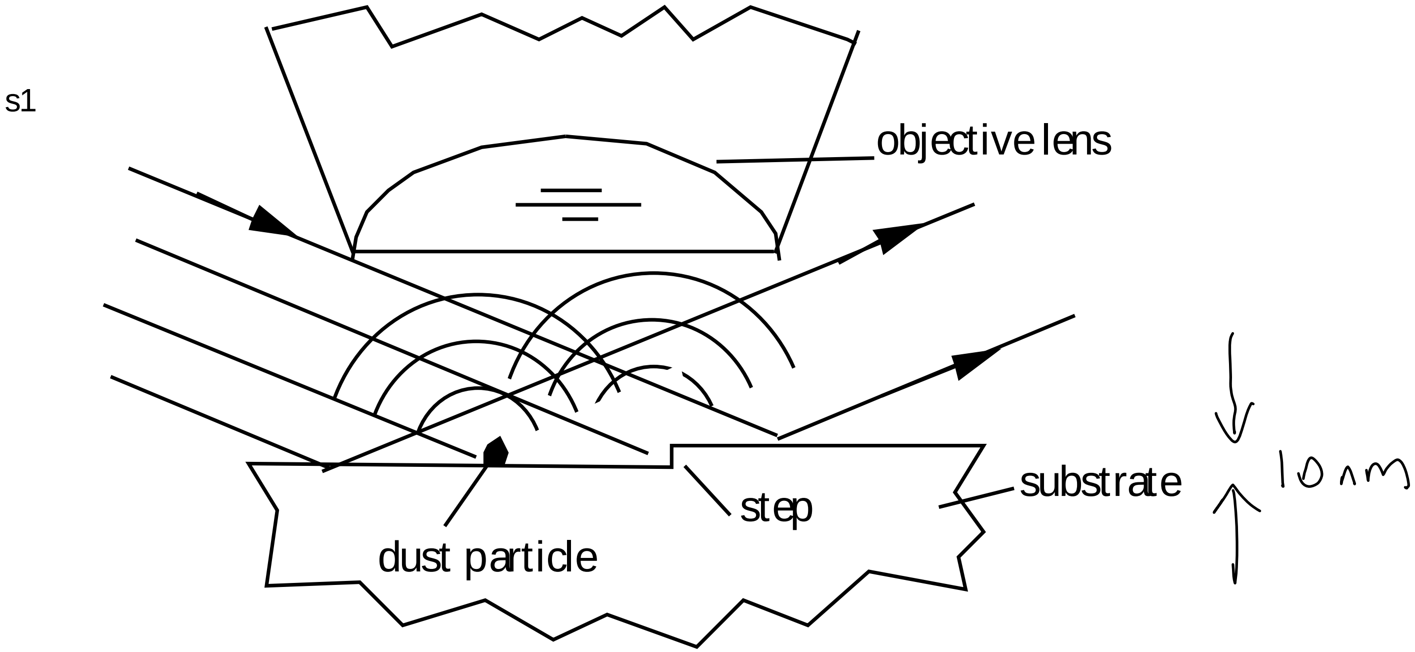
Nanometer Scale Patterning and Processing

Spring 2016

Lecture 12

Optical Lithography - Contrast and Resolution in Microscopy and Lithography Systems

Dark Field Microscopy

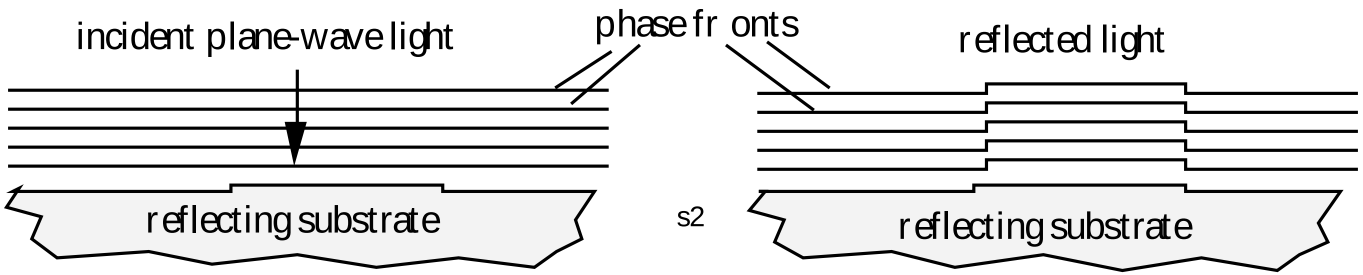


Z-resolution

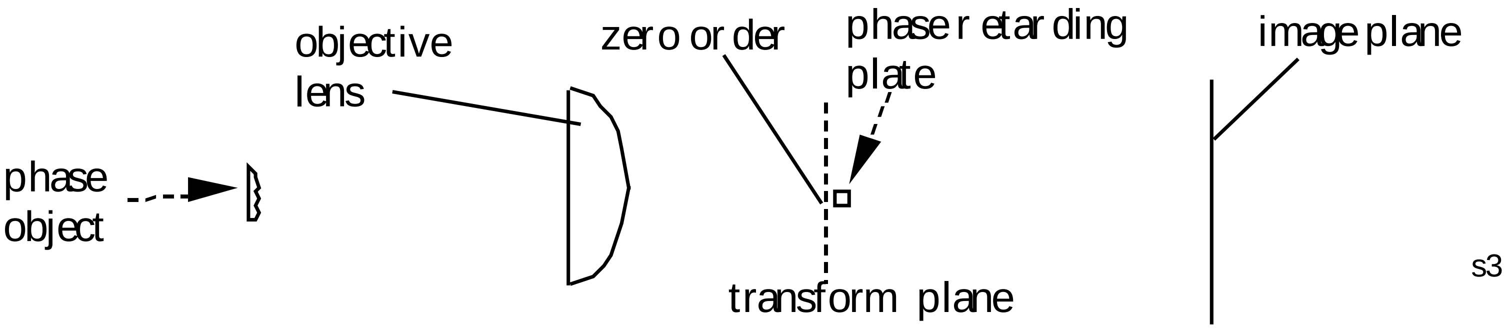
- microsteps about 10 nm high, and (isolated) dust particles < 100 nm, can be seen.
- 10 nm resolution in *z* direction only

Spatial Filtering

- Fritz Zernike, Nobel Prize in 1954



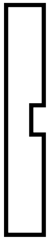
Phase objects cannot be seen as detectors (including eyes) only respond to intensity



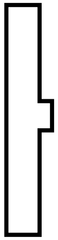
Phase Shifters

Two types of phase plates made of glass:

s4

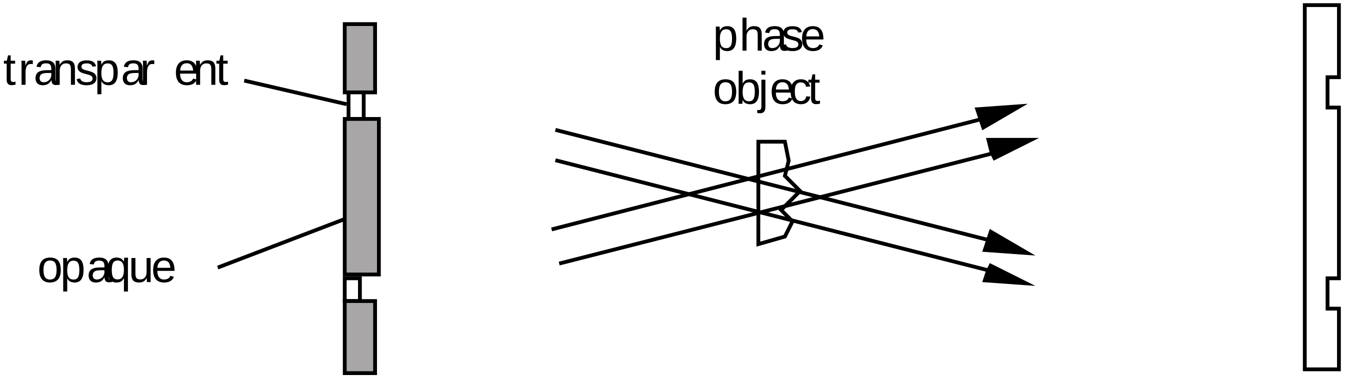


This one advances the phase of the zero order by $\lambda/4$.



This one retards the phase of the zero order by $\lambda/4$.

- Oblique, azimuthally symmetric illumination in high resolution optical microscopes

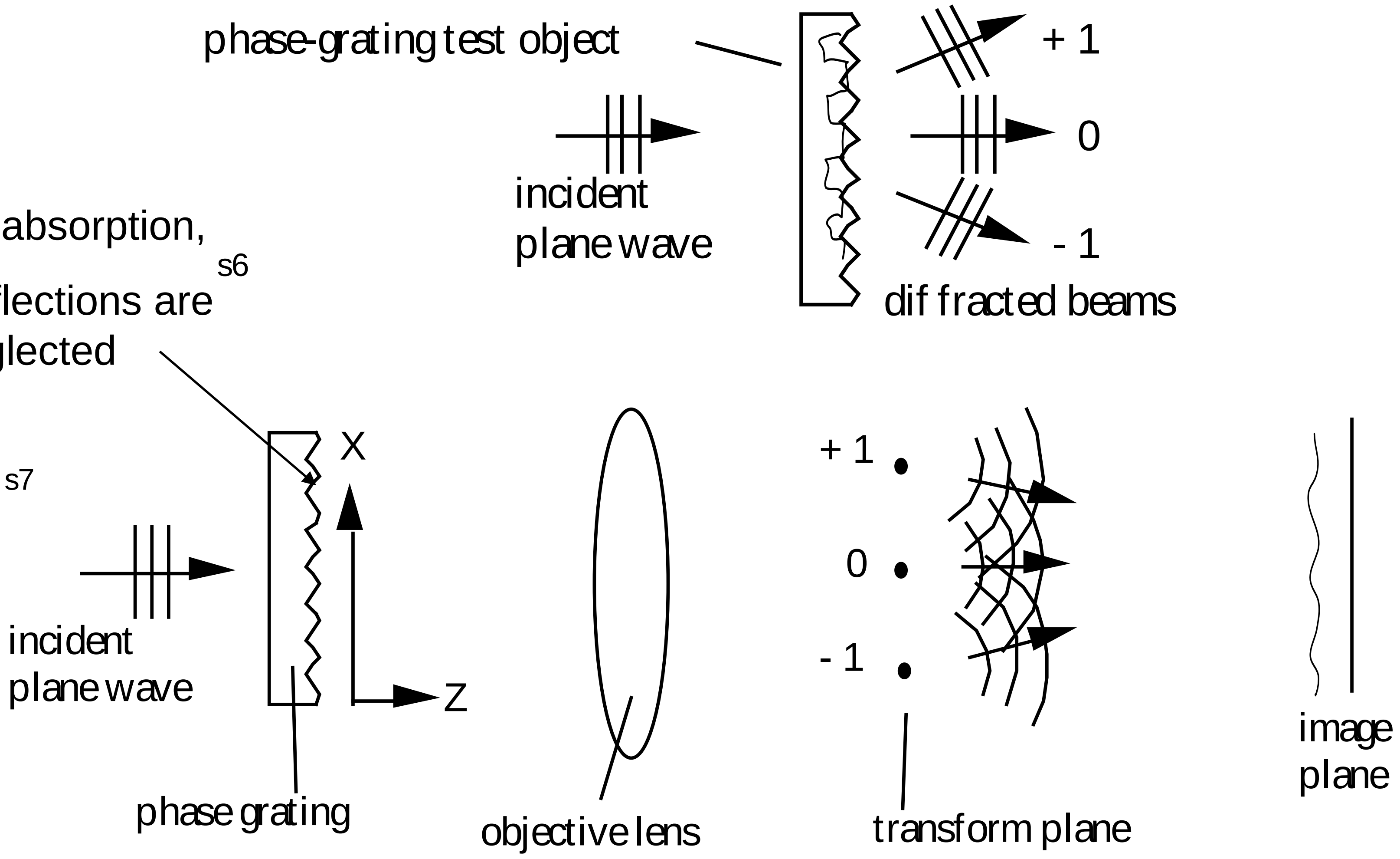


transparent ring at back focal plane of the condenser illuminator

s5

glass plate in the transform plane of the objective lens

Review of image formation



phase-grating test object

incident
plane wave

+ 1

0

- 1

dif fracted beams

No absorption,

s6

Reflections are
neglected

s7

incident
plane wave

X

Z

phase grating

objective lens

+ 1

0

- 1

transform plane

image
plane

Some Math

s9

$$E(x,y,z,t) = Ae^{j(k_x x + k_y y + k_z z - \omega t + \phi)}.$$

Zeroth order:

$E_0(x,y,0)=Ae^{j(\phi-\omega t)}$

$$k_x = k_y = 0$$

$$k_z = \frac{2\pi}{\lambda}$$

At the plane z = 0,

$$E_{+1}(x) = \varepsilon\, e^{j(k_x x - \omega t)}$$

$$E_{-1}(x) = \varepsilon\, e^{j(-k_x x - \omega t)}$$

where, in general, ε is small compared to A.

ϕ is the phase shift between the zeroth and 1st order diffraction, and is usually 90°

More Math

$$E_{tot}(x) = E_0 + E_{+1}(x) + E_{-1}(x)$$

$$I(x) = E_{tot}\ E^*{}_{tot}$$

$$I(x) = |A|^2 + 2|\varepsilon|^2 + \underbrace{E_0\ E^*_{+1} + E^*_0\ E_{+1}}_{a} + \underbrace{E_0\ E^*_{-1} + E^*_0\ E_{-1}}_{b} + \underbrace{E_{+1}\ E^*_{-1} + E^*_{+1}\ E_{-1}}_{c}$$

$$a = 2A\varepsilon\cos(\phi - k_x x)$$

$$b = 2A\varepsilon\cos(\phi + k_x x)$$

$$c = 2\varepsilon^2\cos(2k_x x)$$

$$a + b = 4A\varepsilon\left[\cos\phi\cos(k_x x)\right]$$

Artifacts, small in amplitude

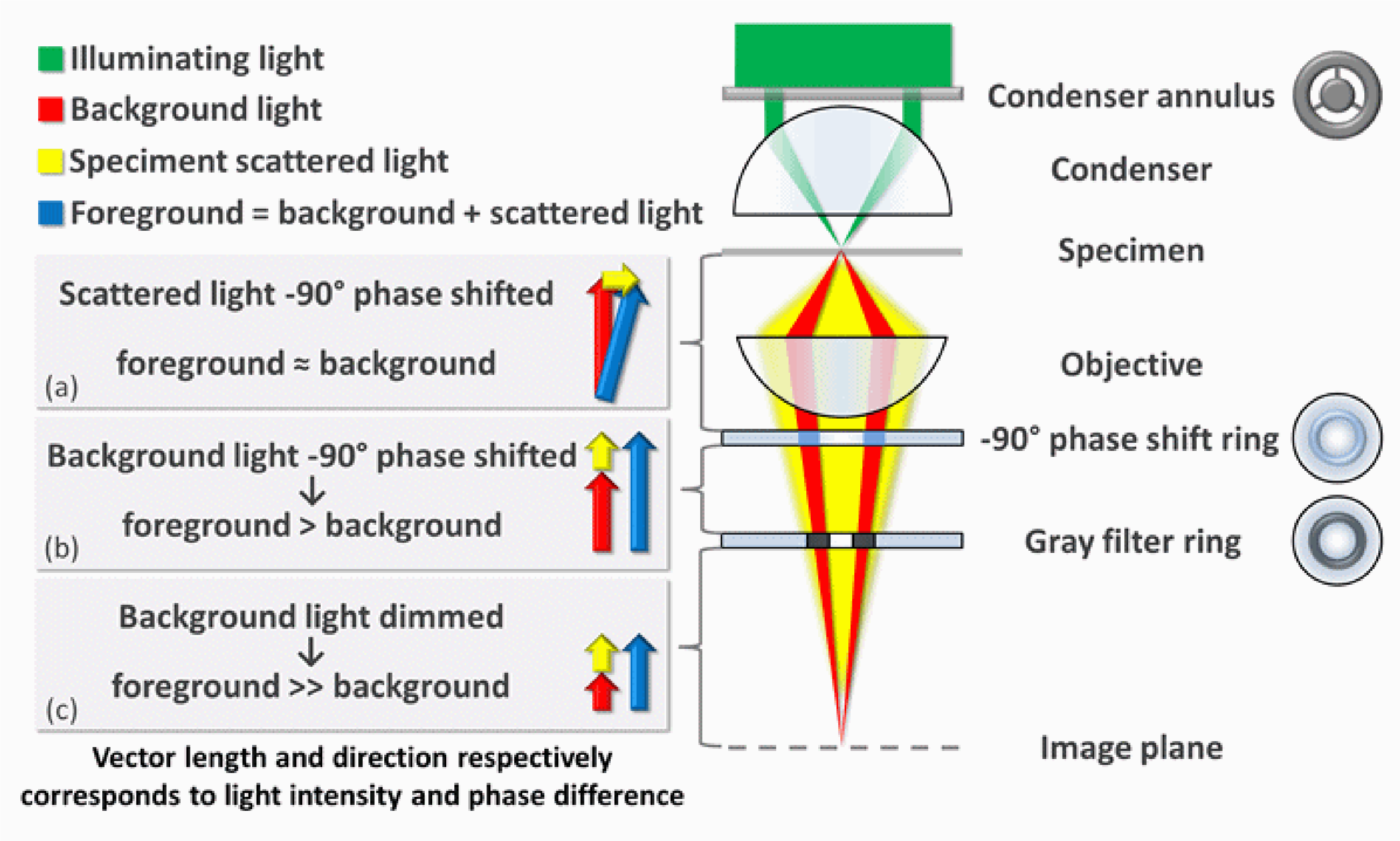
$$I(x) = A^2 + 2\varepsilon^2 + 4A\varepsilon[\cos\phi\cos(k_x x)] + 2\varepsilon^2\cos(2k_x x)$$

$\phi = \pm\pi/2$ or $\pm 3\pi/2$ → No image contrast

If we shift ϕ by ± π /2 or λ/4:

$$I(x) = A^2 + 2\varepsilon^2 + 4A\varepsilon\cos(k_x x)$$ → Contrast!

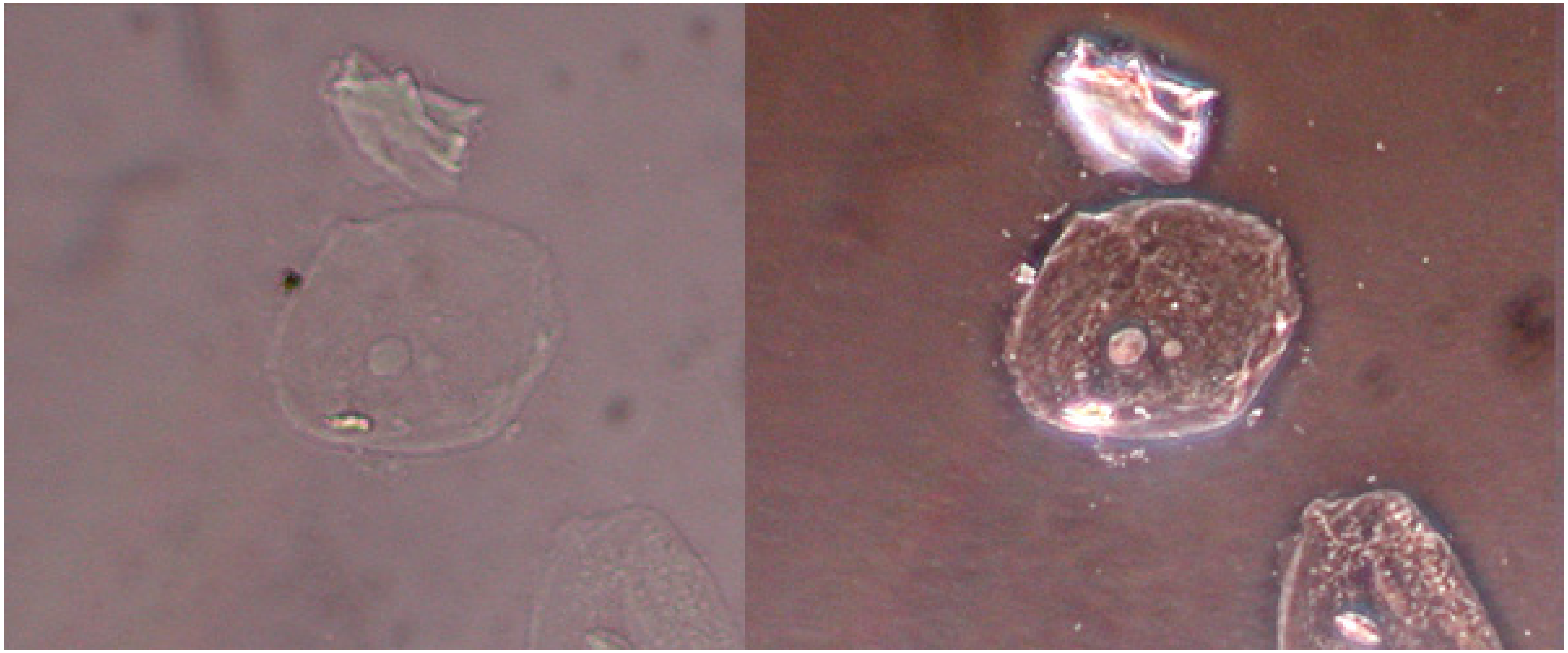
Working Principle of Phase Contrast Microscopy



Vector length and direction respectively corresponds to light intensity and phase difference

https://commons.wikimedia.org/wiki/File:Working_principle_of_phase_contrast_microscopy.gif

Advantage of phase contrast Microscopy

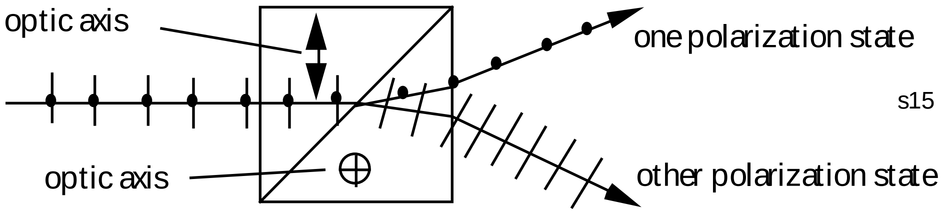


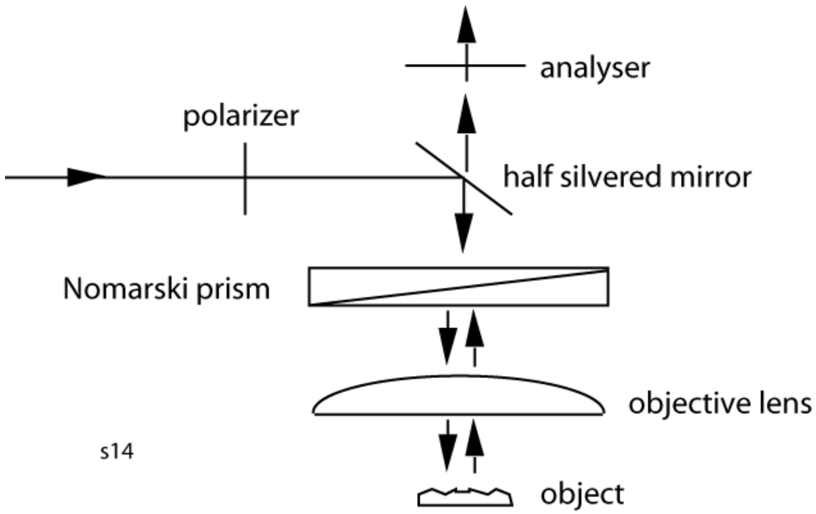
The same cells imaged with traditional bright-field microscopy (left) and with phase-contrast microscopy (right)

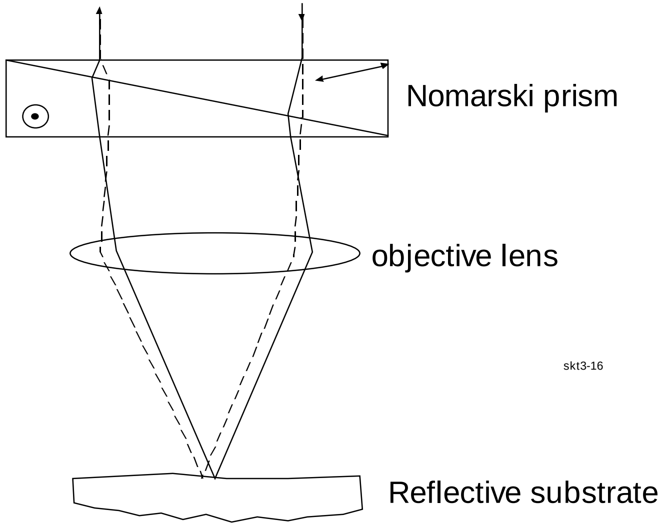
https://commons.wikimedia.org/wiki/File:Brightfield_phase_contrast_cell_image.jpg

Nomarski Differential-Interference Contrast (DIC)

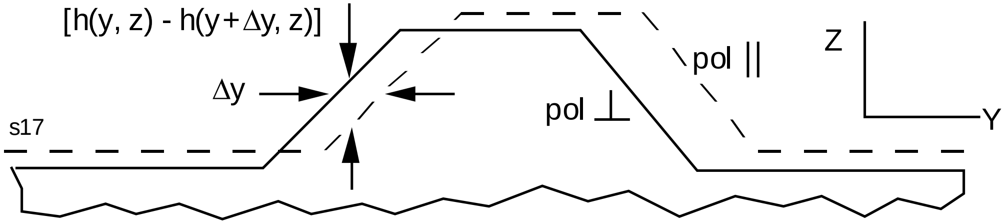
Nomarski or Wollaston Prism



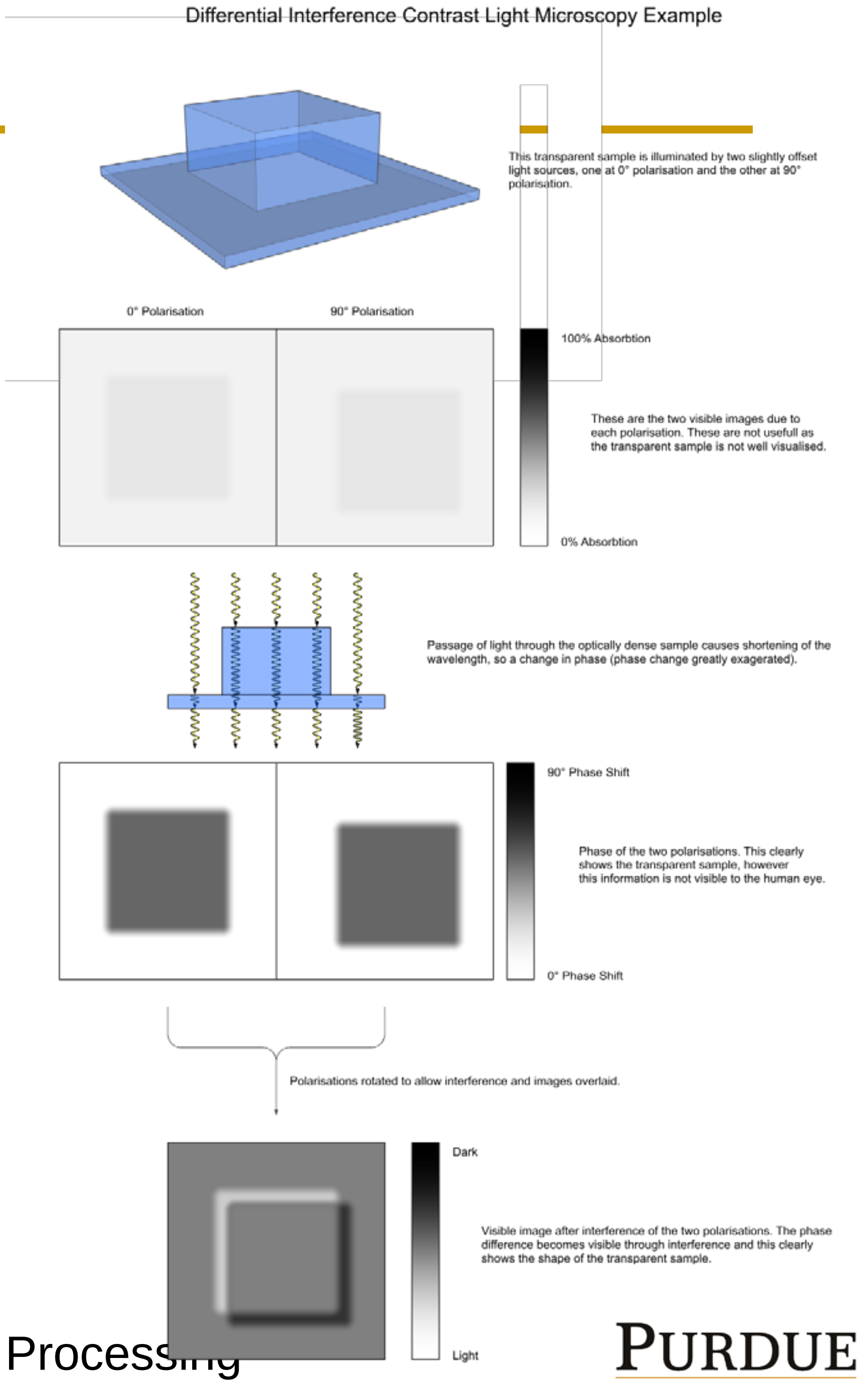




Contrast Mechanism



- Phase shift due to sample surface height variations:
  $\alpha(y,z) = 4\pi[h(y,z) - h(y + \Delta y,z)]/\lambda$.
- The system is adjusted so that Δy is less than the resolution, i.e., $\Delta y < p = \lambda/2NA$.
- Differences in slope show up as differences in color or shading.
- Surface asperities 0.4 nm (4 Å) high are detectable.


Differential Interference Contrast Light Microscopy Example

This transparent sample is illuminated by two slightly offset light sources, one at 0° polarisation and the other at 90° polarisation.

These are the two visible images due to each polarisation. These are not usefull as the transparent sample is not well visualised.

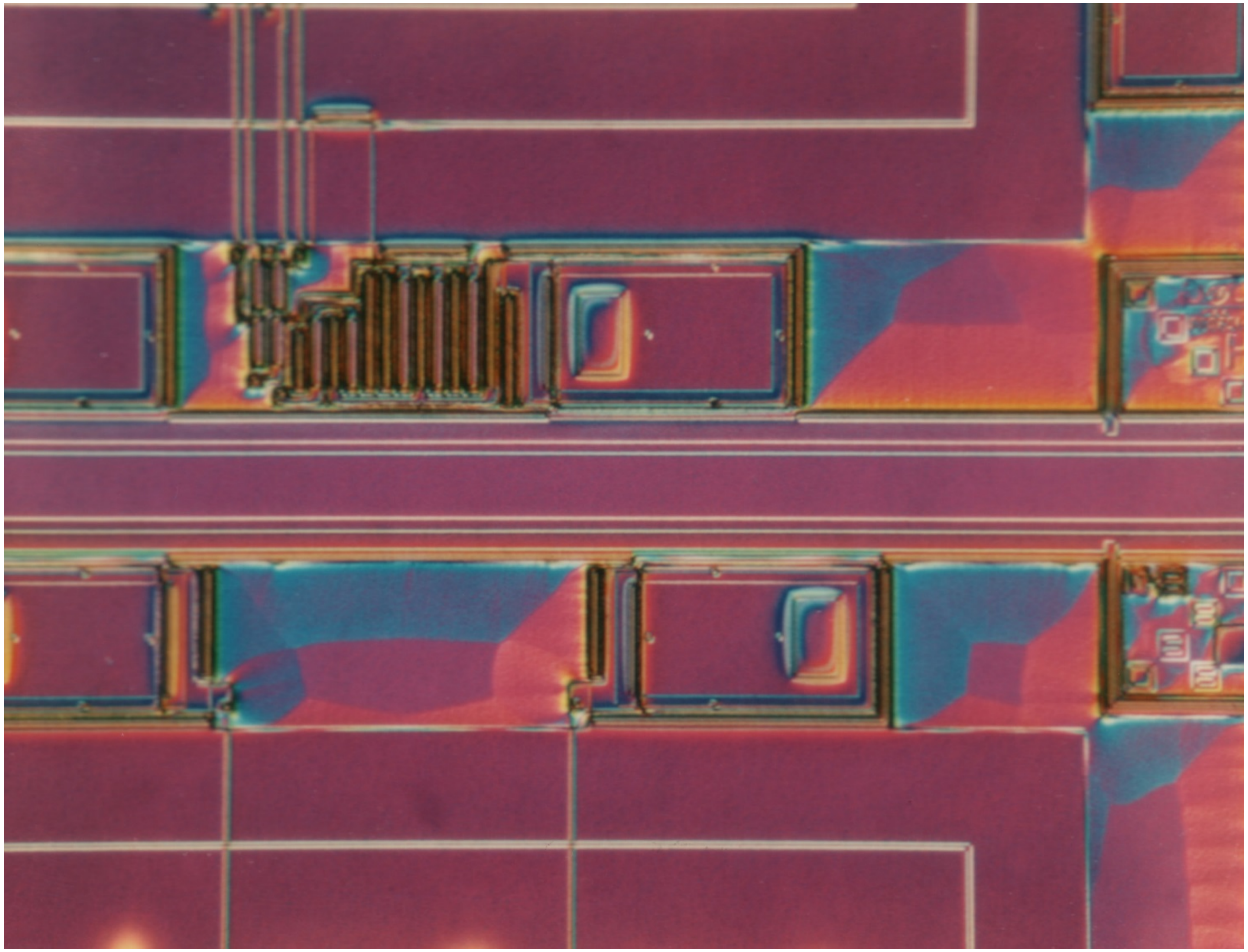
Passage of light through the optically dense sample causes shortening of the wavelength, so a change in phase (phase change greatly exagerated).

Phase of the two polarisations. This clearly shows the transparent sample, however this information is not visible to the human eye.

Polarisations rotated to allow interference and images overlaid.

Visible image after interference of the two polarisations. The phase difference becomes visible through interference and this clearly shows the shape of the transparent sample.

DIC suitable for inspecting Semiconductor Wafers



Partially developed photoresist via Nomarski DIC

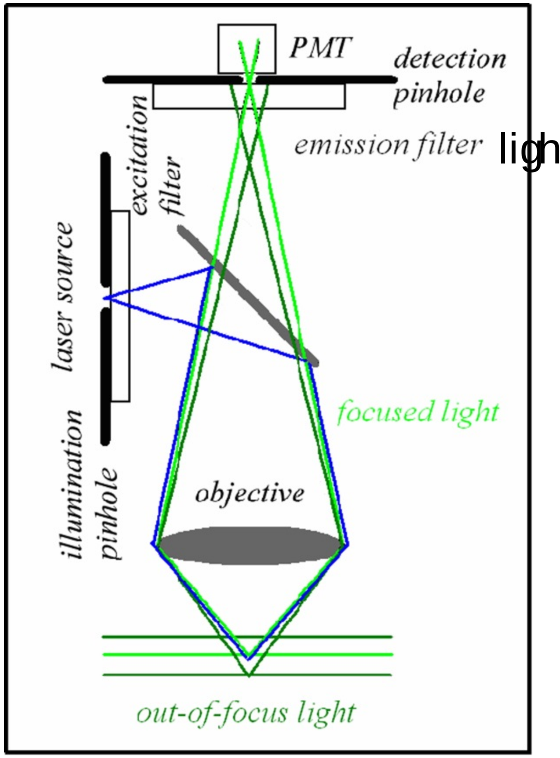
https://commons.wikimedia.org/wiki/File:Al_photoresist_pattern_developed_via_Nomarski_DIC.jpg

DIC inspection of Semiconductor Wafers

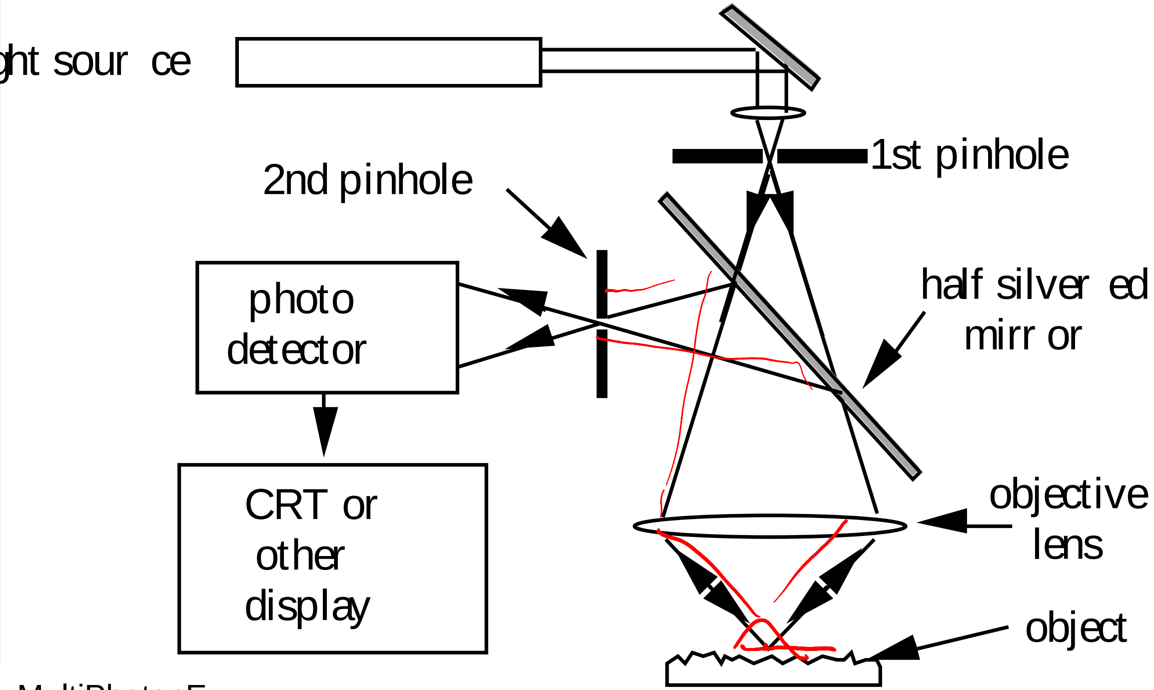
Aluminum-Silicon alloying pit made visible via Nomarski DIC

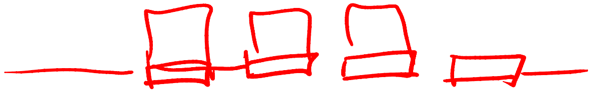
https://commons.wikimedia.org/wiki/File:1-1-1_Pits_from_Aluminum_Alloying.jpg

Scanning Confocal Optical Microscope



https://commons.wikimedia.org/wiki/File:MultiPhotonExcitation-Fig3-doi10.1186slash1475-925X-5-36.JPEG





- Does not increase the resolution!
- Increases contrast by discarding out-of-focus light and enhancing the contrast of edges.

Resolution Limit set by the Wavelength of Light

Fourier expansion of a general Electrical field with frequency ω

$$\mathbf{E}(\mathbf{r},t) = \sum_{\sigma \boxed{k_x,k_y}} \mathbf{E}_\sigma(k_x,k_y) \times \exp\left(\boxed{\underline{ik_z z}} + ik_x x + ik_y y - \boxed{i\omega t}\right)$$

Assume *z* is the axis of the lens, Maxwell's equations give:

dispersion $(\vec{k})^2 = \frac{\omega^2}{c^2}$

$$k_z = +\sqrt{\omega^2 c^{-2} - k_x^2 - k_y^2}, \qquad \omega^2 c^{-2} > k_x^2 + k_y^2 .$$

In order for light to propagate along *z* direction:

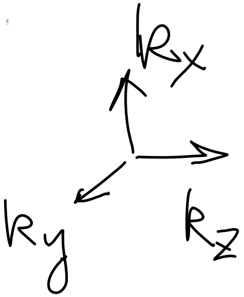
$$\underline{\underline{k_z}} = +\boxed{i\sqrt{k_x^2 + k_y^2}} - \omega^2 c^{-2}, \qquad \omega^2 c^{-2} < k_x^2 + k_y^2$$

Image contrast is set by k_x and k_y

k_z does not contribute to image formation!

$$k_x^2 + k_y^2 < \omega^2 c^{-2}$$

assume $k_y = 0$



Resolution is set by the highest spatial frequency!

$$\frac{2\pi}{\omega/c} = \frac{2\pi}{\hat{k}_x} = \lambda = \Delta \approx \frac{2\pi}{\underset{\sim}{k_{\max}}} = \frac{2\pi c}{\omega} = \boxed{\lambda}$$

$k_y = 0$

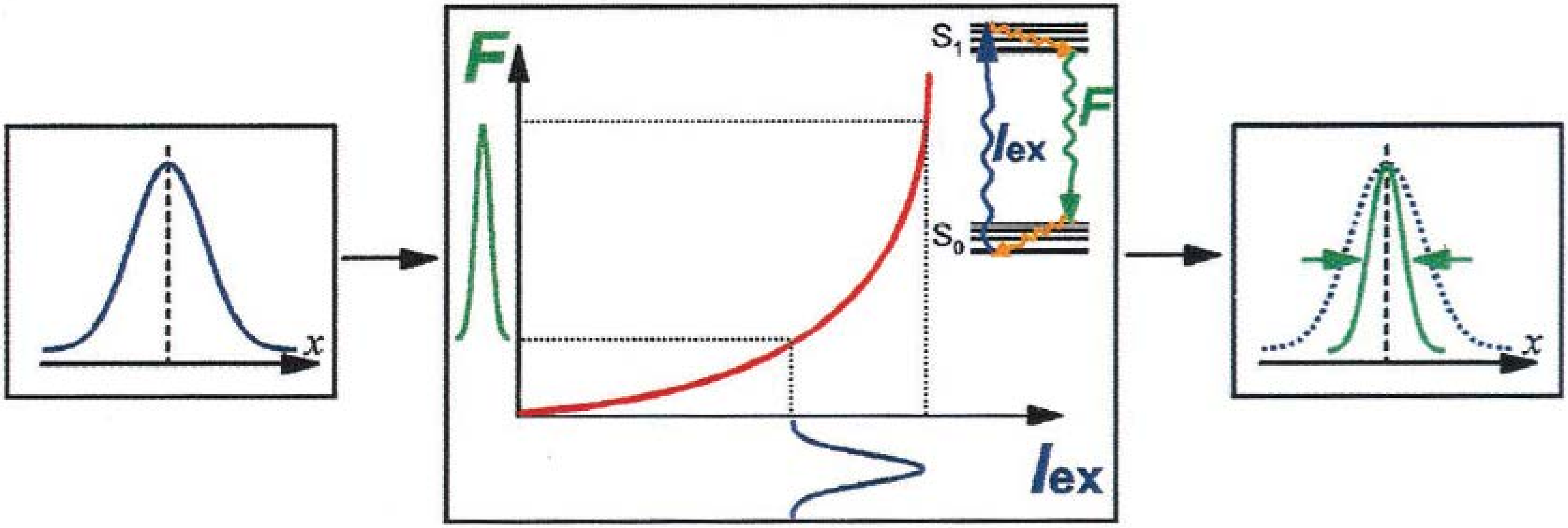
- This is the diffraction limit!

$$\boxed{\frac{\lambda}{2NA}}$$

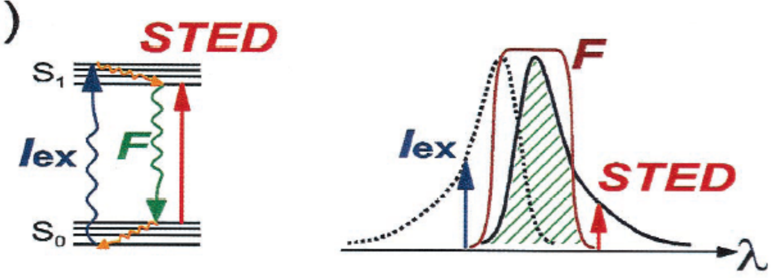
$k_x = 0$

$k_x = \frac{2\pi}{\lambda_x}$

Can we beat the Diffraction Limit?

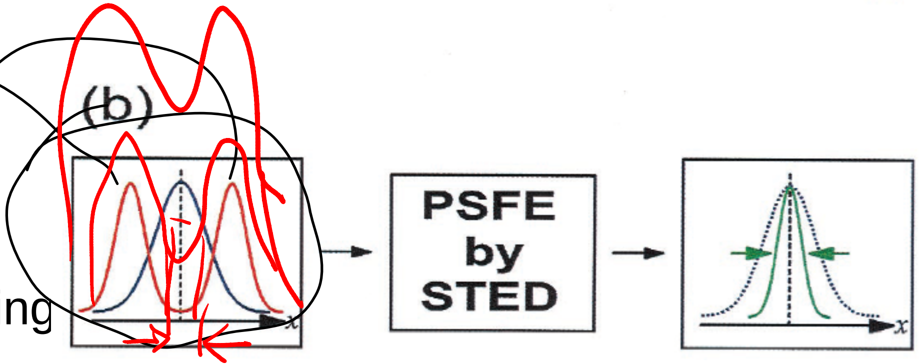


(a)



- Yes, but needs non-linear effects or plasmonics.

(b)



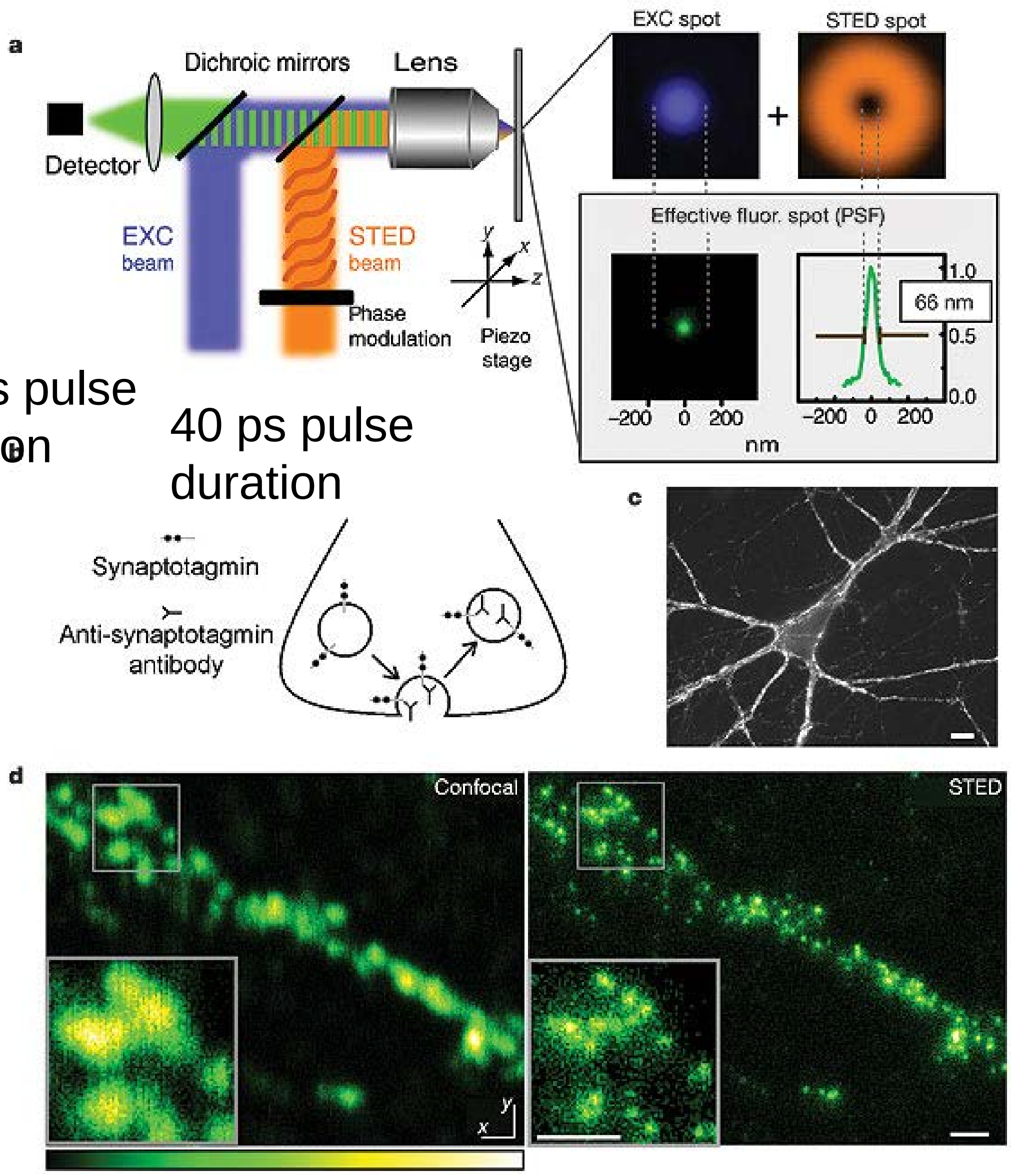
Stimulated Emission Depletion

z

- Developed by Prof. Stefan W. Hell, Max-Planck, Germany
- Nobel Prize 2015

protein

2nm

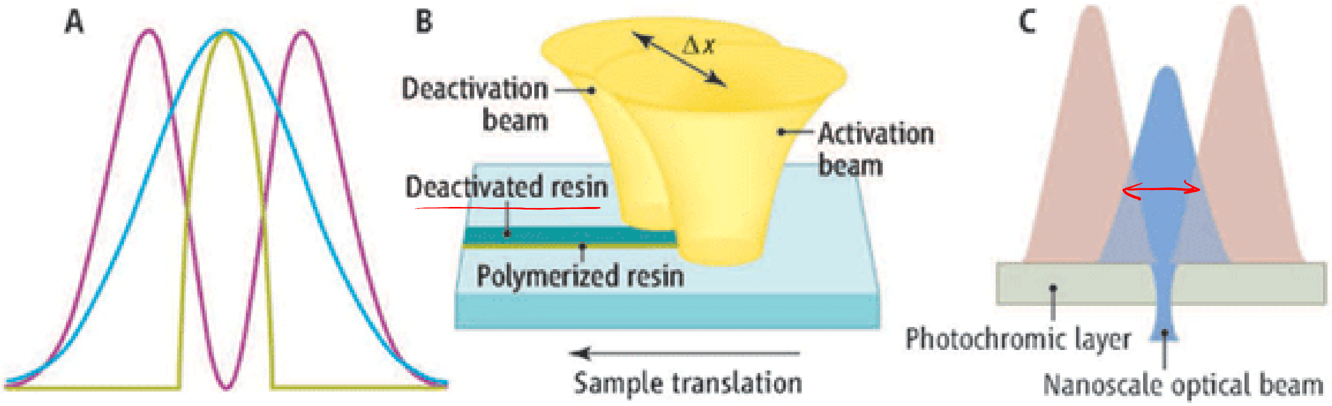


200 fs pulse duration

40 ps pulse duration

Katrin I. Willig, *et al*, *Nature,* 440, p935 (2006)

Application to Lithography



J. W. Perry Science 324, 892 -893 (2009)

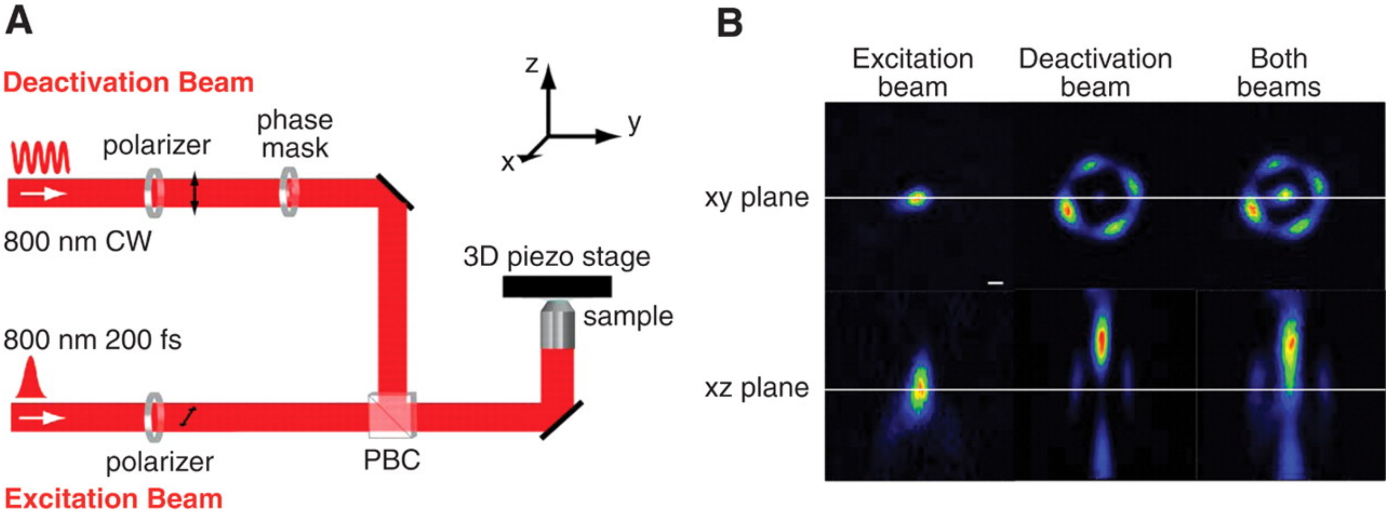
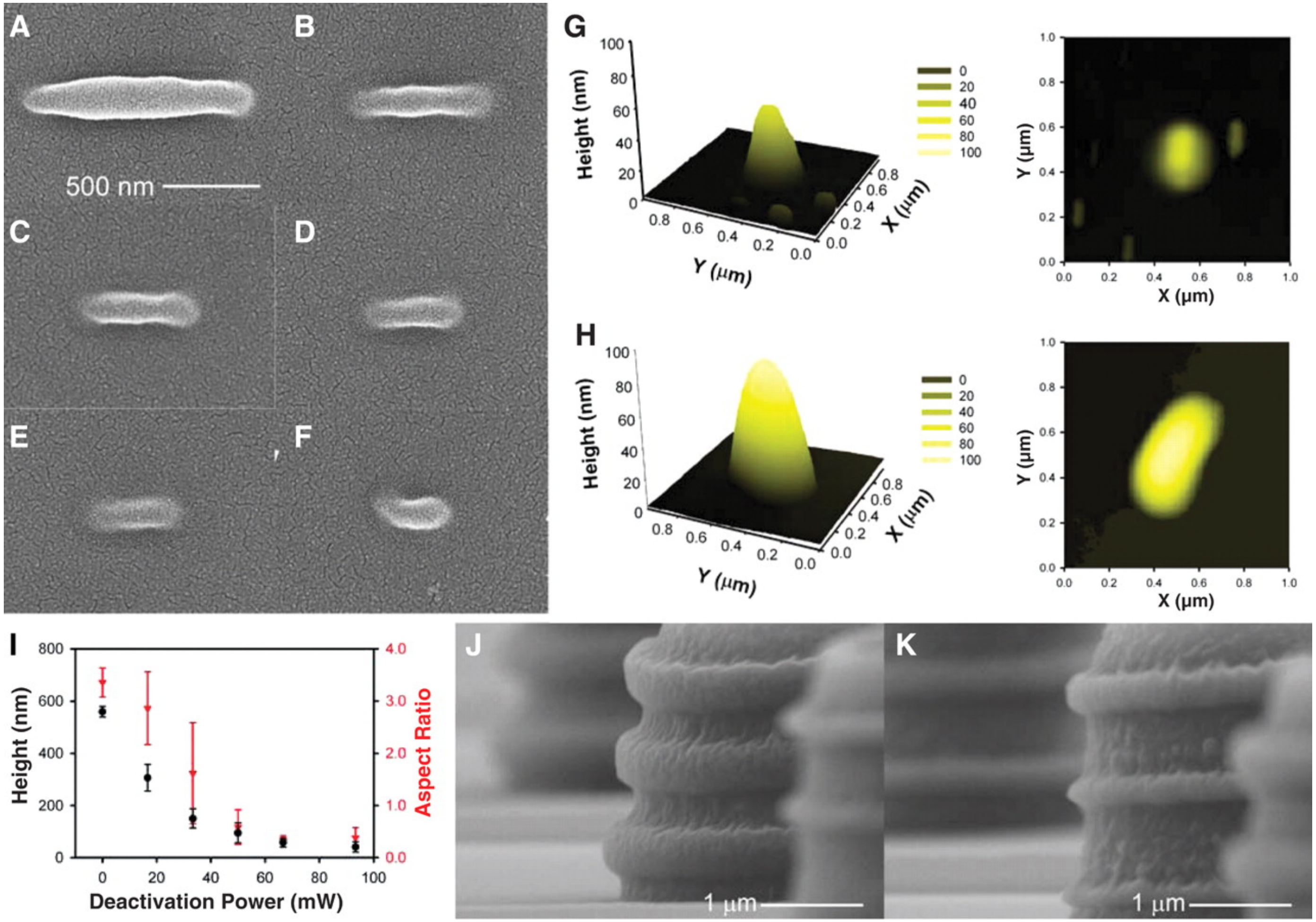


Fig. 2 (A) Schematic experimental setup for RAPID lithography with a pulsed excitation beam and a phase-shaped, CW deactivation beam

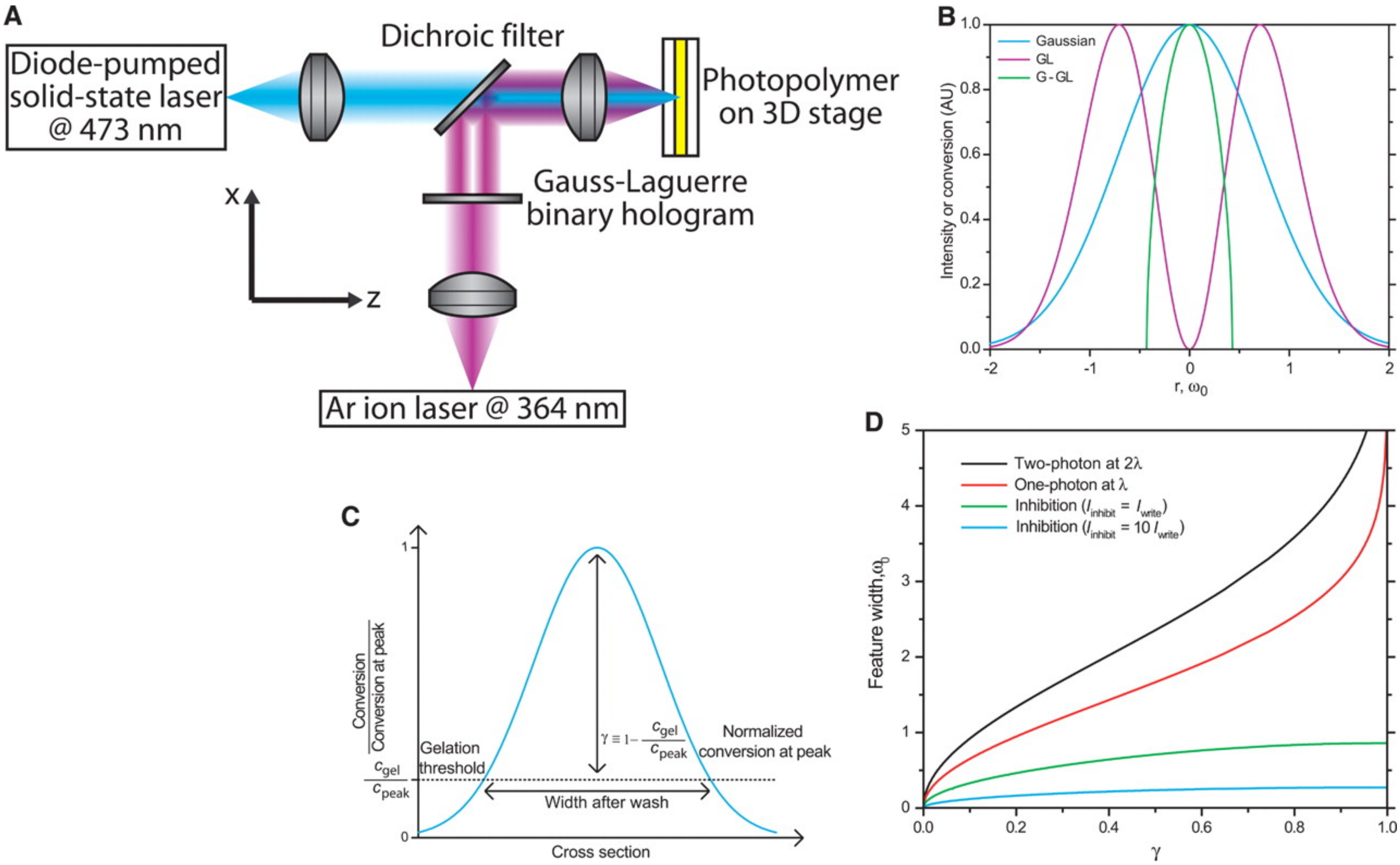
L. Li et al., Science 324, 910 -913 (2009)

Fig. 3 (A to F) SEM images of voxels created with deactivation beam powers of 0 mW, 17 mW, 34 mW, 50 mW, 84 mW, and 100 mW, respectively



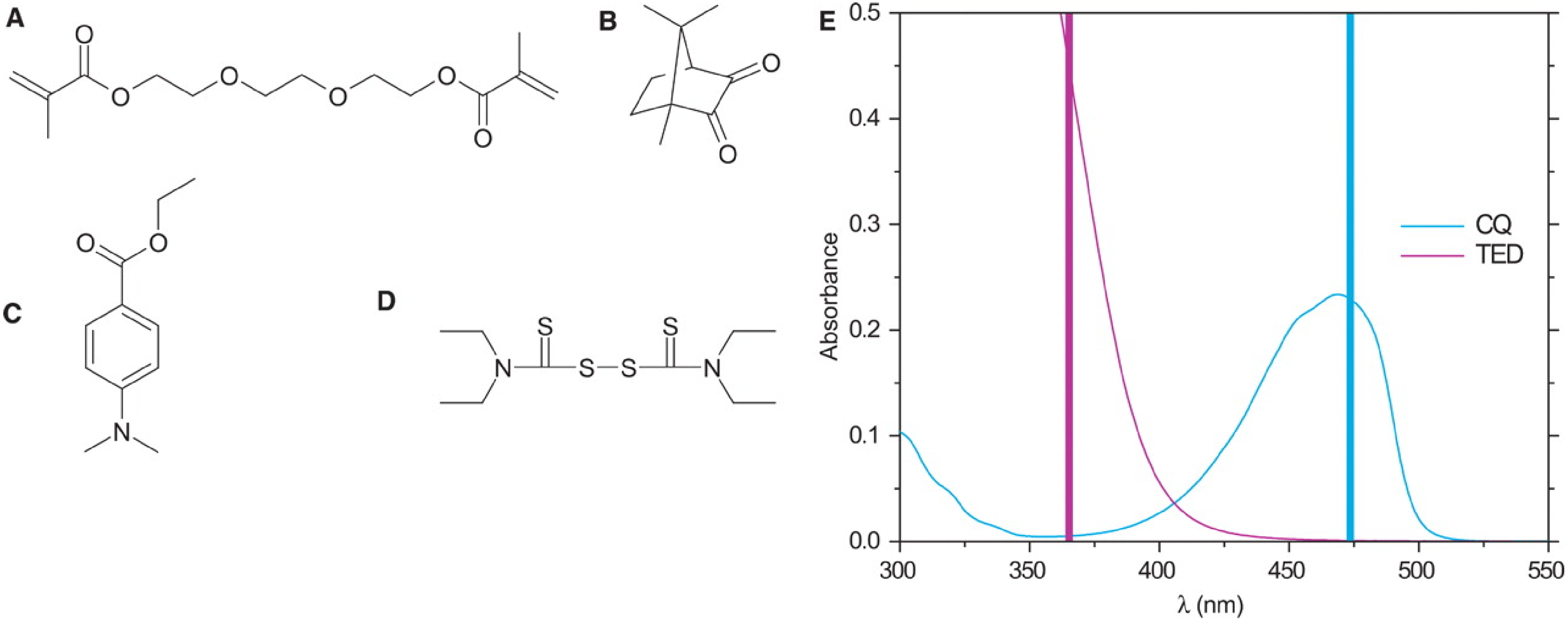
L. Li et al., Science 324, 910 -913 (2009)

Fig. 1 Two-color direct-write photolithography



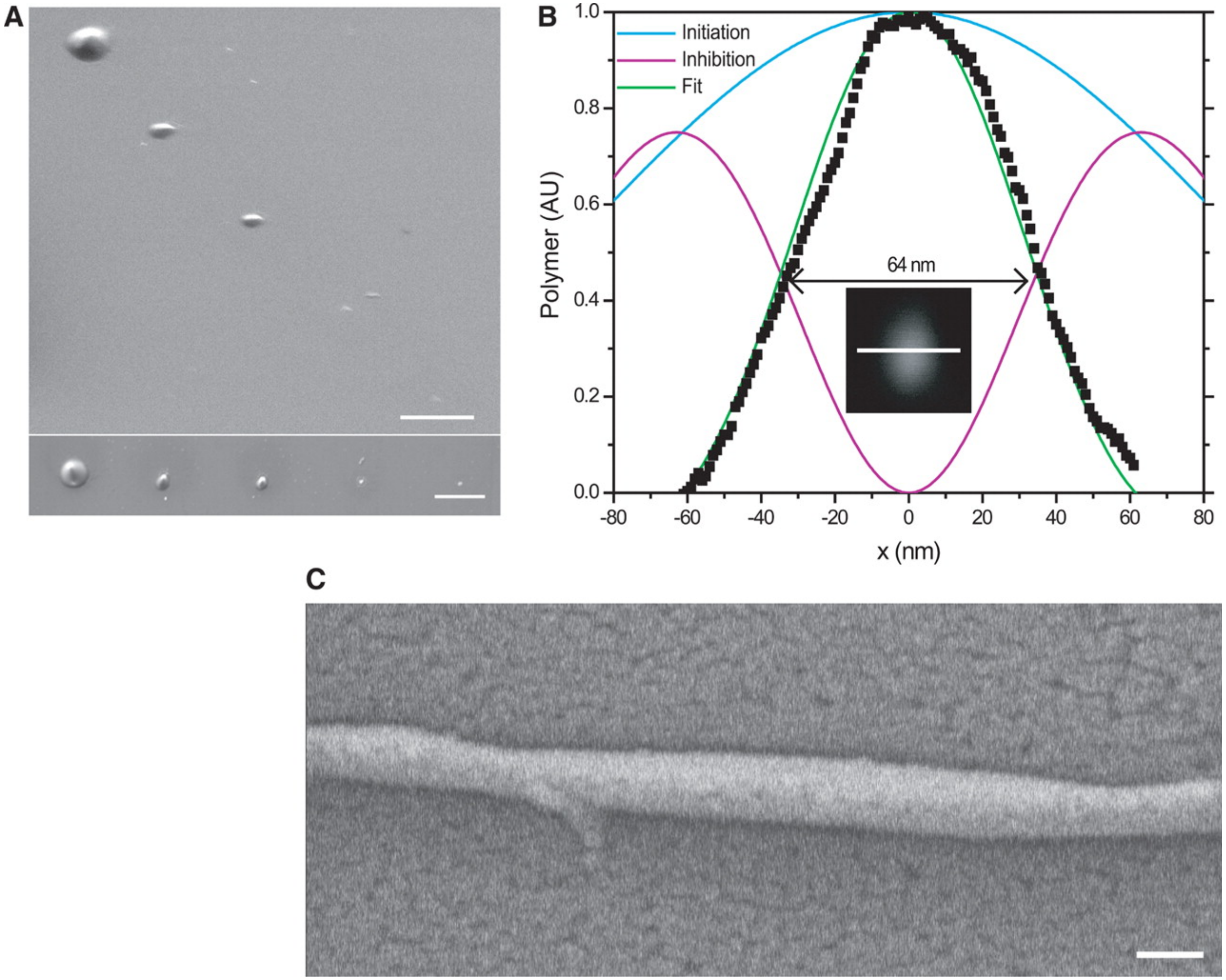
T. F. Scott et al., Science 324, 913 -917 (2009)

Fig. 2 Monomer, photoinitiator, co-initiator, and photoinhibitor used



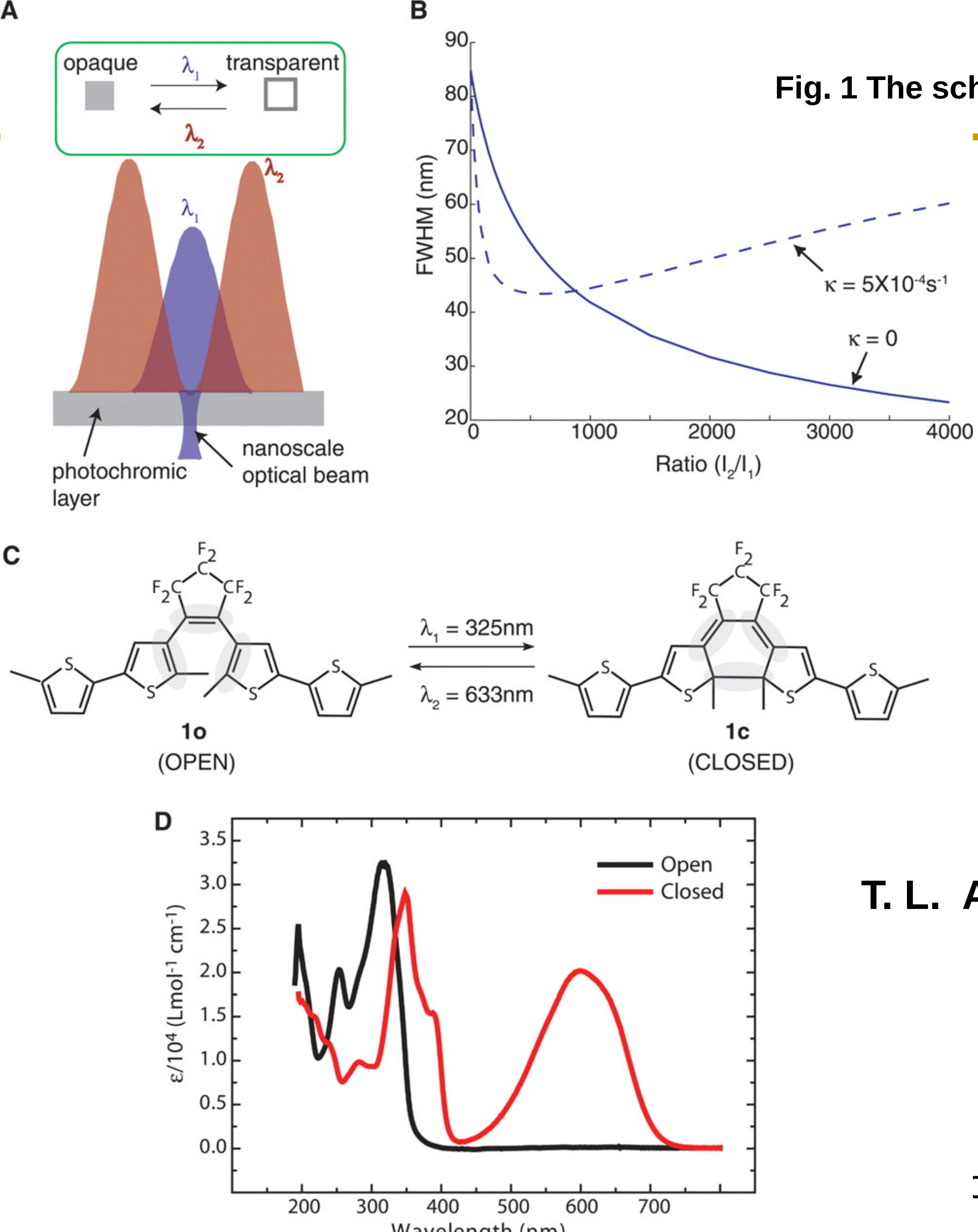
T. F. Scott et al., Science 324, 913 -917 (2009)

Fig. 4 Scanning electron micrographs of polymerized features



T. F. Scott et al., Science 324, 913 -917 (2009)

Fig. 1 The scheme of absorbance modulation



T. L. Andrew et al., Science 324, 917 - 921 (2009)

cessing

Science

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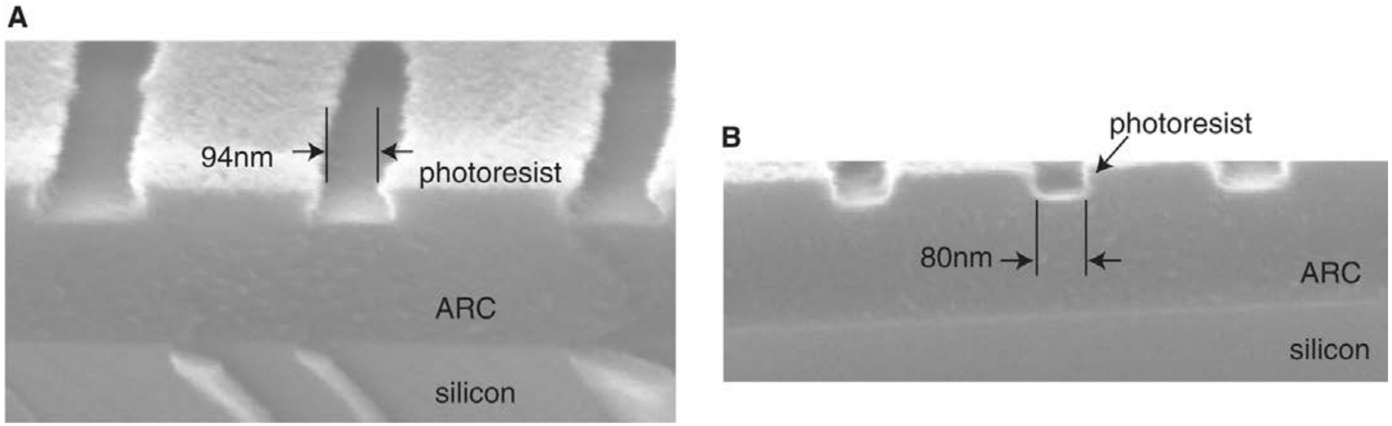
Fig. 3 Scanning electron micrographs of cross sections of exposed and developed lines in photoresist in which the PVA barrier layer thickness was (A) 25 nm and (B) 8 nm, respectively



T. L. Andrew et al., Science 324, 917 -921 (2009)

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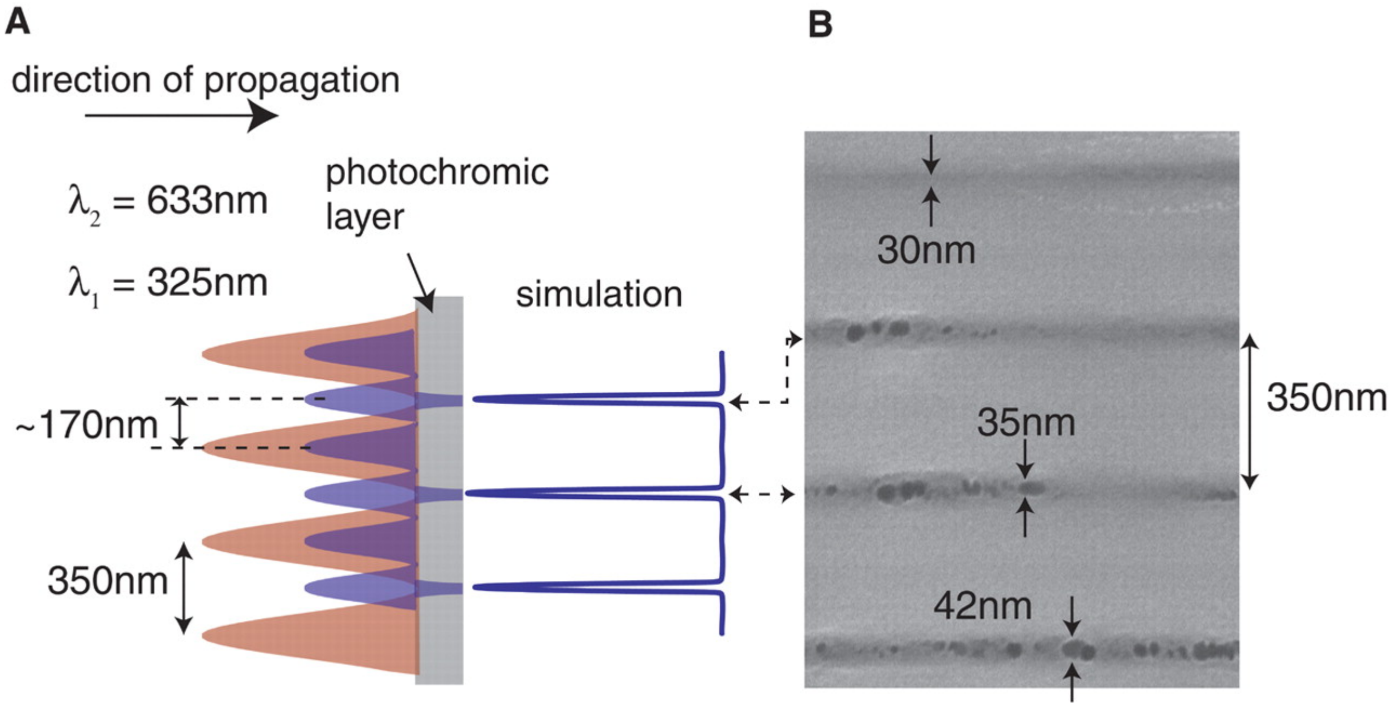
Fig. 4 Deep subwavelength patterning using absorbance modulation



T. L. Andrew et al., Science 324, 917 -921 (2009)

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