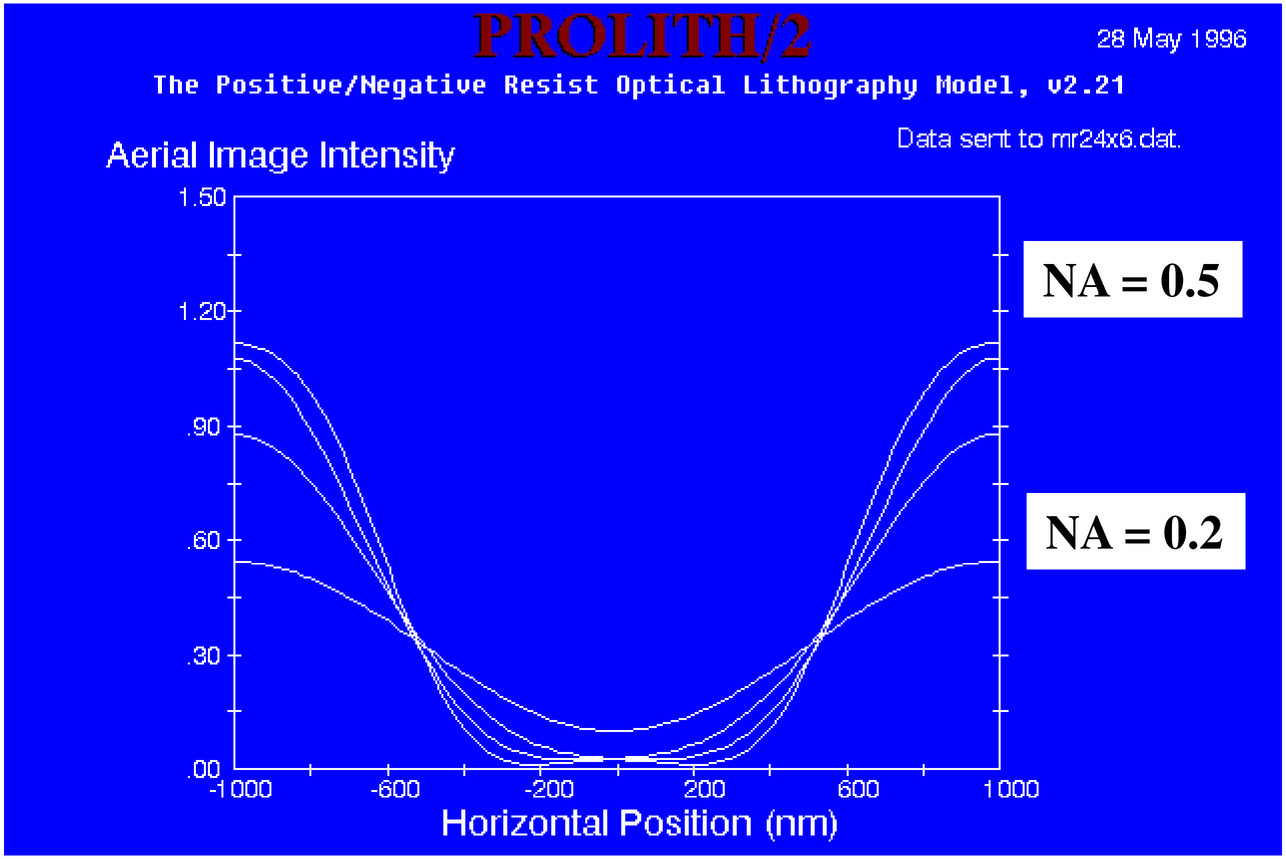
AERIAL IMAGE VERSUS NA



NA = 0.5

NA = 0.2

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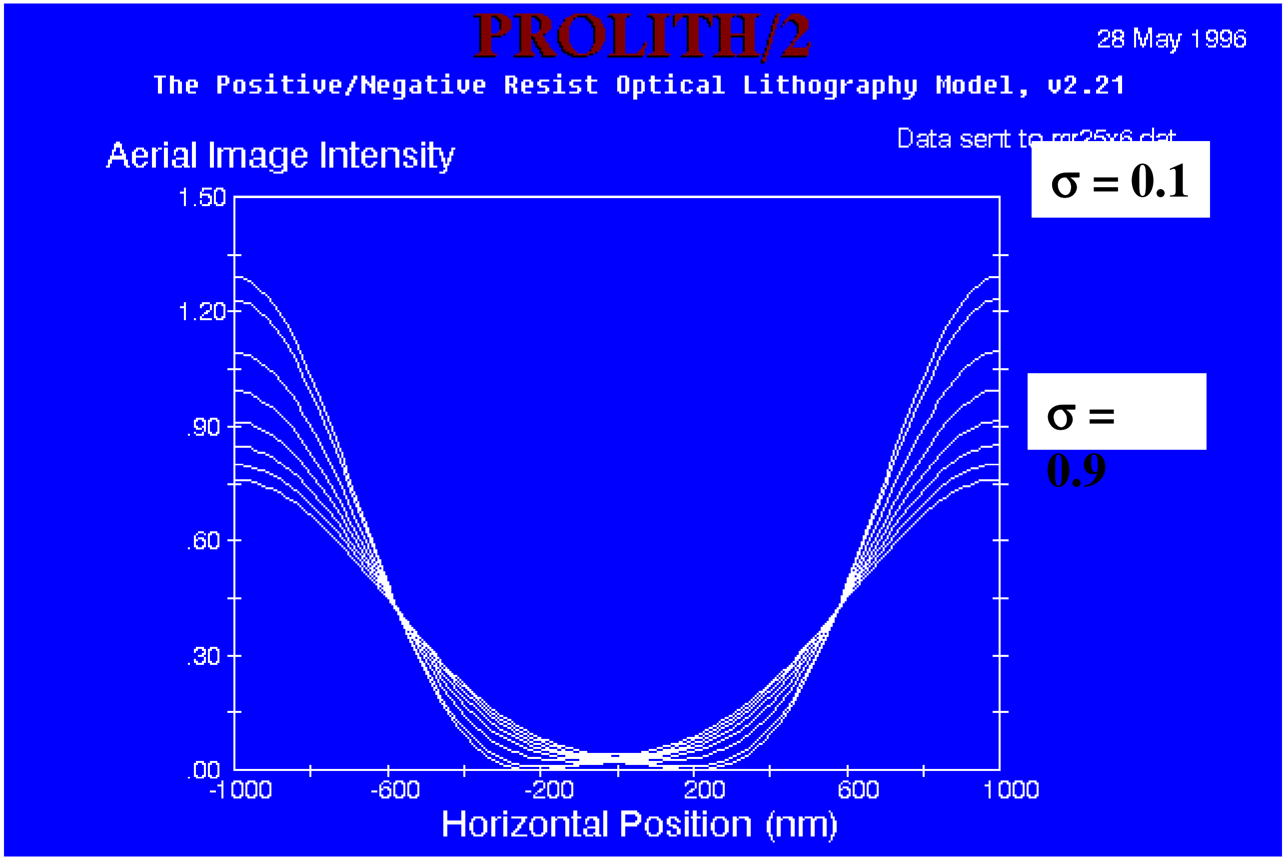
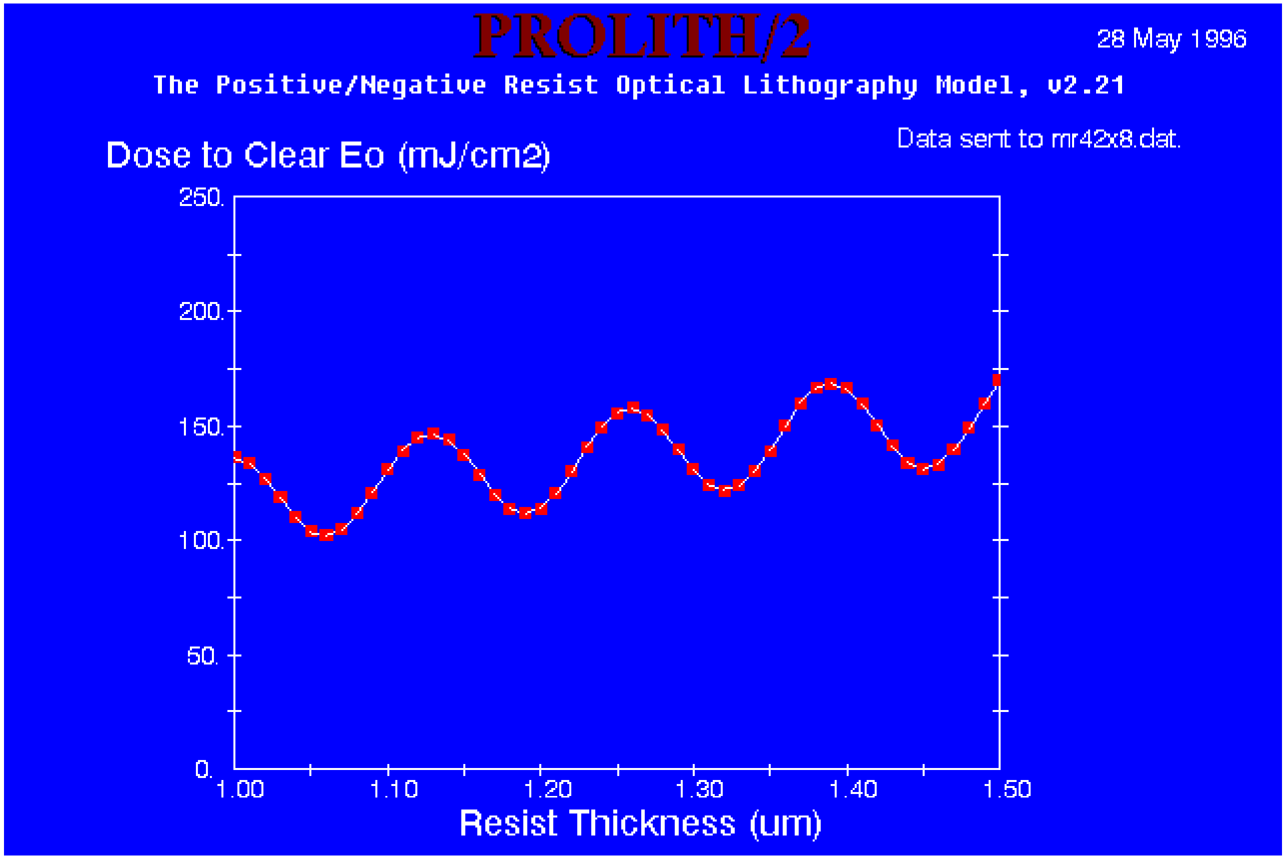
AERIAL IMAGE VERSUS COHERENCY σ



σ = 0.1

σ = 0.9

SWING CURVE (DOSE TO CLEAR VS THICKNESS)



PROLITH/2

28 May 1996

The Positive/Negative Resist Optical Lithography Model, v2.21

Data sent to mr42x8.dat.

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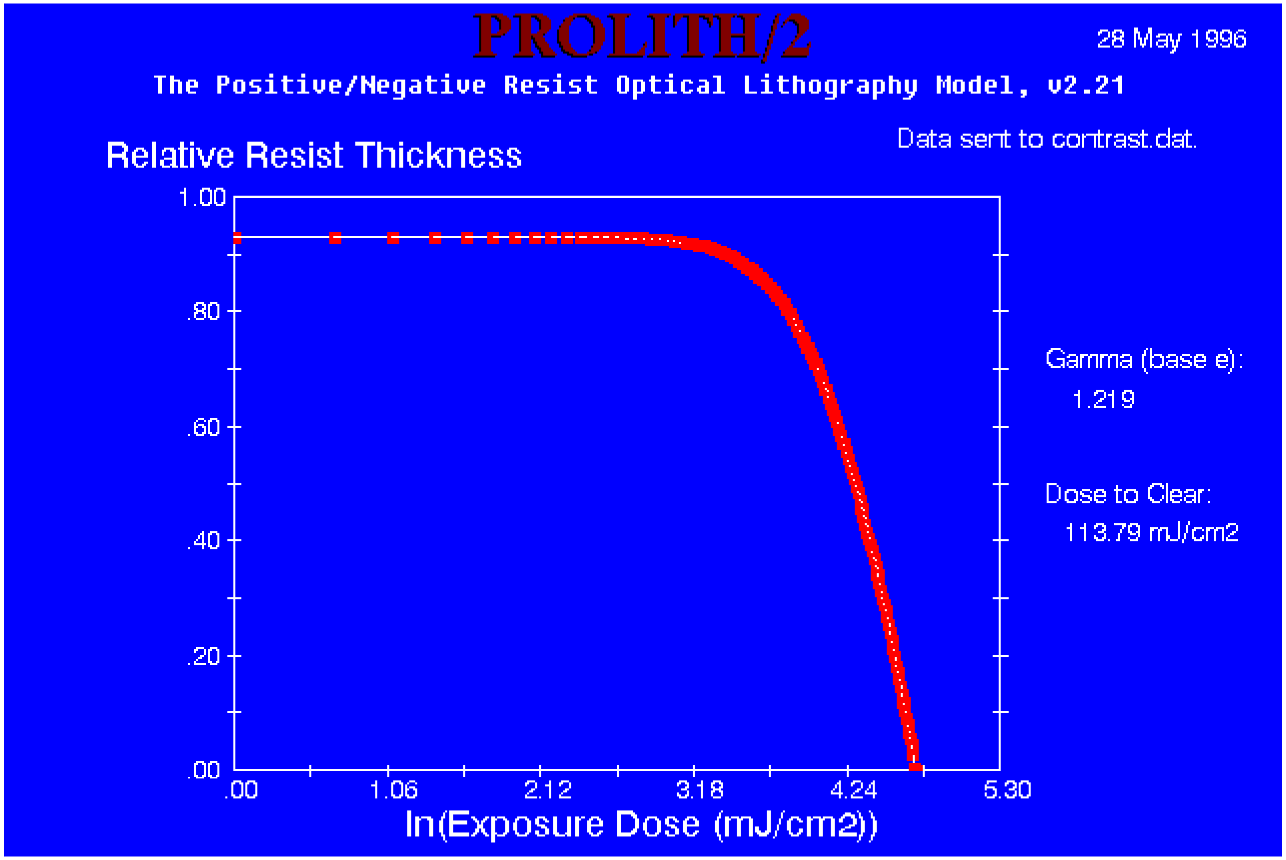
THICKNESS VERSUS ln EXPOSURE



PROLITH/2

28 May 1996

The Positive/Negative Resist Optical Lithography Model, v2.21

Data sent to contrast.dat.

Gamma (base e):
1.219

Dose to Clear:
113.79 mJ/cm2

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HOMEWORK – MODELING FOR LITHOGRAPHY

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