Building College-University Partnerships for Nanotechnology Workforce Development

Optical Lithography

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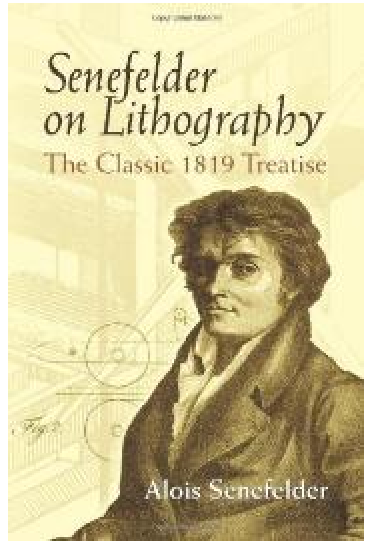
Outline

- Where do we use optical lithography?
- Moore's Law
- Optical Lithography Steps
- Hands-on Demo with Rich Hill (ECC)
- Understanding optical lithography by numerically solving real life scenarios

Where do we use optical lithography?

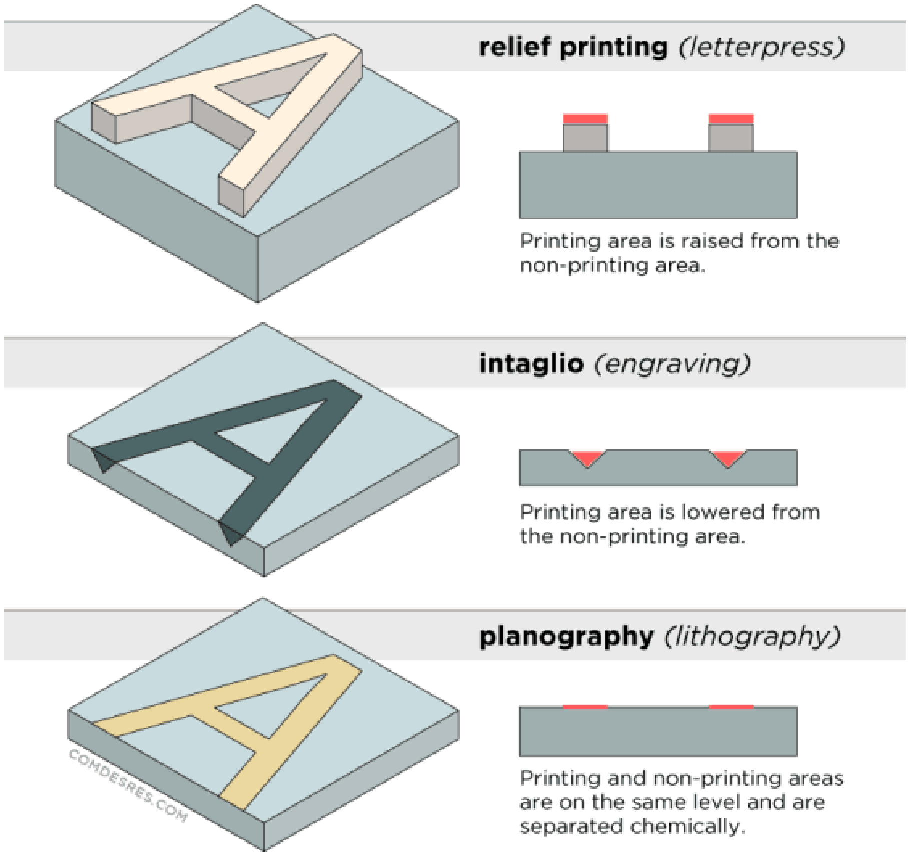


What is lithography?

- A word of Ancient Greek origin.
- λίθος (lithos) γράφειν (graphia)
- Alois Senefelder used non-mixing oils on stone for mass production
- Andy Warhol comes to mind: In the art world, lithography is a two-century-old printing technology used to make prints and posters

Where do we use optical lithography?

What is lithography?



http://comdesres.com/visiting-alois-senefelder/

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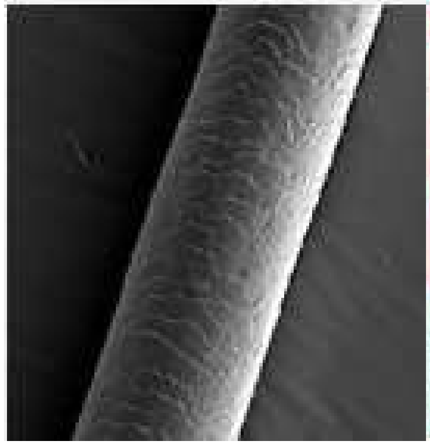
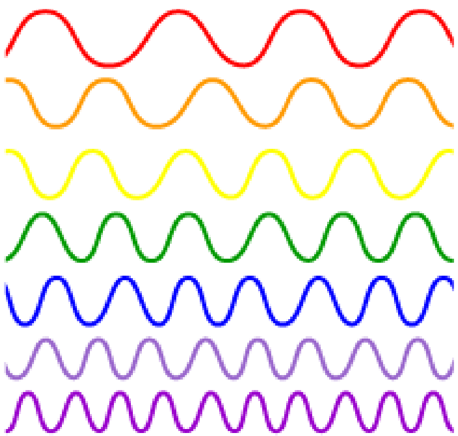
Where do we use optical lithography?

A Note on "Small"

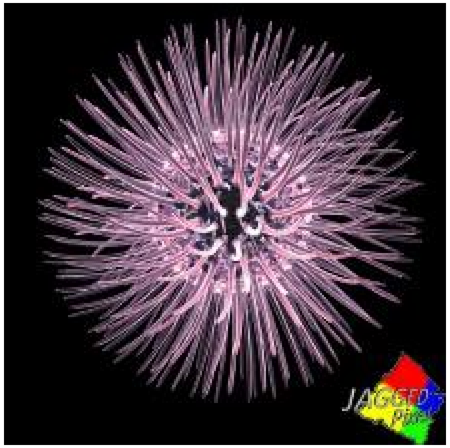


Human Hair
~70 micron

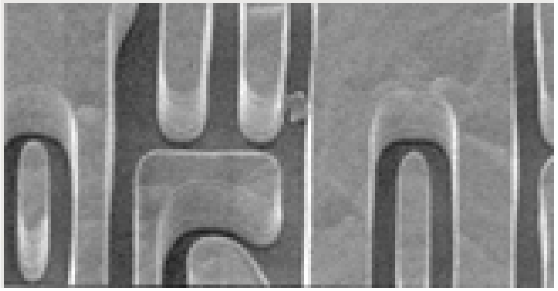
Red Blood Cell
~7 micron



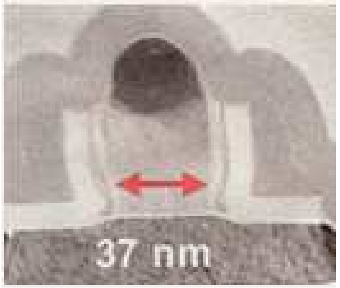
Red Light Wavelength
~700 nanometer



Retrovirus
~70 nanometer



Patterns printed with lithography to make transistors are as small as 25 nm today, and still getting smaller!



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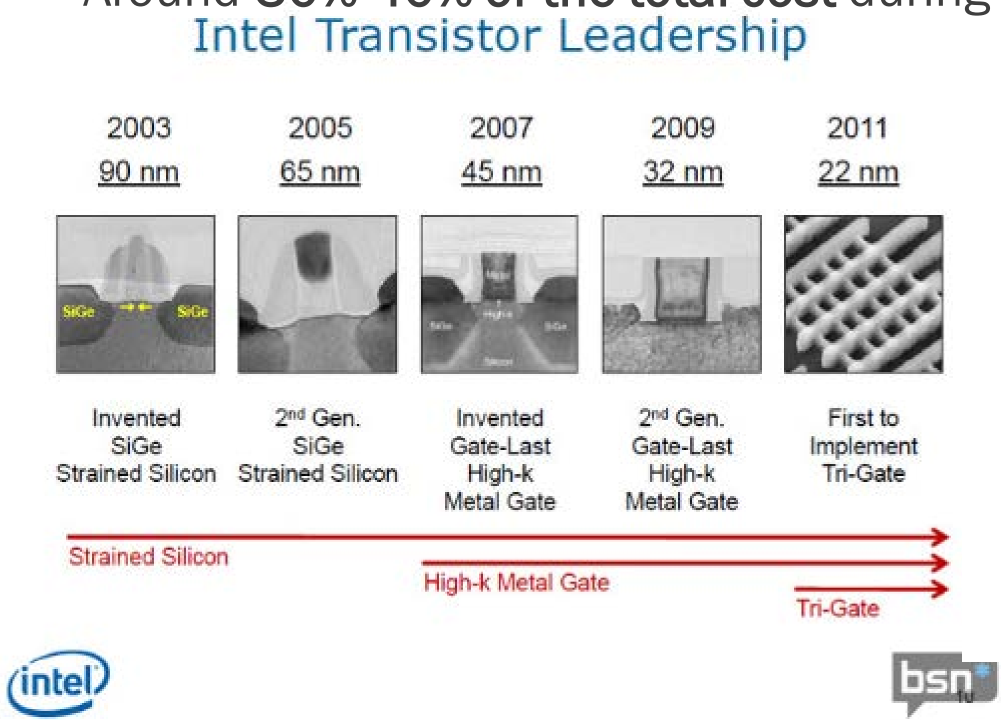
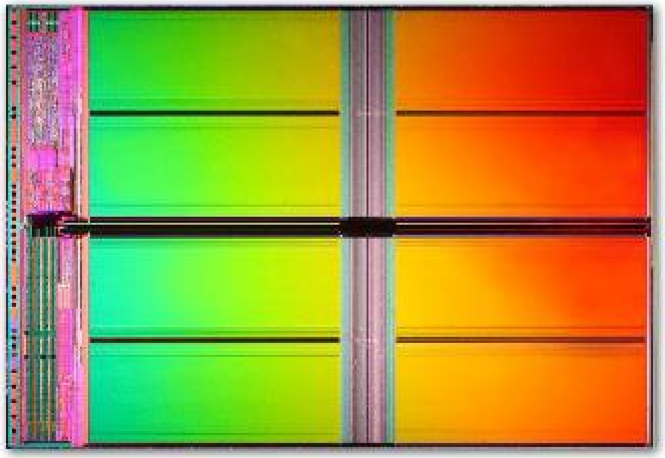
Where do we use optical lithography?

In the semiconductor world, lithography is the printing technology used to **mass-produce chips** like microprocessors, memory and flash that are at the heart of electronic devices.

Around **30%-40% of the total cost** during IC manufacturing





32nm Flash Memory
2008, Intel

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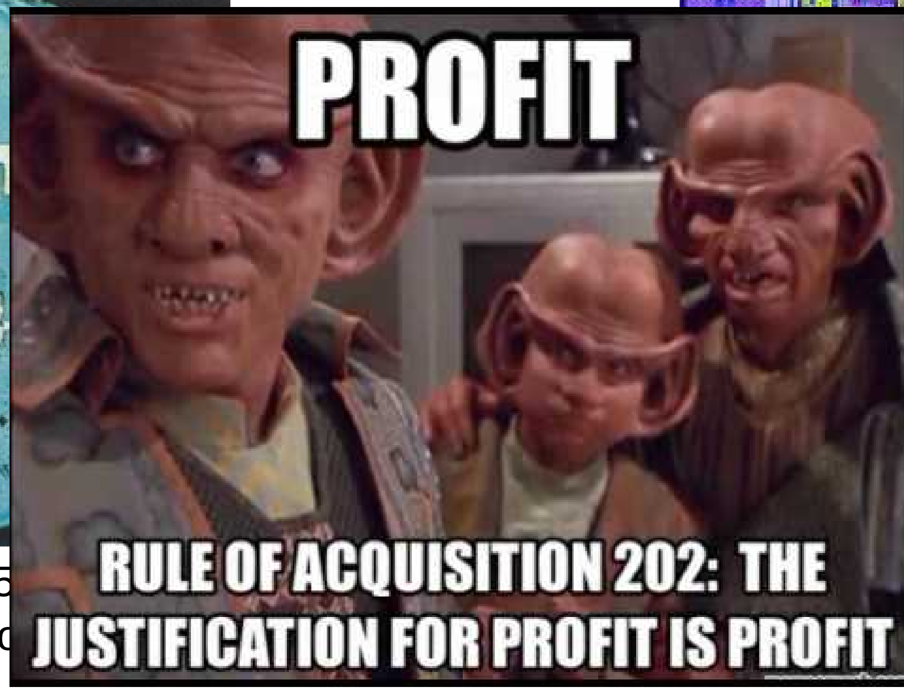
Where do we use optical lithography?

Why size matters?

1961

2011



Feature size = 25
(one thousandth o

e = 25 nanometers
nth of an inch)

Lithography improvements must enable the printing of smaller features *without* significantly increasing the cost of making the chip. These chips cost the same!

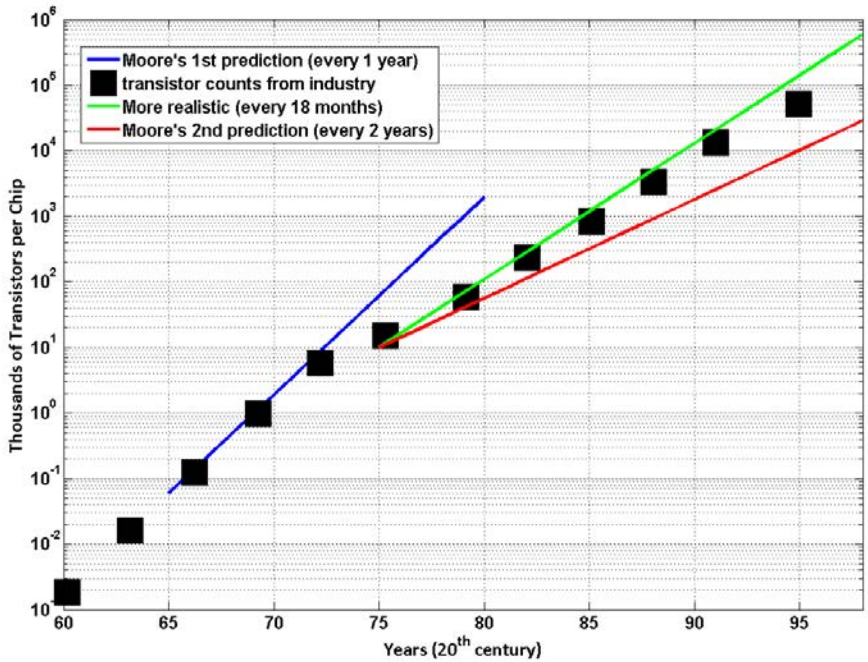
Moore's Law

5MB being shipped in 1958

In 1965: “# of electrical components per chip will double every year”

1- https://b2bstorytelling.files.wordpress.com/2012/10/gordon_moore.jpg
2- http://www.telegraph.co.uk/technology/2016/02/25/end-of-moores-law-whats-next-could-be-more-exciting/

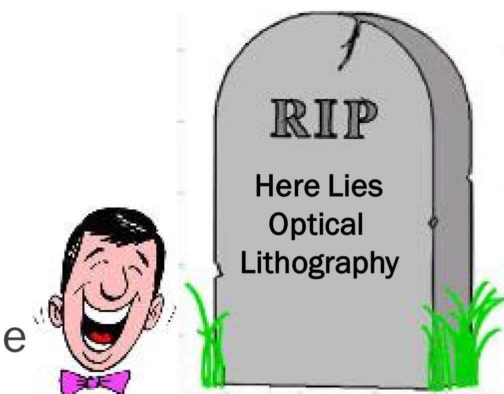
Moore's Law



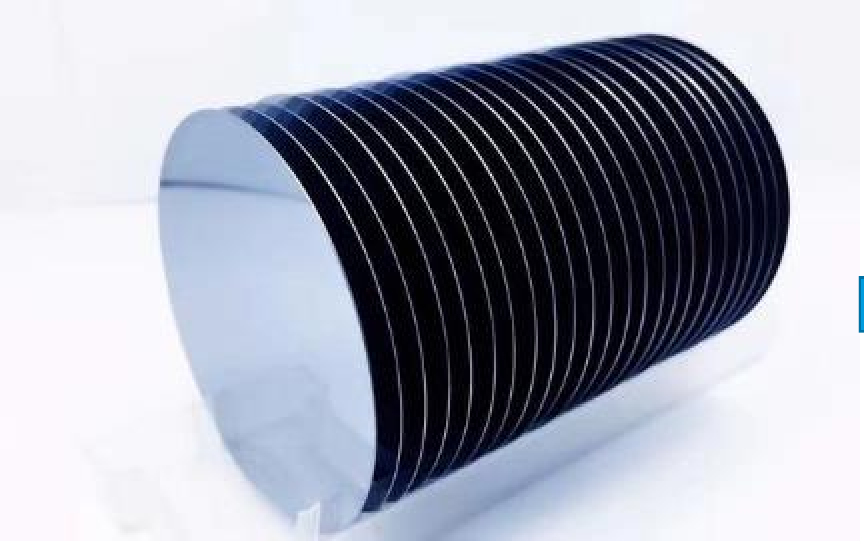
1994: NTRS
1999: ITRS
Accepted Moore's Law as industry standard

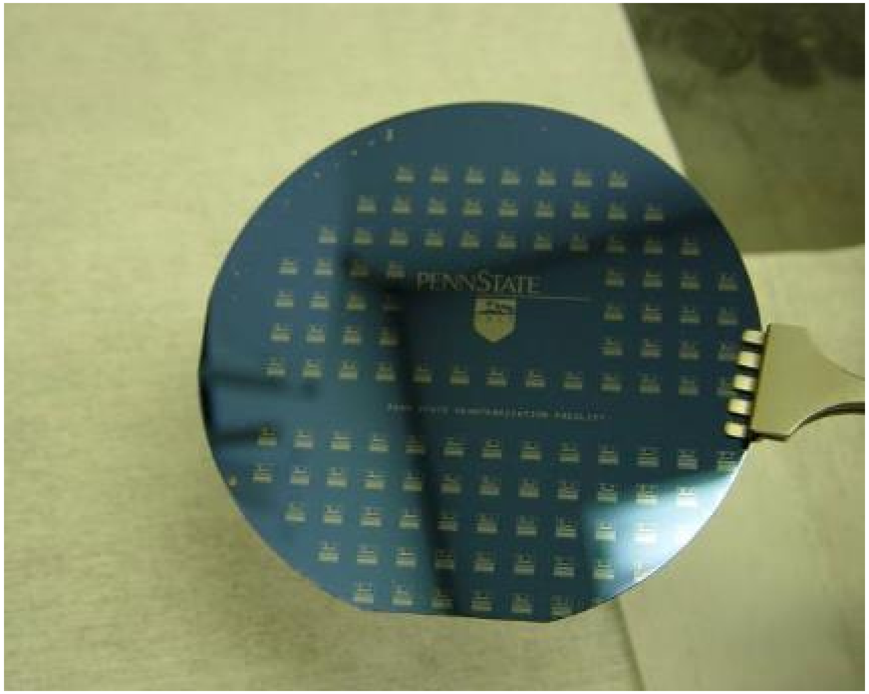
Where are we heading? When will optical lithography die?

- 1979: 1µm
- 1985: 0.5µm
- 2006: 65nm
- X-ray litho + e-beam litho great resolution but cost is the issue



Optical Lithography Steps





Optical Lithography Steps

Photoresist:

Applied to Si wafer through spin casting technique

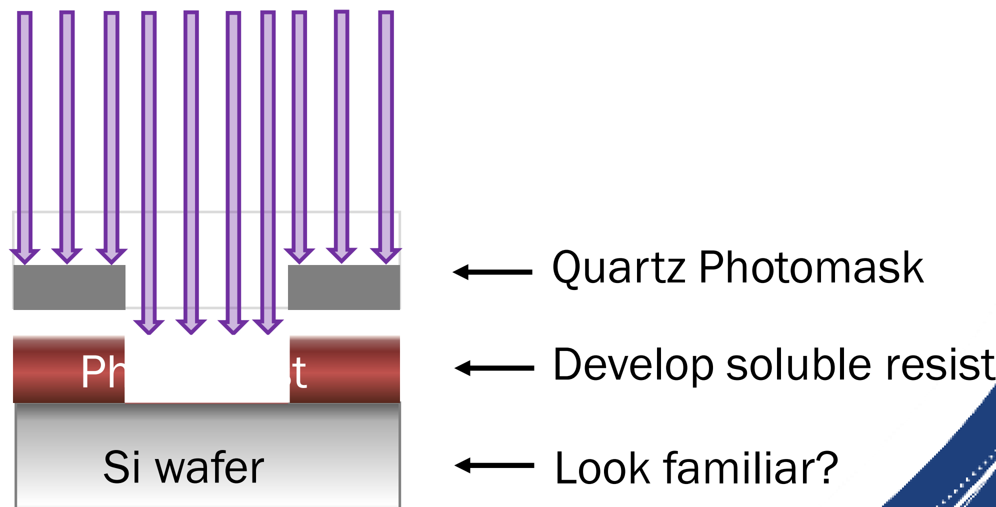
Baked on hot plate → drives out solvents

Liquid precursor → uniform solid thin film

Soluble resist

Insoluble resist

This was an example of positive lithography: What shows goes



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Optical Lithography Steps

Sequence

Wafer Coating Prebake Expose Post Exposure Bake Developing Metrology

A fantastic hands-on demo (transferrable) from Erie Community College Cleanrooms with Rich

Lithography Demo

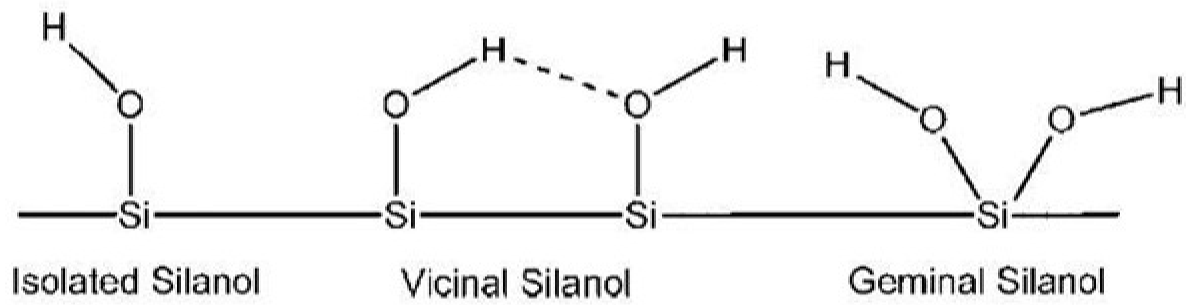
Optical Lithography Steps

- Substrate Preparation
  - Contamination free surface

  - Improve the adhesion of PR to the surface + kill defects
    - Particulates
    - Organic films
    - Inorganic films
    - Adsorbed water

Optical Lithography Steps

- Substrate Preparation
  - Dehydration baking
    - 200-400 °C up to 60 mins.
    - can get rid of organic contaminants, too.
    - can be omitted in some cases.

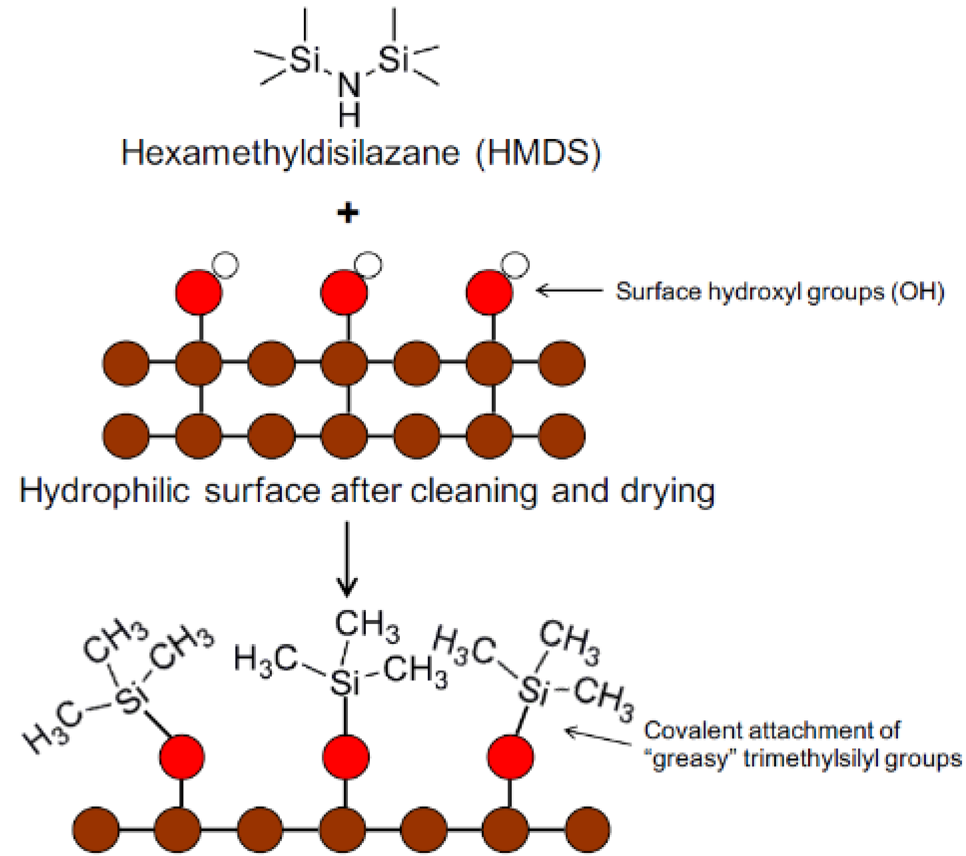


Optical Lithography Steps

- Substrate Preparation
  - Hexamthyl disilizane (HMDS) application

Step1: NH steals H from silanol
Step2: Si bonds of HMDS get free

Step3: Si of HMDS bonds to O
Step4: CH_3 makes very strong bonds with PR.



Hydrophobic surface after priming with HMDS

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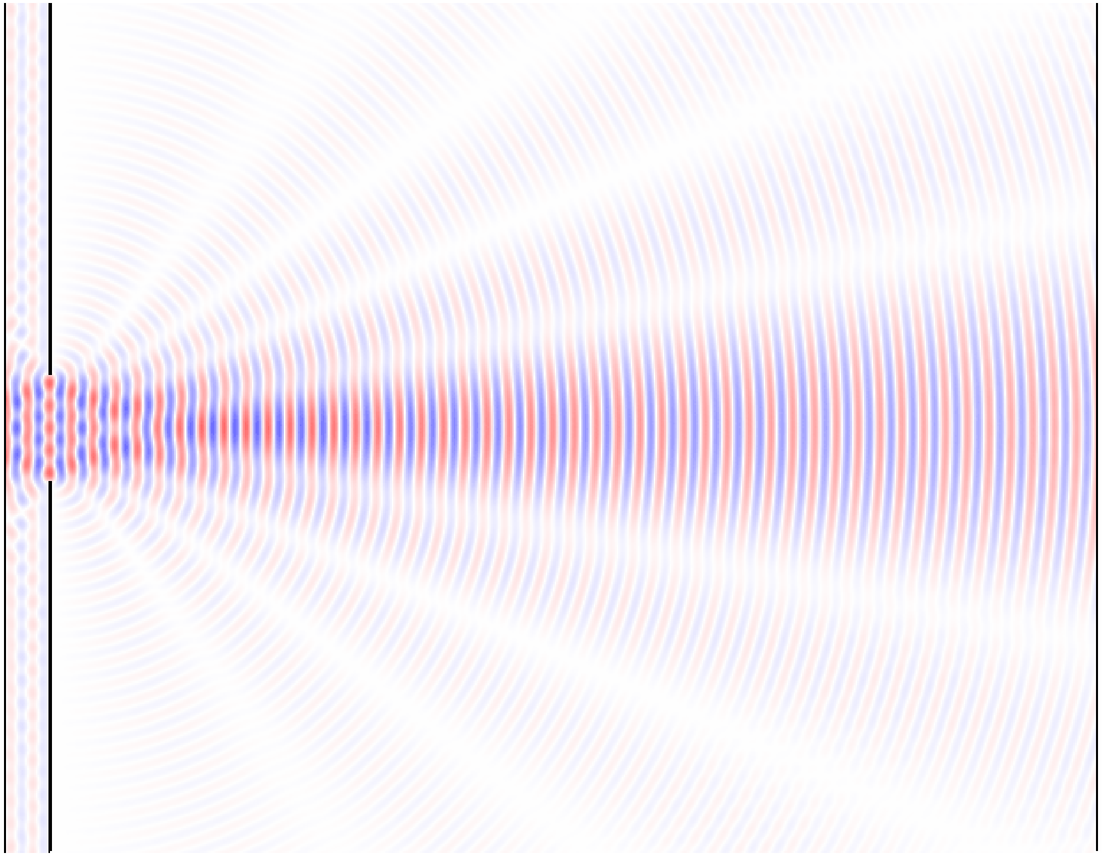
Lithography Demo

Understanding optical lithography

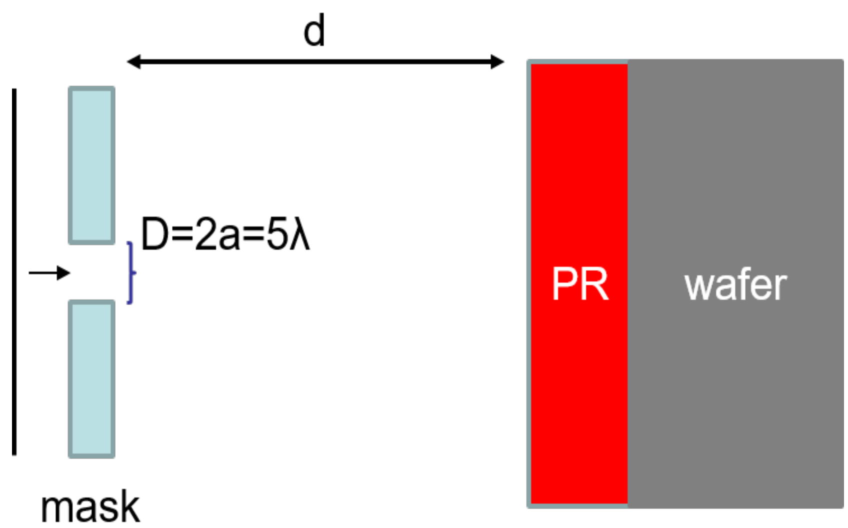
- Diffraction



Understanding optical lithography

- Diffraction: Fresnel-type

Augustin-Jean Fresnel



Joseph von Fraunhofer

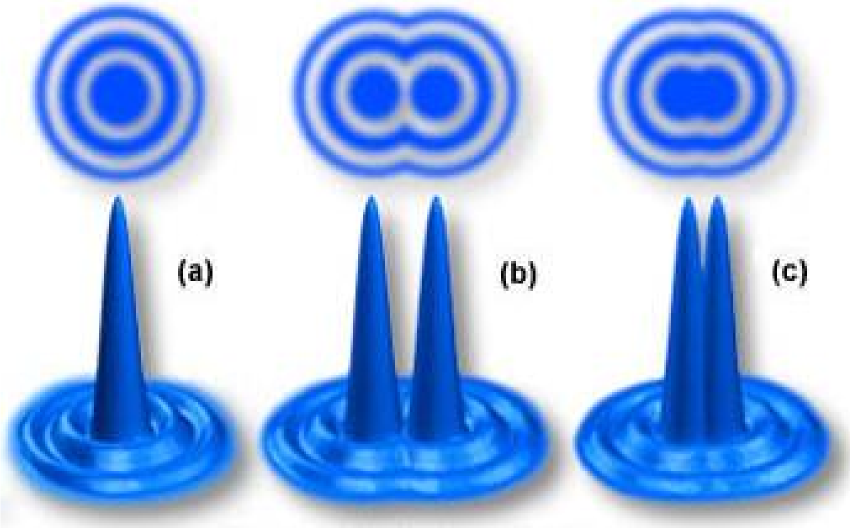
fresnel.m

Distance
0.625λ = 228nm
6.25λ =2.28μm
62.5λ = 22.8μm

Understanding optical lithography

- Diffraction: Bessel Beams

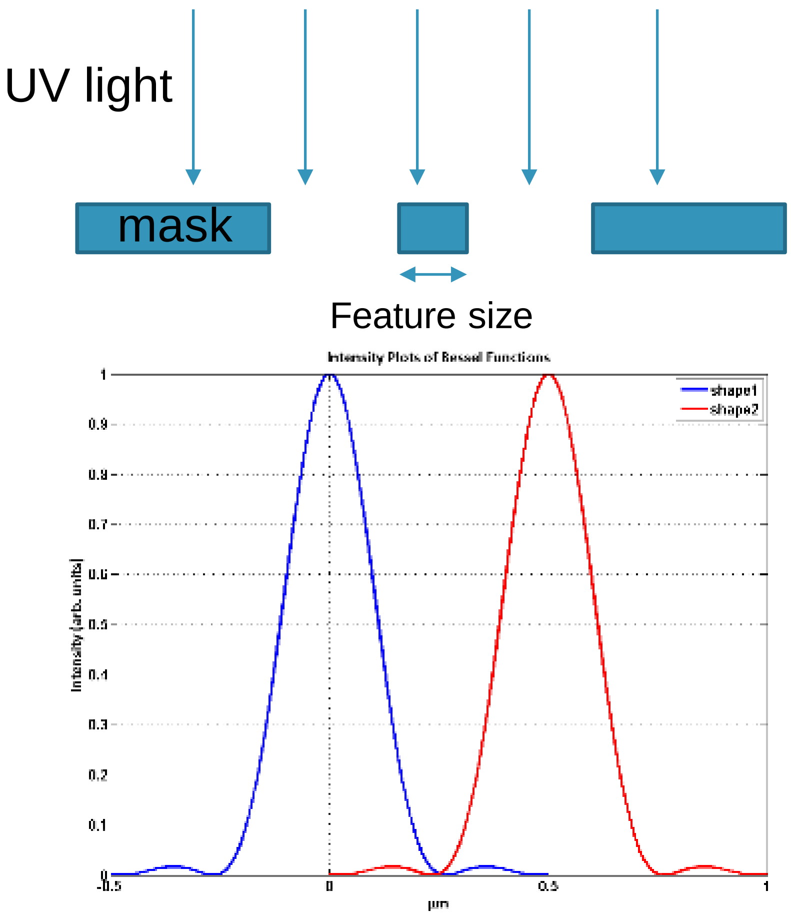
Friedrich Wilhelm Bessel

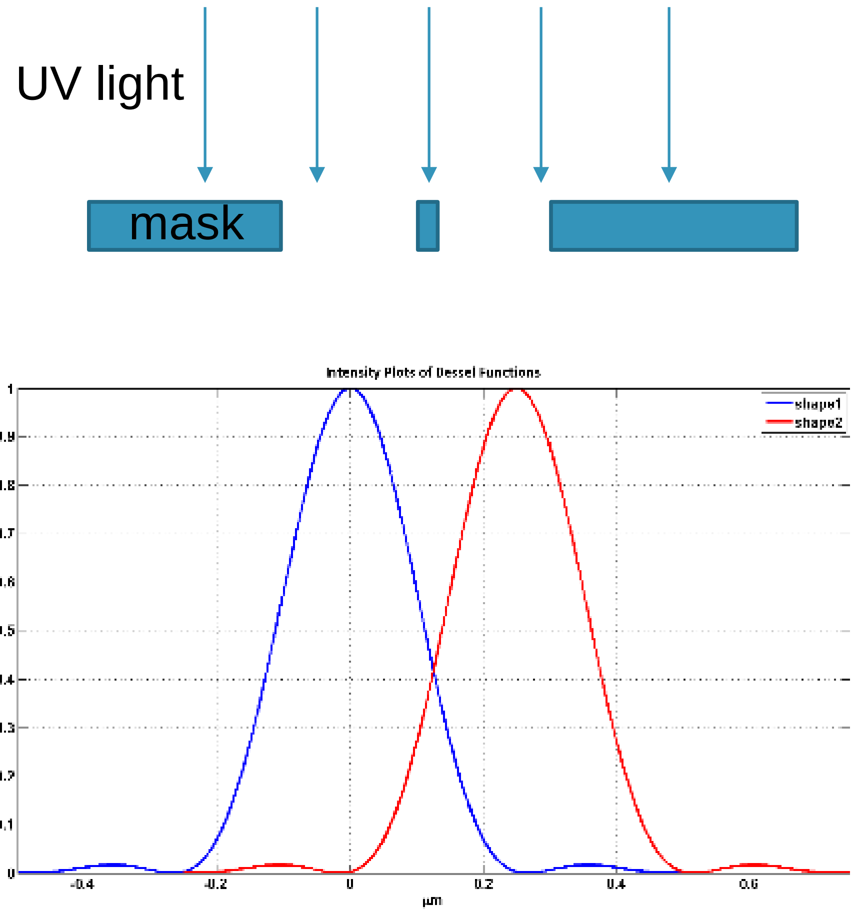


Lord Rayleigh

Understanding optical lithography

- Diffraction





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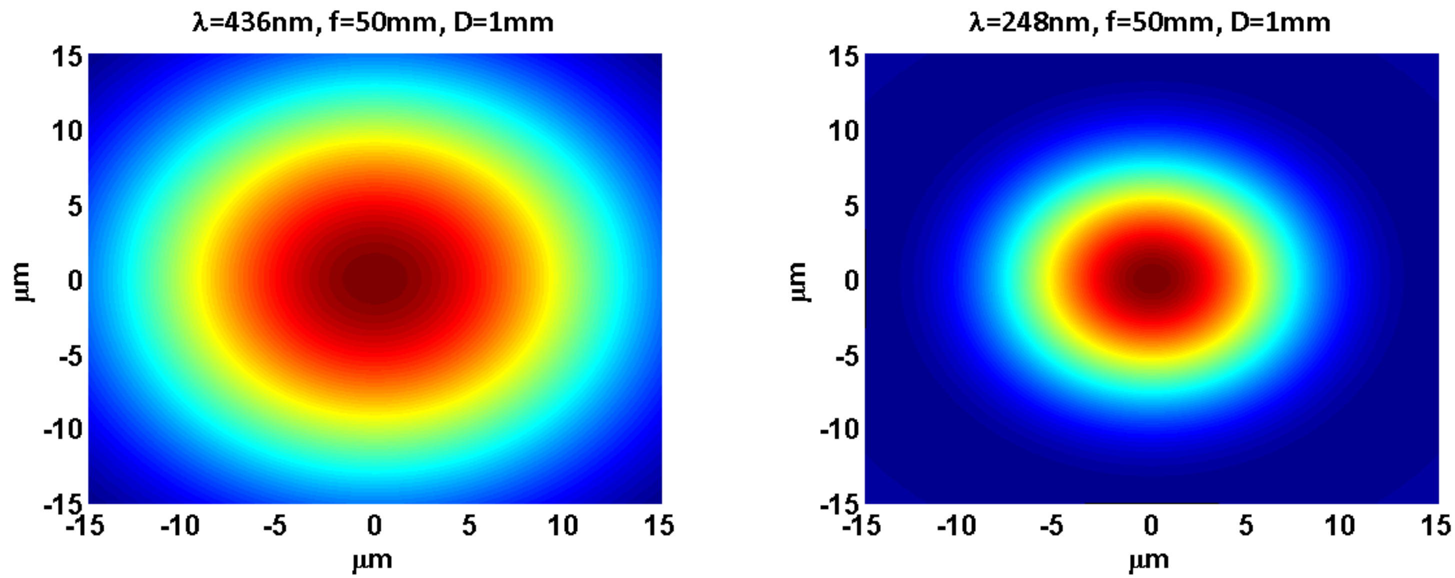
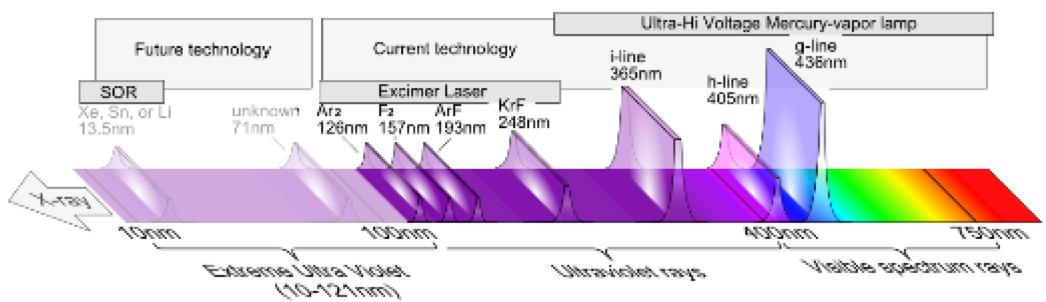
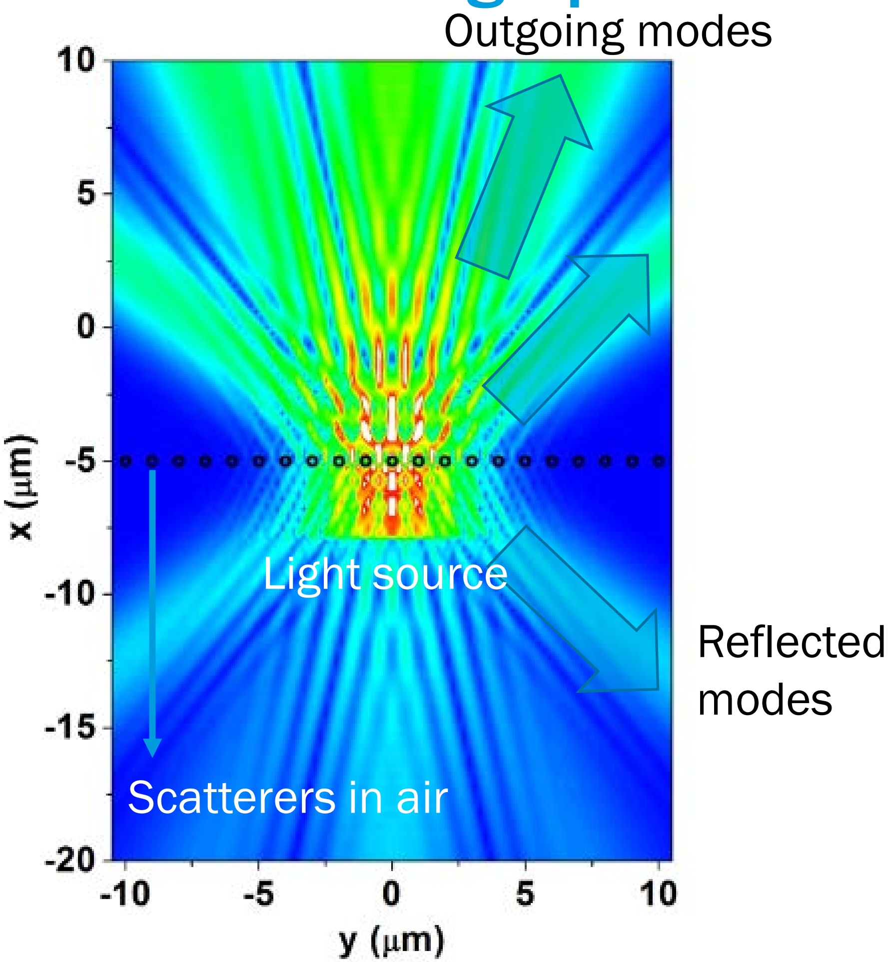
Understanding optical lithography



As the wavelength shrinks down, the resolution gets better!

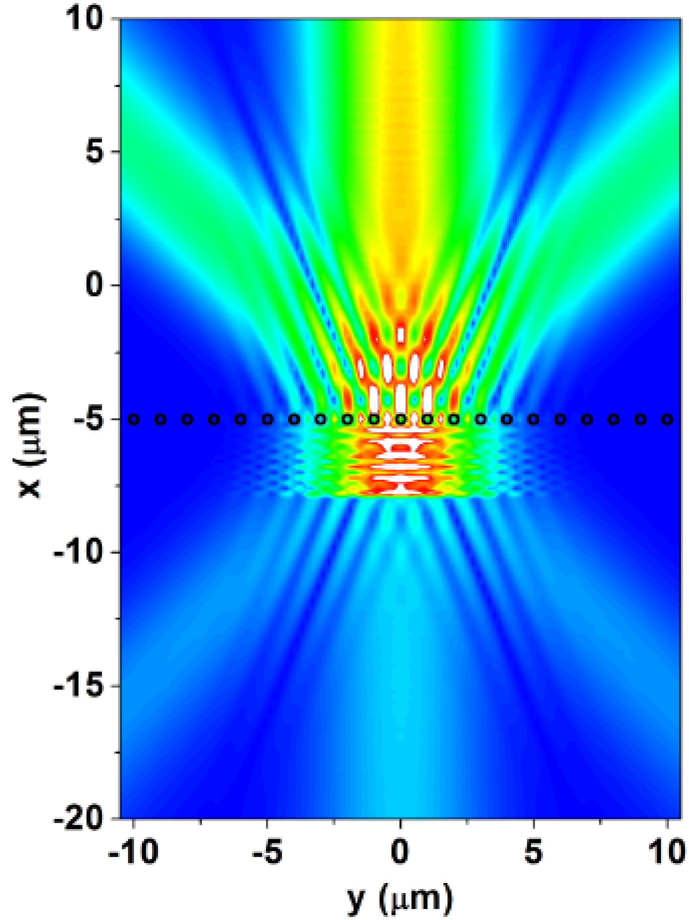


Understanding optical lithography



λ=400 nm
L=1000 nm

At normal incidence

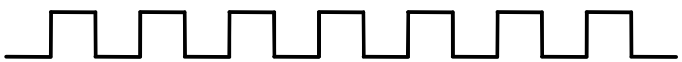


λ=700 nm
L=1000 nm

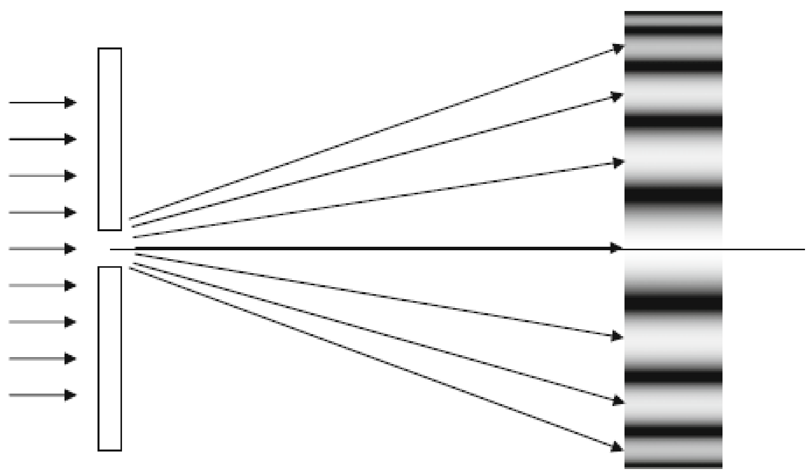
Understanding optical lithography

- Diffraction

Diffraction from a periodic mask



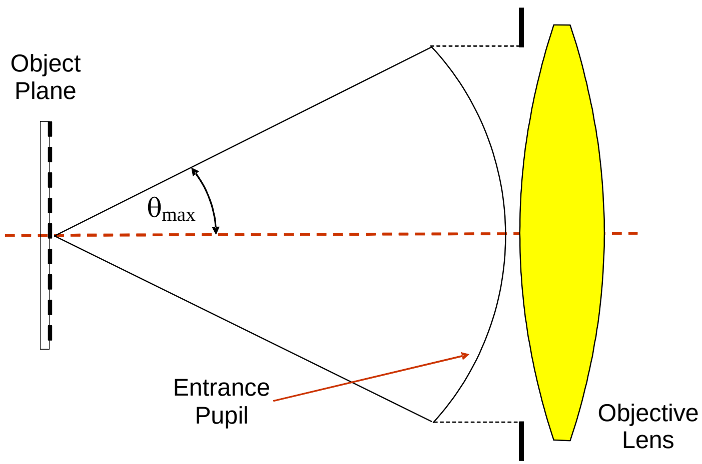
Intensity



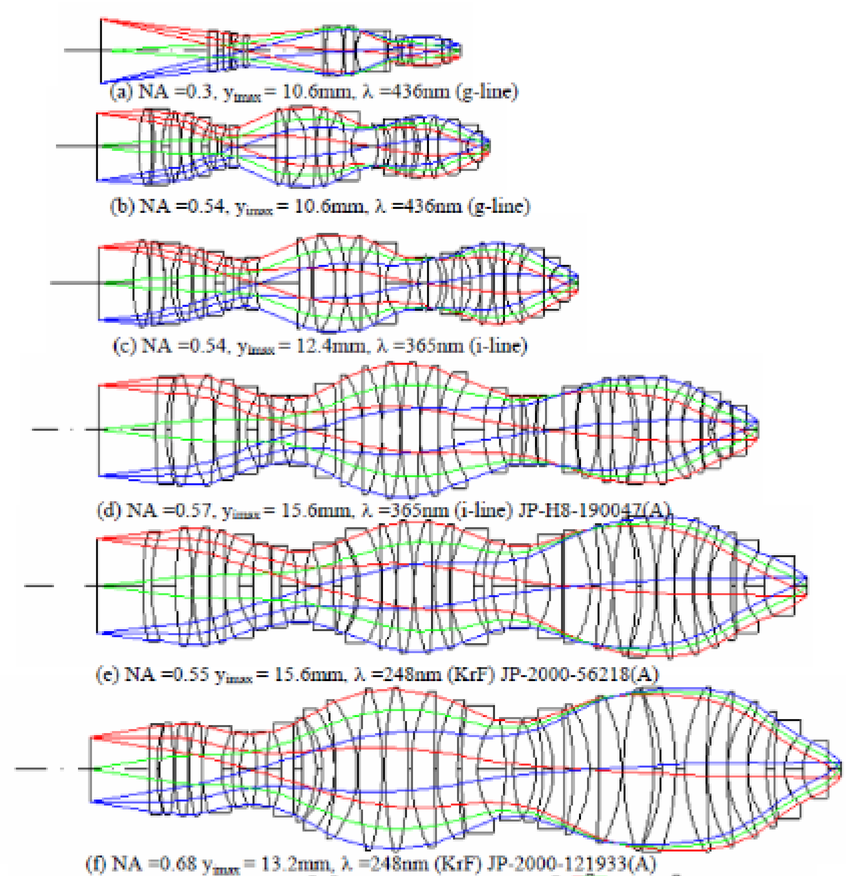
diff_orders.m

Understanding optical lithography

- Imaging with Lens



History of optics in lithography

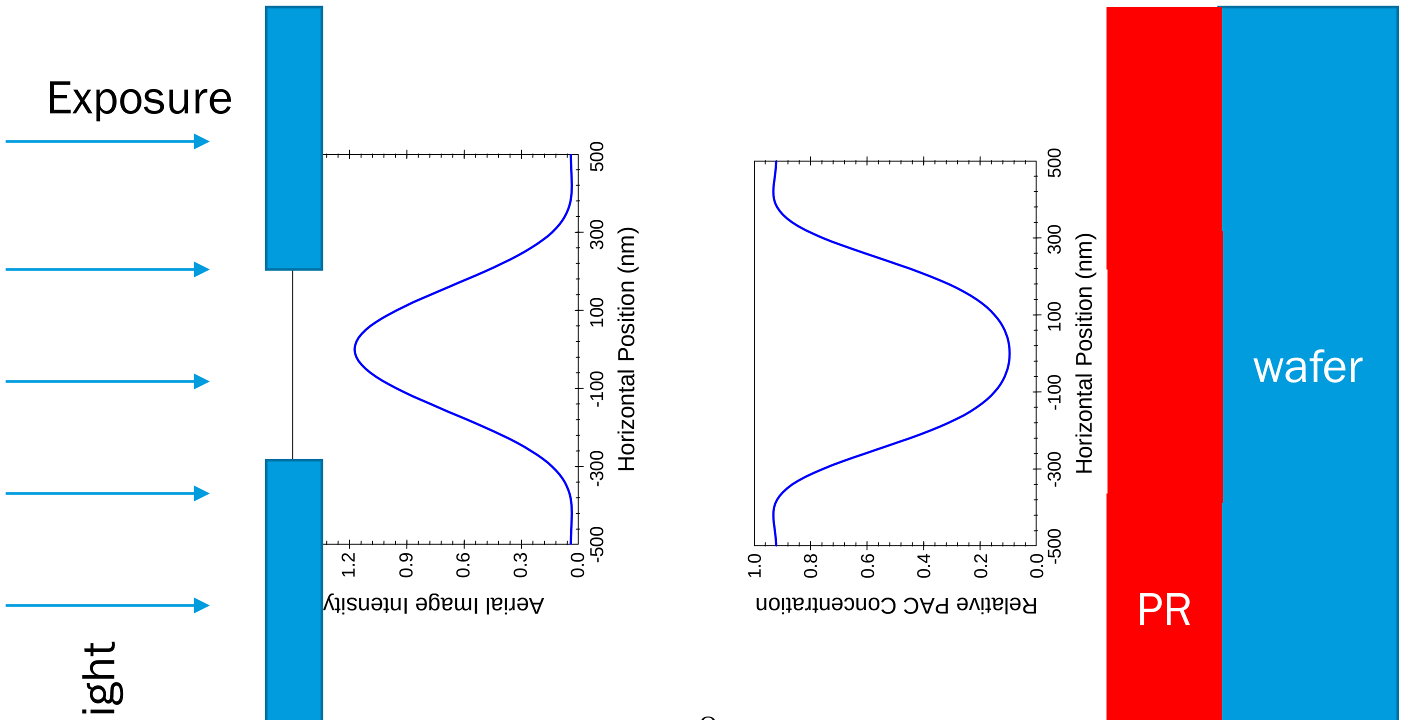


Q1: What does NA correspond to? What is the effect of working with a higher NA?

Q2: How does the light source's wavelength affect the final pattern created?

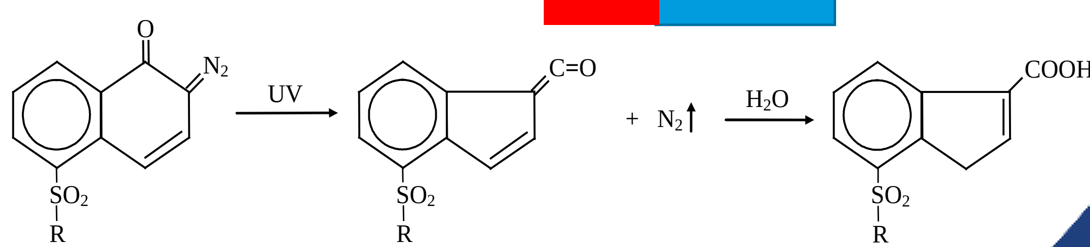
Understanding optical lithography

- Exposure



UV light

mask

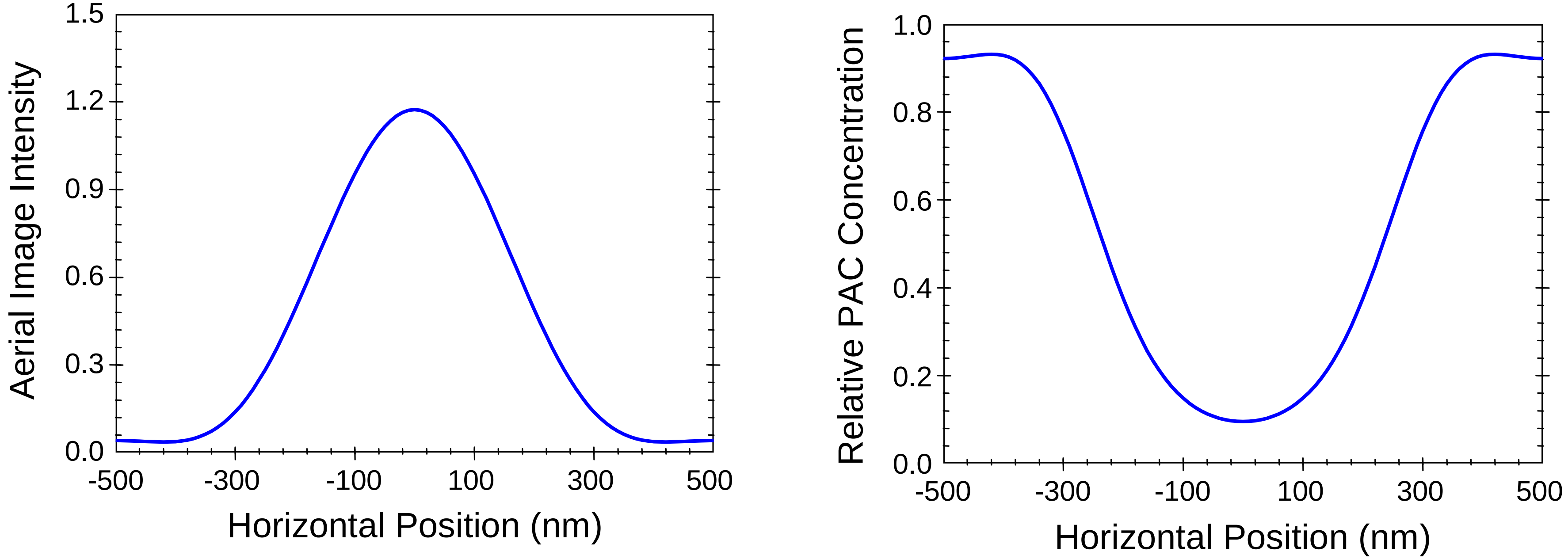


DNQ (dissolution inhibitor)

Carboxylic Acid

Understanding optical lithography

- Exposure



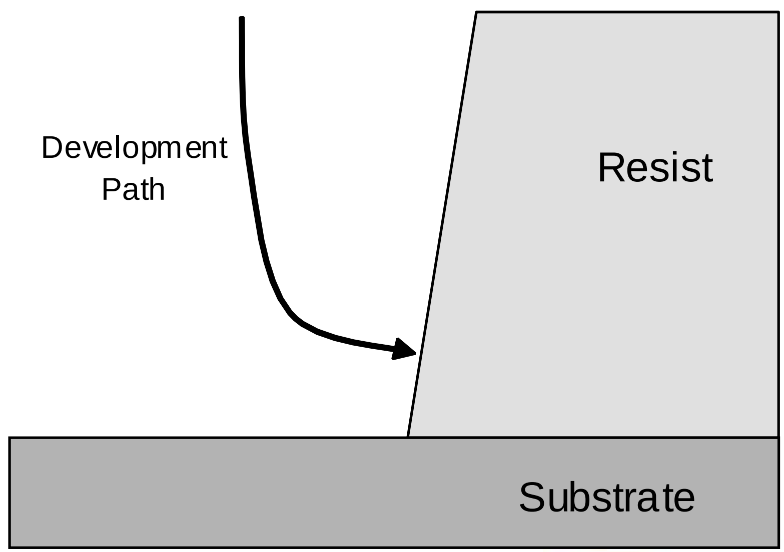
(a) (b)

The exposure process takes an aerial image (a) and converts it into a latent image (b).

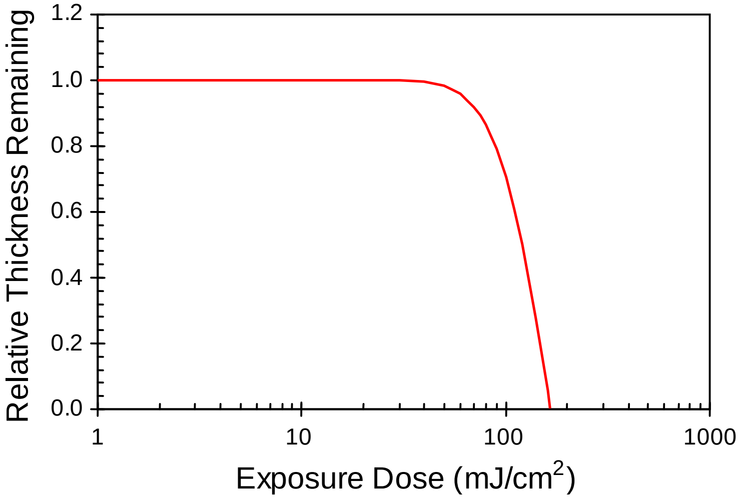
Understanding optical lithography

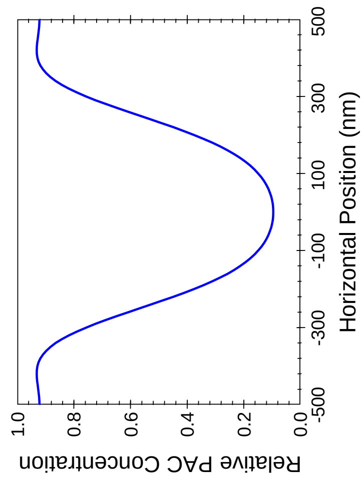
- The Development

How does the developer-resist front propagate through time and space? The rate of development at a given point equal to the rate at which the interface moves down in z. In general we can define the path of development by tracing the position of the resist surface, which will always have a perpendicular direction to the surface. We should expect a path that starts out vertically, travels down through the resist thickness, then turns horizontally, stopping at the resist edge.



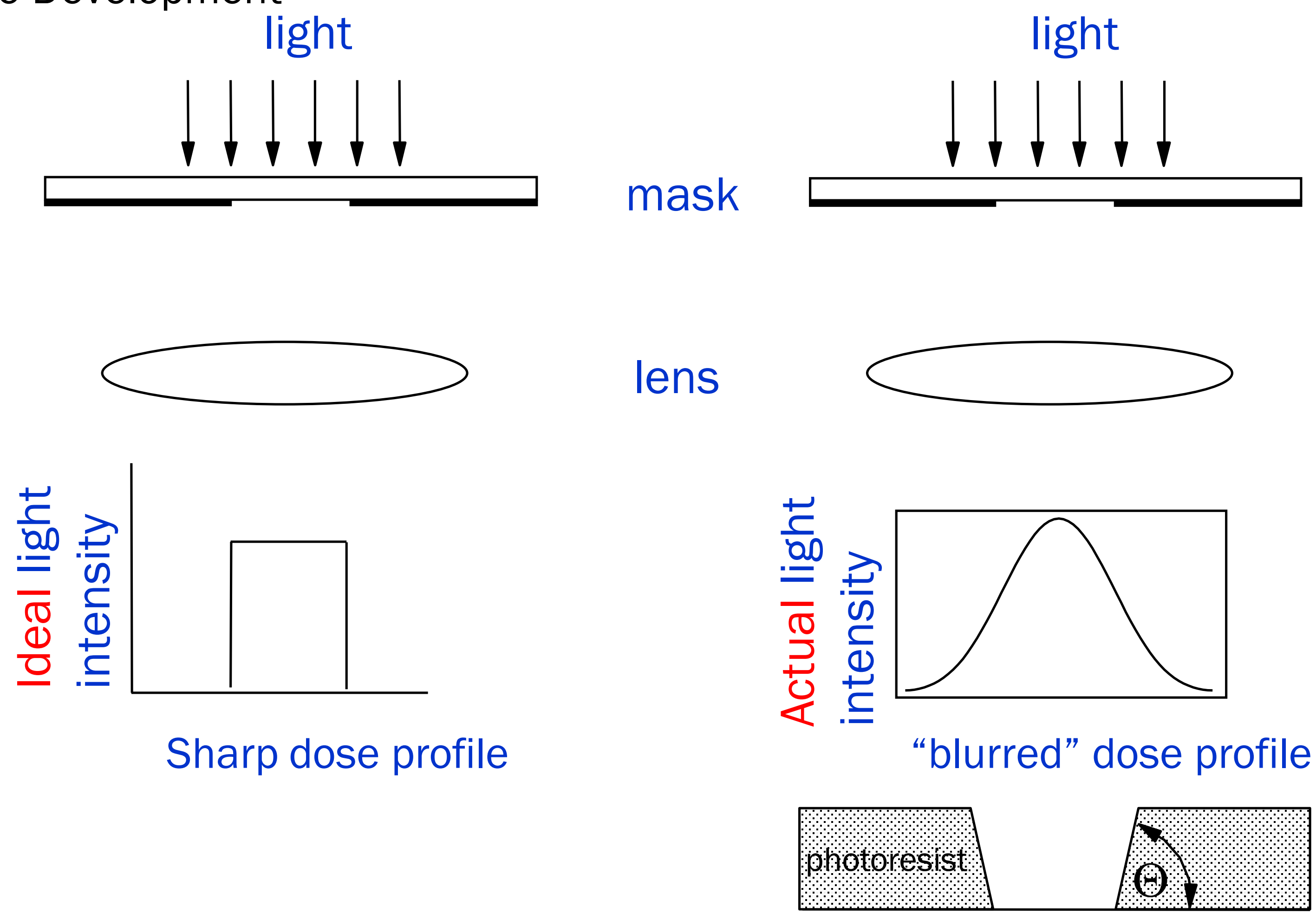
Understanding optical lithography



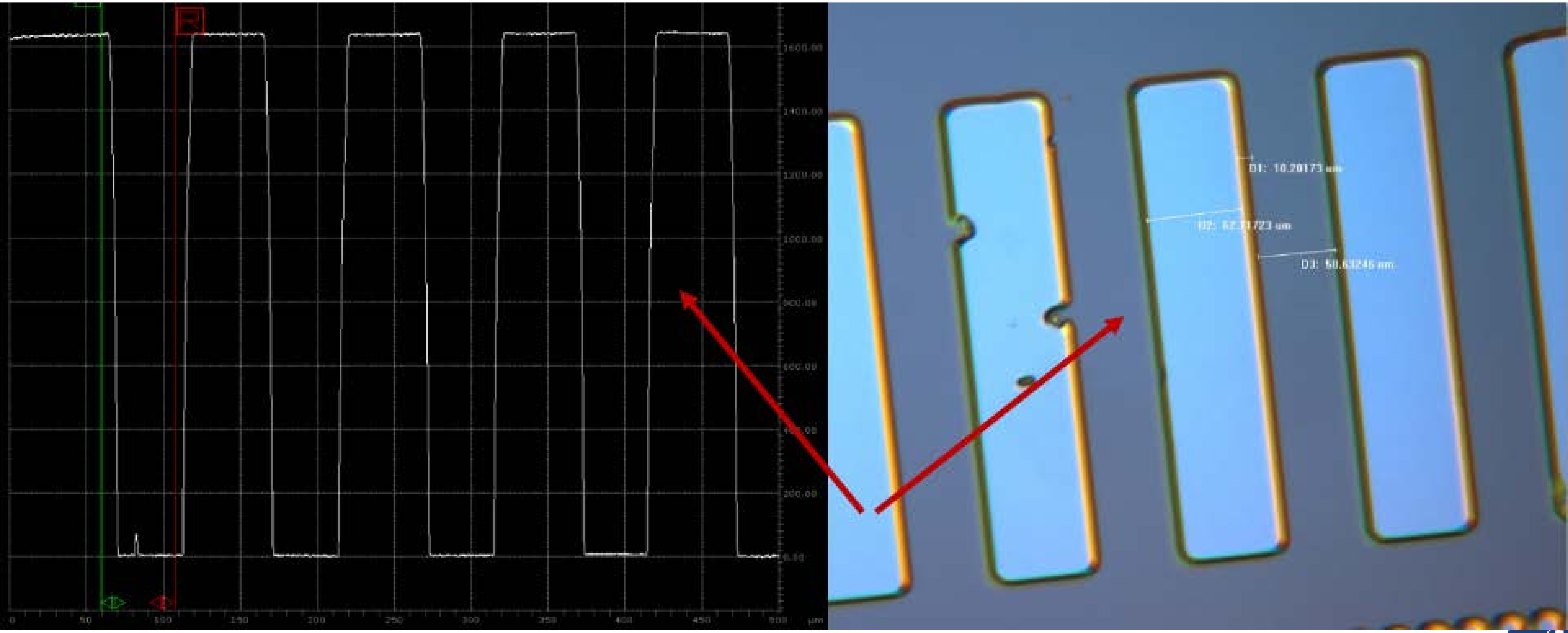


Understanding optical lithography

- The Development

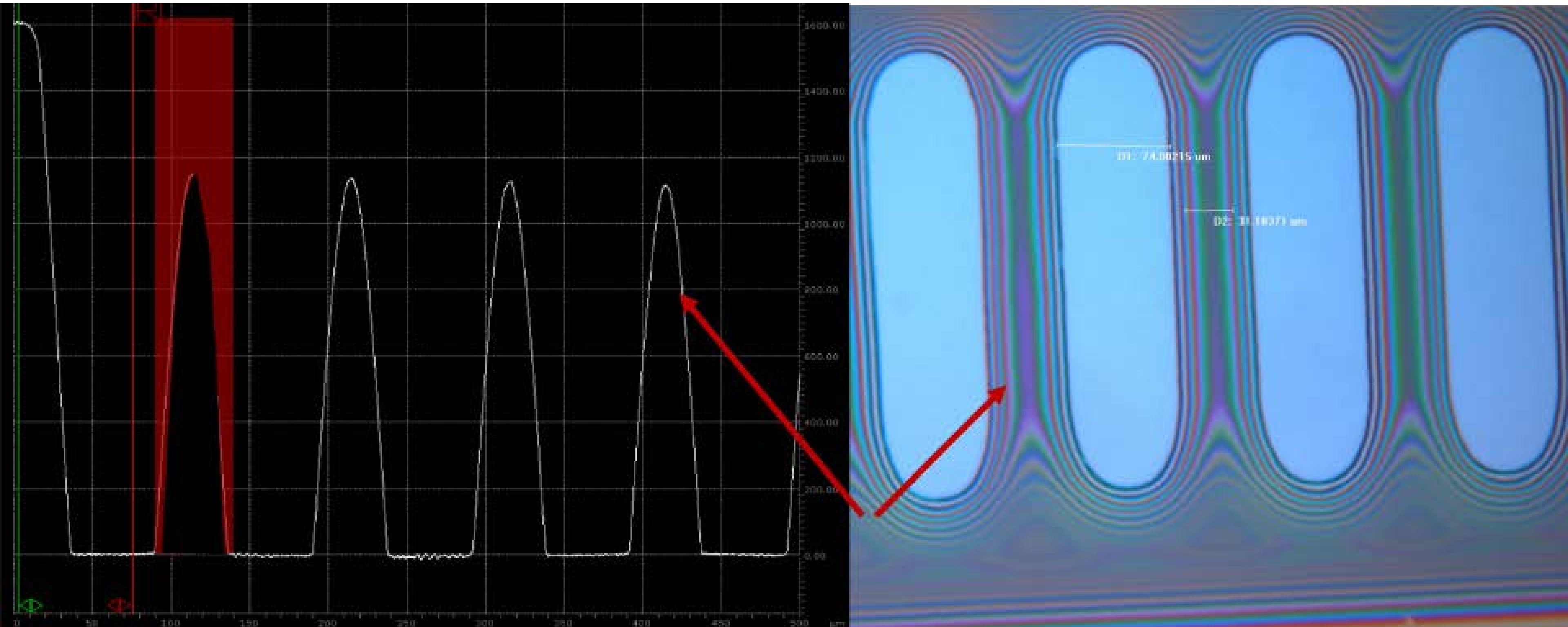


Understanding optical lithography



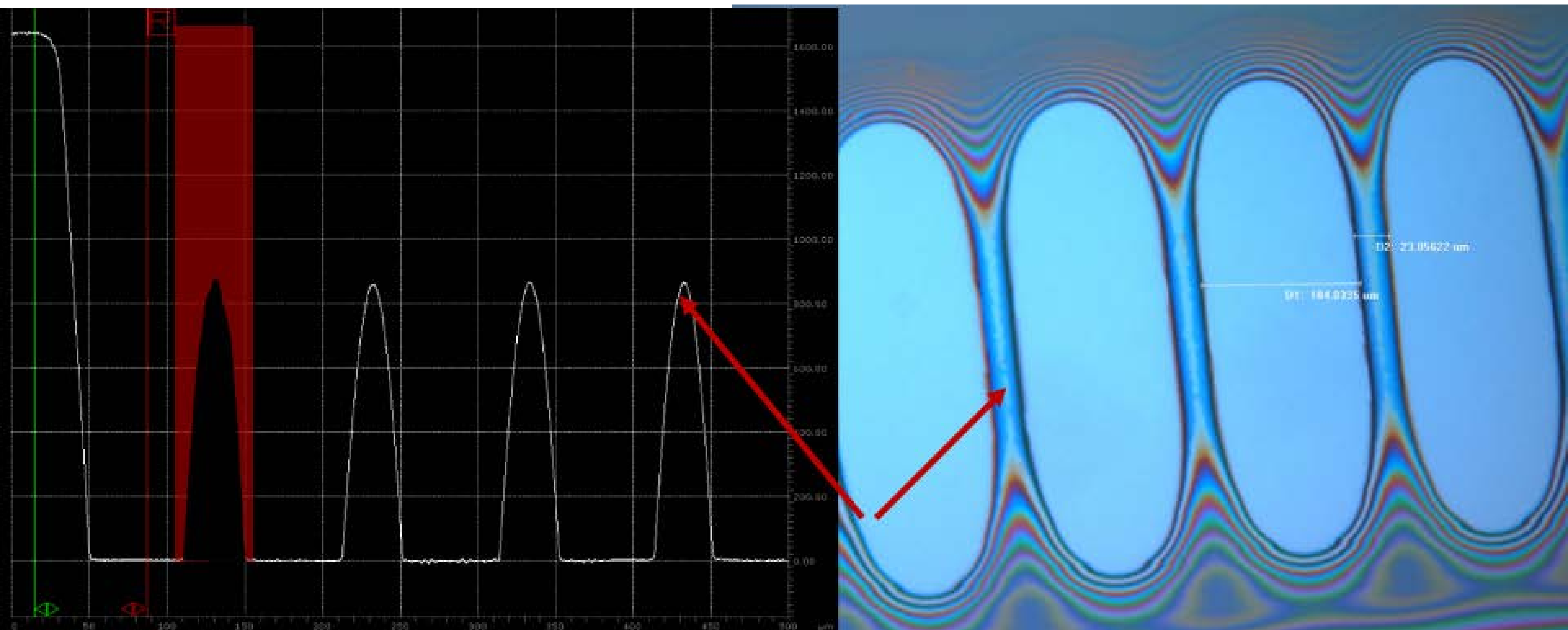
Optimum

Understanding optical lithography



Over exposed and/or over developed

Understanding optical lithography



Over exposed and/or over developed

Understanding optical lithography

- Ideal Exposure and Resolution

TABLE 1 Summary of the activities in Scenario 1 with the given parameter settings

Period (nm)	λ (nm)	NA	Exposure time (s)	Comments
600	193	0.5	2	Severe underexposure/underdevelopment
600	193	0.5	22.5	Ideal exposure time to obtain 300-nm spaces
300	193	0.5	22.5	Could not resolve (below limit)
300	193	0.96	22.5	Resolved: 146-nm-wide spaces
300	13	0.5	22.5	Resolved: 149-nm-wide spaces Notice the sharp slopes

Note: The rest of the parameters have default settings; students can hit "Set0" button to retrieve them.

Q3: Under the observations, comment on the famous formula of $R = k_1 \frac{\lambda}{NA}$ in the world of lithography.

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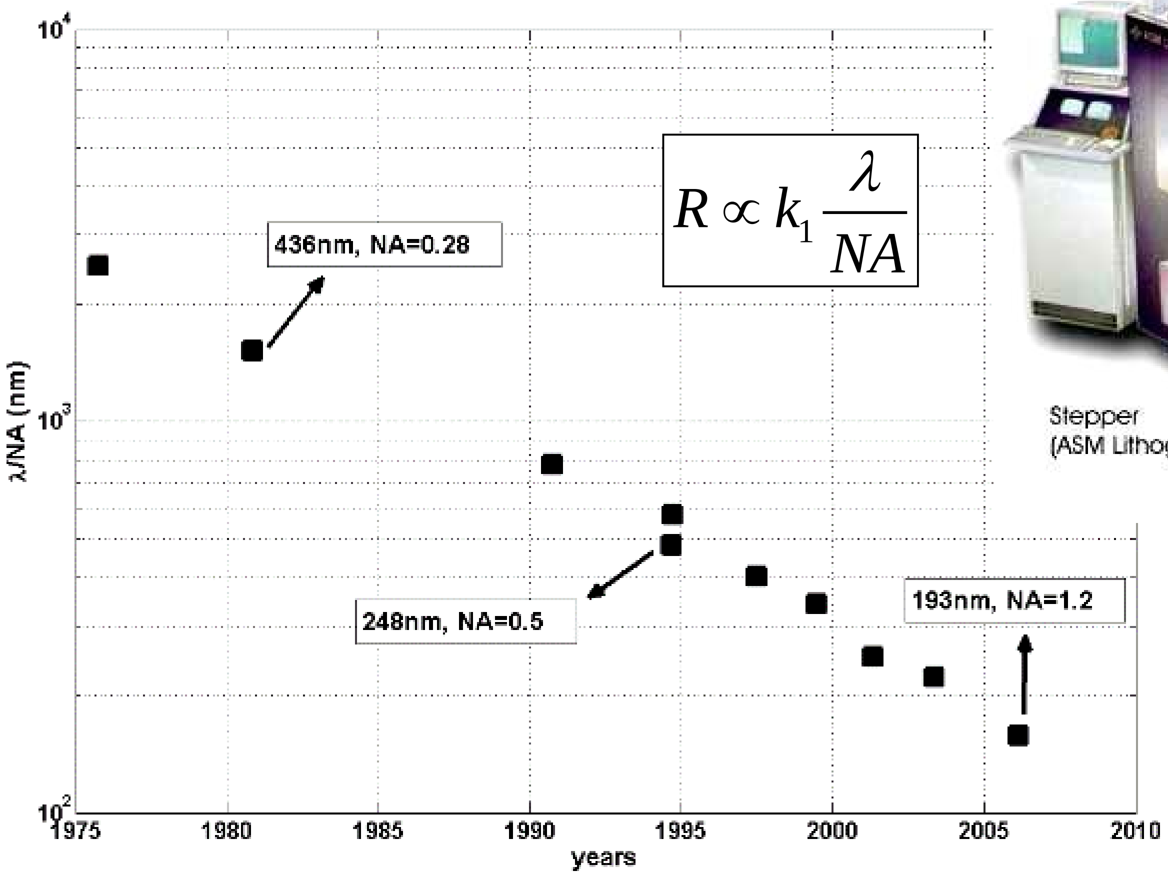
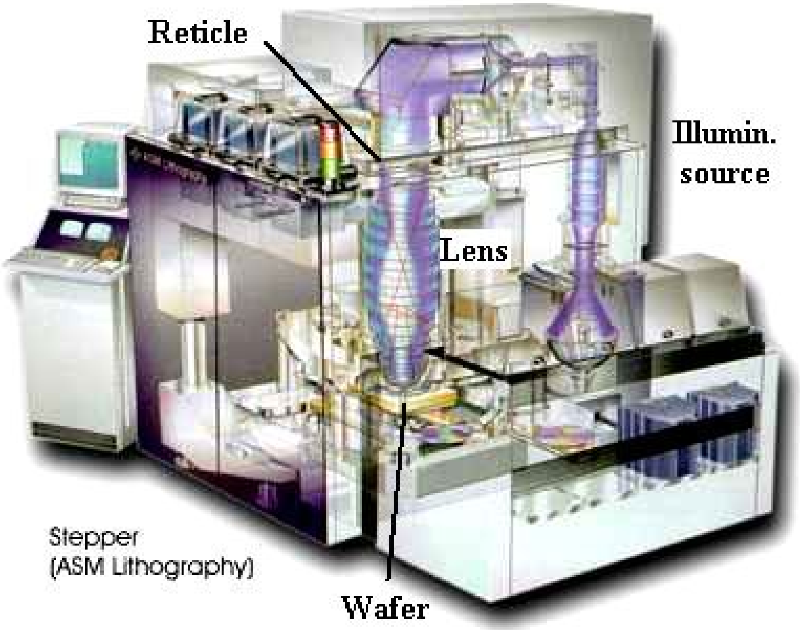
Understanding optical lithography

- Imaging with Lens

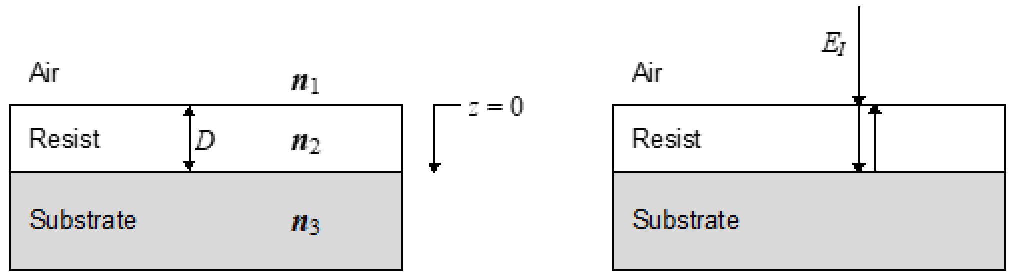


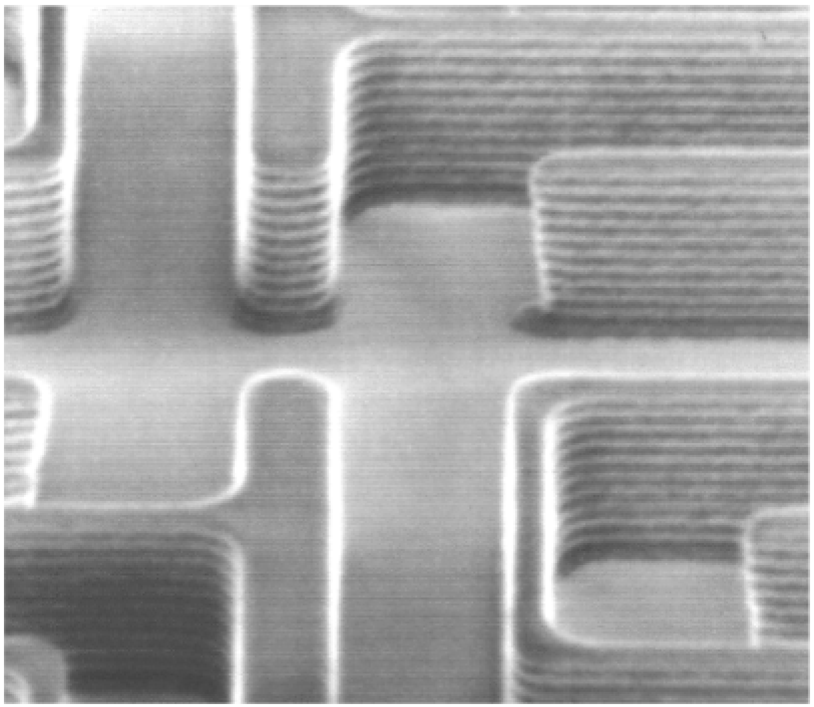
$$R \propto k_1 \frac{\lambda}{NA}$$

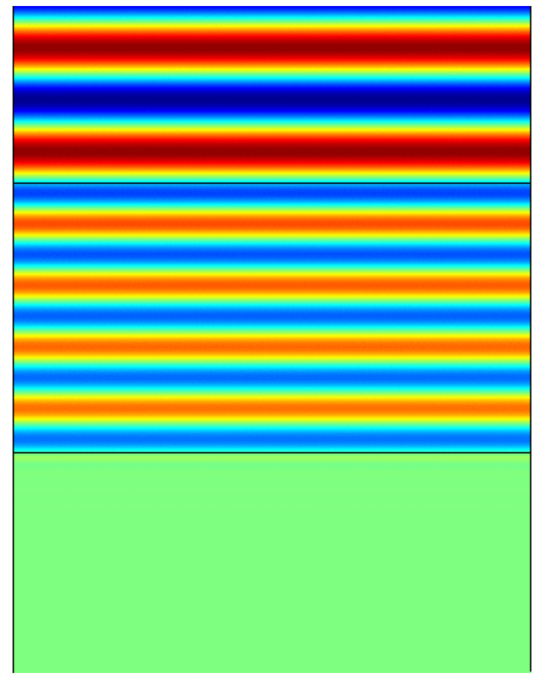


Understanding optical lithography

- BARC and TARC

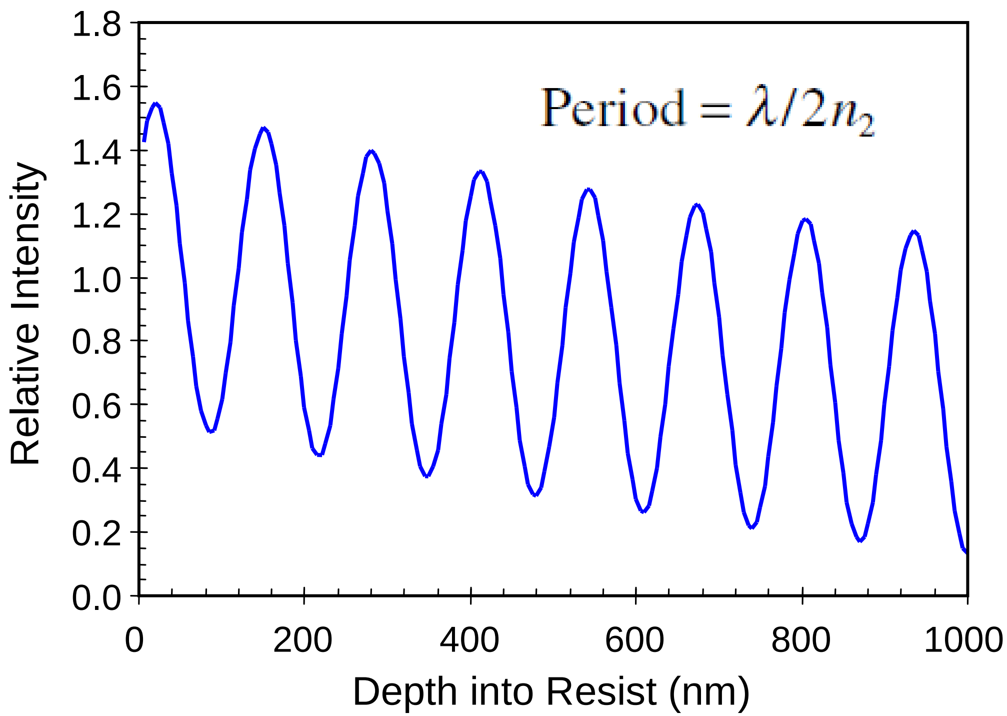


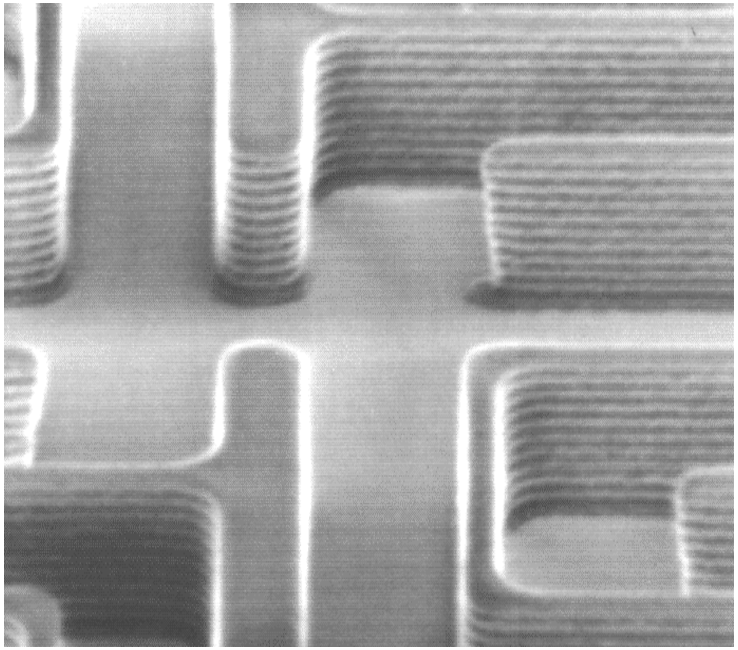




Understanding optical lithography

- BARC and TARC

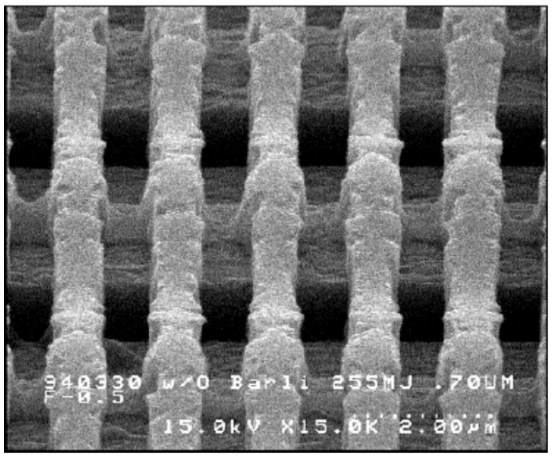


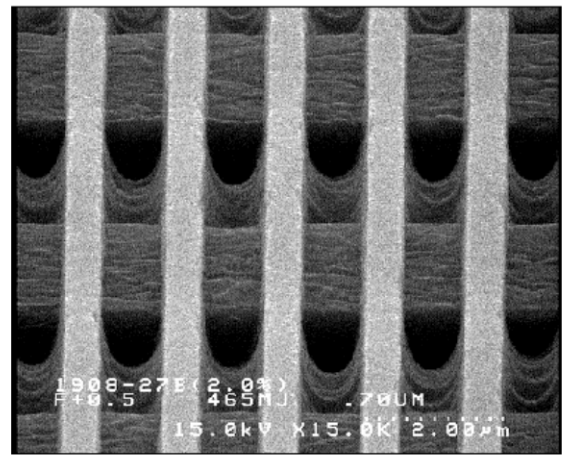


Standing wave intensity in one micron of photoresist on a silicon substrate for an i-line exposure.

Understanding optical lithography

- BARC and TARC





Imaging of lines and spaces over reflective topography without BARC (left) showing reflective notching, and with BARC (right) showing the reflective notching effectively suppressed.

Understanding optical lithography

- Road to Extreme UV

TABLE 2 Summary of the activities in Scenario 2 with the given parameter settings

Period (nm)	λ (nm)	Lamp intensity (mW cm^{-2})	Exposure time (s)	q (duty cycle)	Comments
300	193	10	25.5	0.5	Ideal exposure time to obtain 150-nm spaces
300	157	1.66	25.5	0.5	Underexposure gives a width of 45 nm only
300	157	1.66	150	0.5	Ideal exposure time to obtain 150-nm spaces
300	157	1.66	150	0.05	Severe underexposure
300	13	2	110	0.05	Ideal exposure time to obtain 15-nm spaces

Note: The rest of the parameters have default settings; students can hit "Set0" button to retrieve them.

Table 2.1 Excimer lasers and their relative power

Wavelength	Active gases	Relative power
157 nm	Molecular Fluorine (F_2)	10
193 nm	Argon fluoride (ArF)	60
248 nm	Krypton fluoride (KrF)	100
308 nm	Xenon chloride (XeCl)	50
351 nm	Xenon fluoride (XeF)	45

Did not pursue 157nm!
=> very lossy

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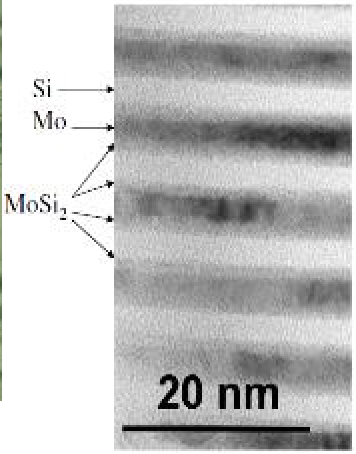
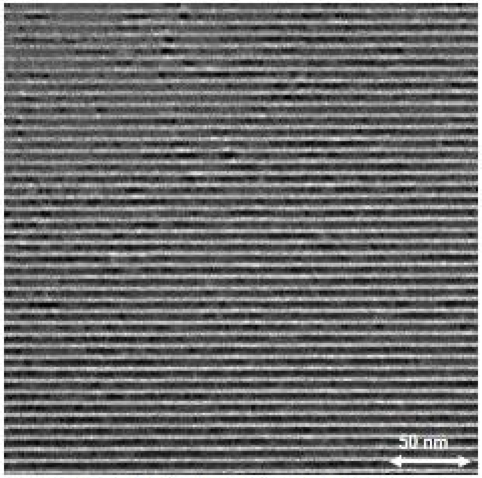
Understanding optical lithography

- Extreme UV Mirror Design

HR TEM reveals interfacial $MoSi_2$



TEM of a Mo/Si EUV mirror, N=50, Λ=6.8 nm



Deposited by magnetron sputtering

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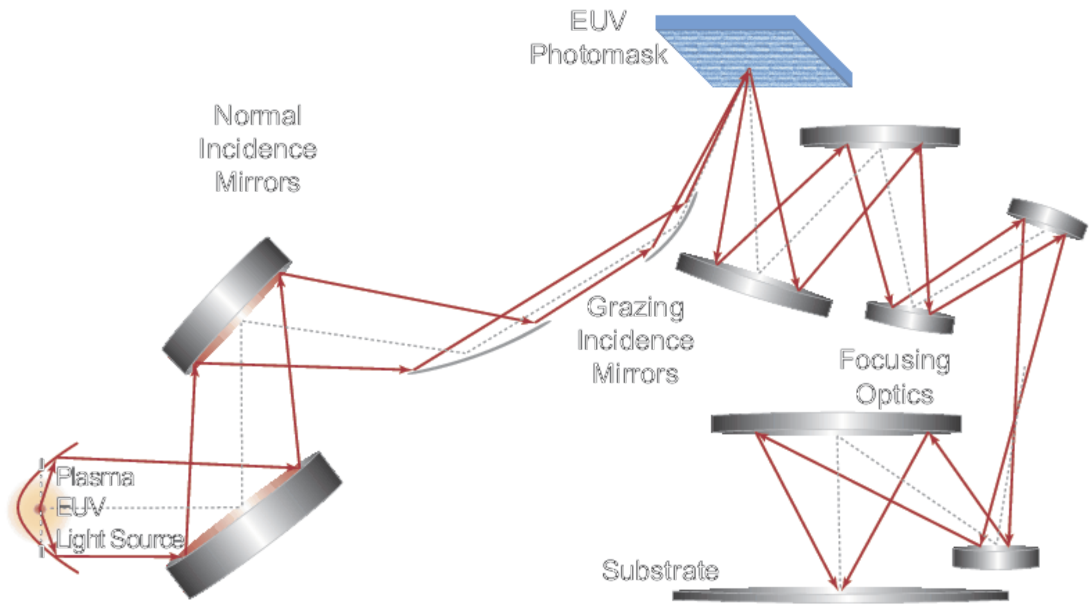
Understanding optical lithography

- Road to Extreme UV



Under vacuum

Understanding optical lithography

- Extreme UV Mirror Design

TABLE 11 Summary of the activities in Scenario 13 with the given parameter settings

N alternating pairs	Stack	Comments
50	Mo/Si	69.25% reflection
20	Mo/Si	31.49% reflection
50	Mo/SiO_2	34.57% reflection, peak shifted to 13.18 nm

Note: High *Z* atom film thickness: 2.76 nm; low *Z* atom film thickness: 4.14 nm, normal incidence angle.

Reflection_UV.m

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Understanding optical lithography

- Dill Parameters

TABLE 4 Summary of the activities in Scenario 4 with the given parameter settings

Dill parameter *C* ($cm^2\ mJ^{-1}$)	**Exposure time (s)**	**Comments**
0.25	25.5	Ideal exposure time to obtain 150-nm spaces
0.1	25.5	Underexposure gives a width of 112 nm only
0.1	62	Ideal exposure time to obtain 150-nm spaces

Note: The rest of the parameters have default settings; students can hit "Set0" button to retrieve them.

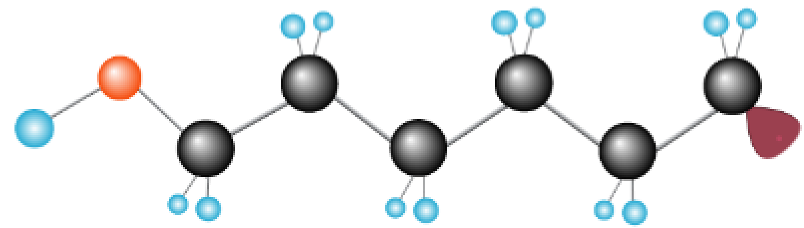
Understanding optical lithography

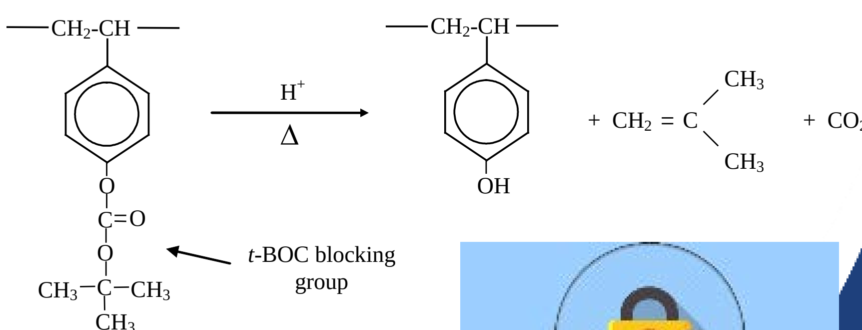
- Contrast

TABLE 5 Summary of the activities in Scenario 5 with the given parameter settings

Polymer chain length (n)	Exposure time (s)	Comments
2	25.5	156-nm width Sidewall angle = 57°
2	30	161-nm width Sidewall angle = 56°
2	35	166-nm width Sidewall angle = 56°
30	25.5	149-nm width Sidewall angle = 64°
30	30	154-nm width Sidewall angle = 67°
30	35	159-nm width Sidewall angle = 65°

Note: The rest of the parameters have default settings; students can hit "Set0" button to retrieve them.





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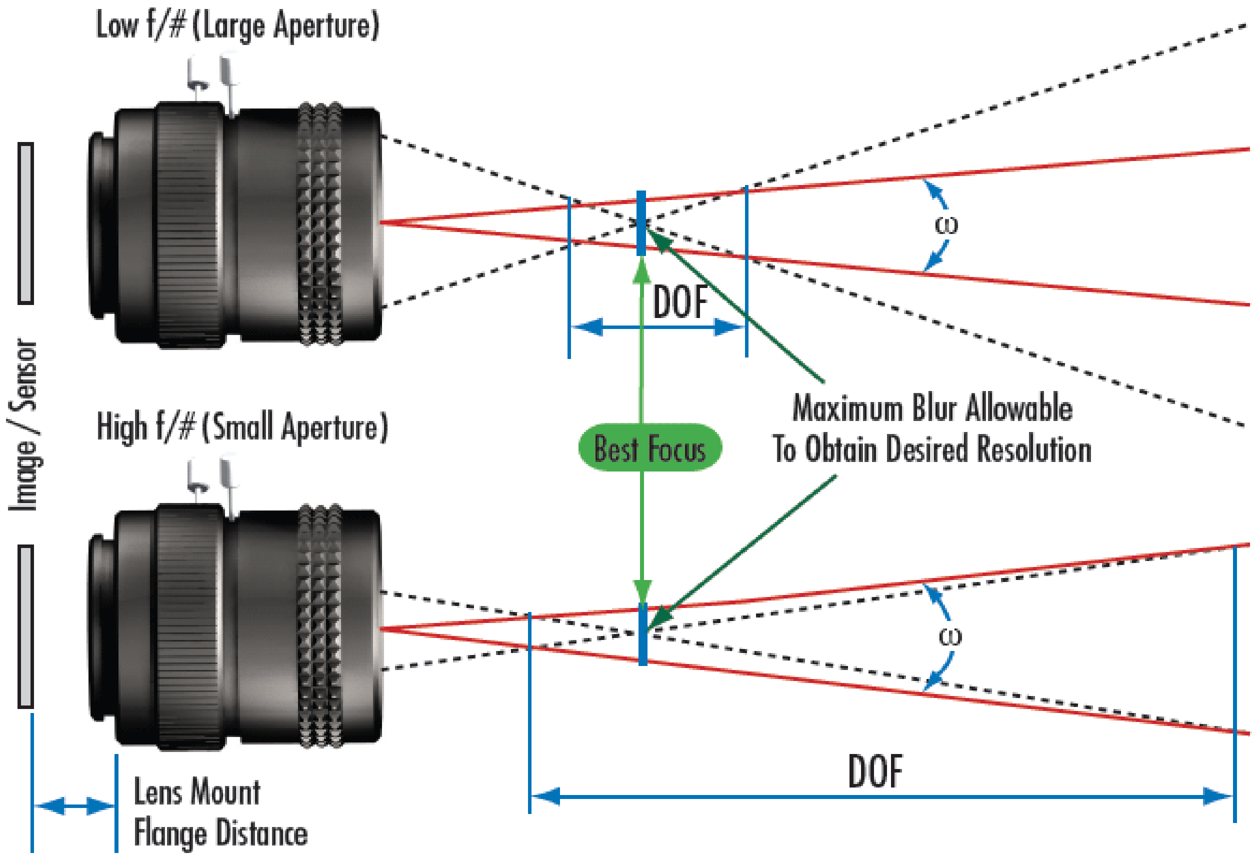
Understanding optical lithography

- Depth of Focus



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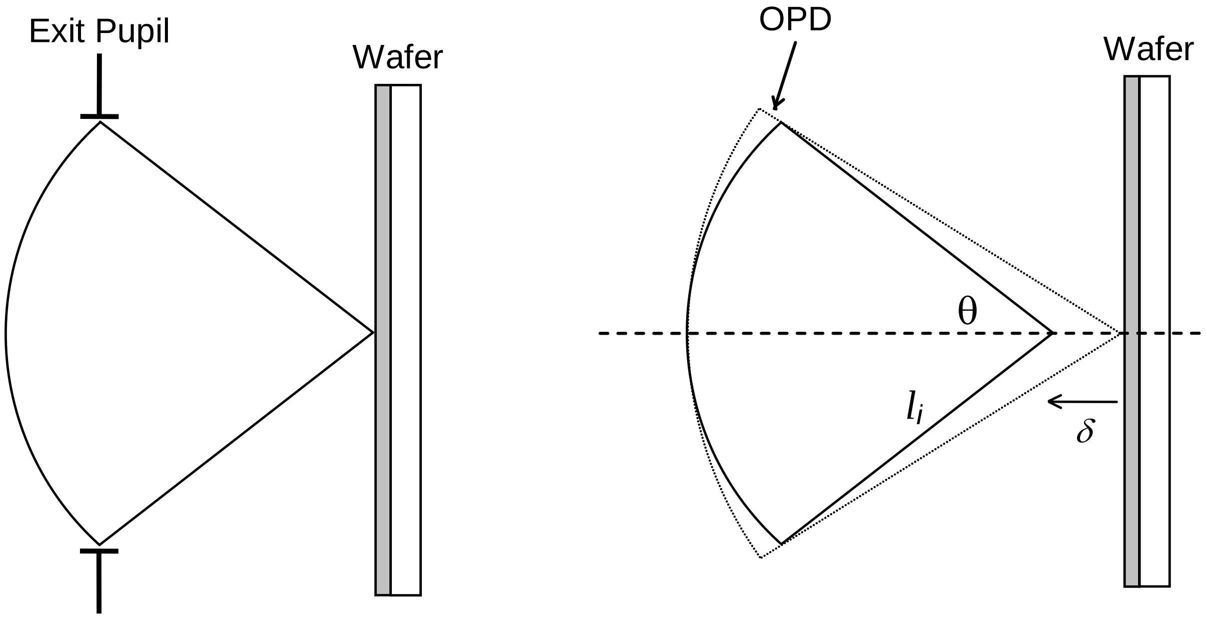
Understanding optical lithography

- Depth of Focus



Understanding optical lithography

- Immersion Lithography

https://www.youtube.com/watch?v=It0N9t-j34k

Understanding optical lithography

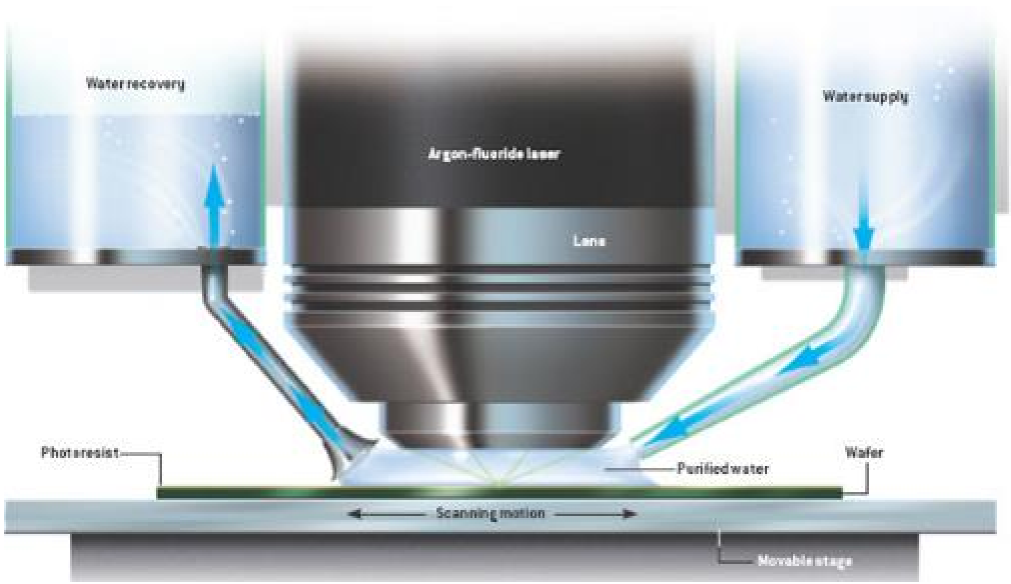
- Immersion Lithography

From research idea

to development

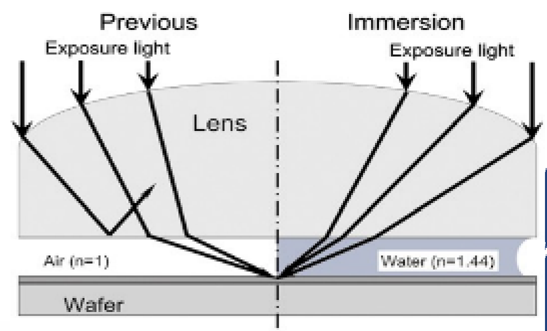
Understanding optical lithography

- Immersion Lithography



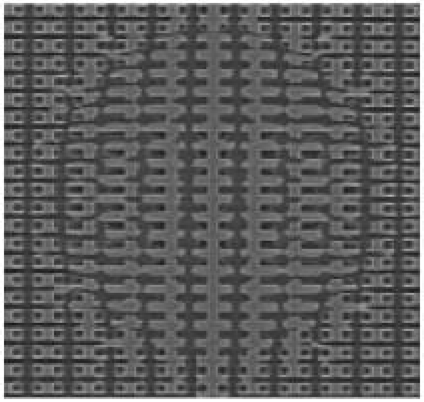
Gary Stix Scientific American, vol. 293 pp. 64-67, 2005.

– A few words on lenses and refraction: Immersion Lithography
  – Water has a refractive index of 1.44, new liquids should be higher than 1.6
  – Should not have a large dn/dT
  – Should have at least 90% transparency
  – Should have a viscosity close to water
  – Should not wet the surface of PR → critical for lens movement
  – Should not be soluble in air
  – Minimum interaction with PR
  – Should not be corrosive
  – Should be safe to handle, should be stable under UV
  – Supply and Cost



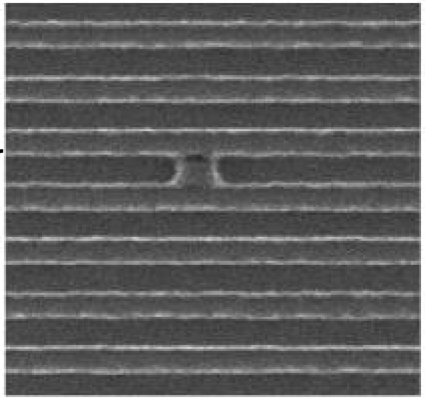
Understanding optical lithography

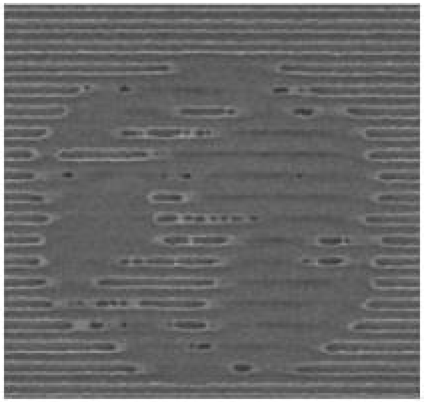
- Immersion Lithography



Air bubbles

Resist/TC – water interaction





Water marks and drying stains
(Try to make super-hydrophilic surface)

Particles from water