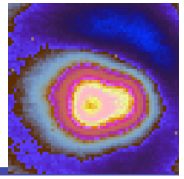
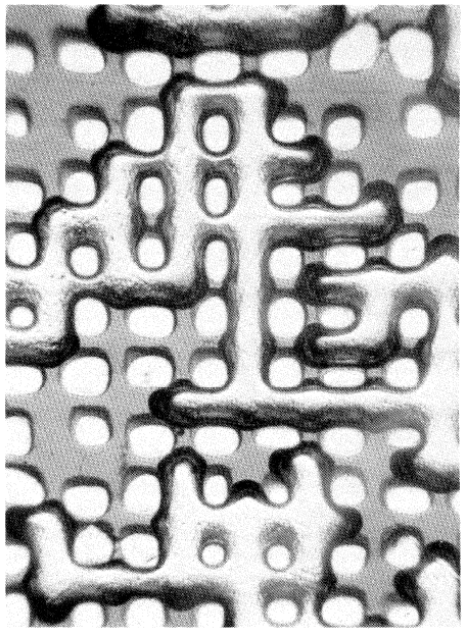


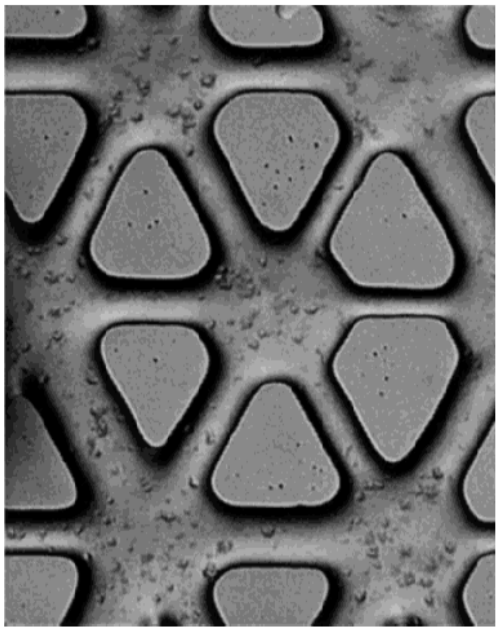
Lecture 1: Fabrication & Image Analysis

Laura J. Pyrak-Nolte ‡*

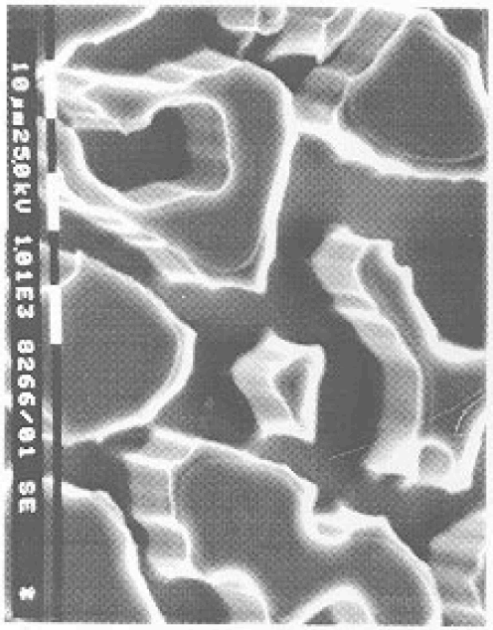
*Department of Physics
‡ Department of Earth & Atmospheric Sciences
Purdue University



(Lenormand et al., 1983)

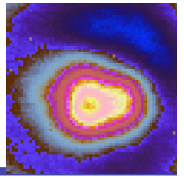


(Stewart & Fogler, 2001)



(Keller et al., 1997)

http://www.physics.purdue.edu/rockphys/mmliterature.php



Laboratory for Applied Experimental Geophysics Department of Physics Purdue University

http://www.physics.purdue.edu/rockphys/mmliterature.php

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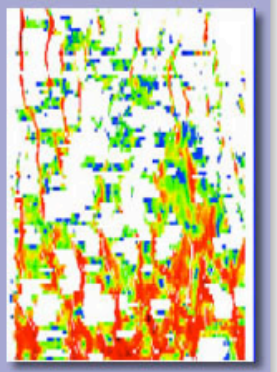
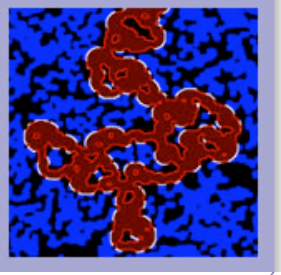




Home | Wave Propagation | Fracture Geometry | Fluid Flow | Porous Media | Food

Literature Related to Micro-Model Lectures given on July 20, 2009 by Prof. Laura J. Pyrak-Nolte at the Summer School on

"Role of Interfacial Area in Two-Phase Flow and Transport in Porous Media: Theory, Experiment, Modeling"

in Utrecht, Netherlands 19-24 July 2009.

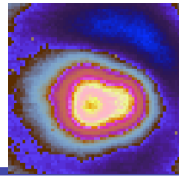
Glass Beads & Glass Shards

Chatenever, A. and J. C. Calhoun, Jr., Visual examinations of fluid behavior in porous media - Part 1, Petroleum Transaction, AIME, vol 195, T.P. 3310, 149-156, 1952

Fourar, M., Bories, S., Lenormand, R. & P. Persoff, Two-Phase Flow in Smooth and Rough Fractures' Measurement and Correlation by Porous-Medium and Pipe Flow Models, WATER RESOURCES RESEARCH, VOL. 29, NO. 11, PAGES 3699-3708, NOVEMBER 1993

Montemagno, C. D. and W. G. Gray, Photoluminescent volumetric imaging: A technique for the exploration of multiphase flow and transport in porous media, GEOPHYSICAL RESEARCH LETTERS, VOL. 22, bIO. 4, PAGES 425-428, FEBRUARY 15, 1995

Outline



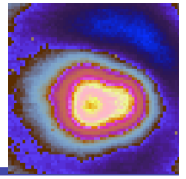
*What is a micro-model?

*Fabrication & Examples

*Imaging Modalities

*Image Analysis

What is a micro-model?



*A transparent flow cell that enables direct visualization of fluid motion, chemical reactions, biological behavior and other processes

Why use micro-models?

*To test theoretical hypotheses on the relationships among capillary pressure, saturation and interfacial area per volume…and other things

Micro-Model Applications

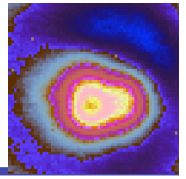


Table 1. Selected applications of micromodels.

Class	Objective	Micromodel	Pore structure	Reference
Microbiology	Dispersion of *E. coli*	glass	homogen., cylinder	Lanning and Ford (2002)
	Growth and mobility of biofilms		homogen., triangular network	Stewart and Fogler (2002, 2001), Kim and Fogler (2000)
			cubic channel with heterog. apertures	Dupin and McCarty (2000), Nambi et al. (2003)
Multiphase processes	Dissolution of NAPLs, determination of mass transfer rates	glass	homogen., tubes	Sahloul et al. (2002), Jia et al. (1999), Zhong et al. (2001)
		glass	monolayer of glass beads	Kennedy and Lennox (1997)
		silicon wafer	homogen., heterogen.	Chomsurin and Werth (2003)
	Transport of NAPLs in unsat. porous media	silicon water	pore structure taken from a thin section of sand stone	Keller et al. (1997)
	Soil cleanup with surfactants	glass	homogen. cubic network, heterogen. network	Jeong et al. (2000)
	Numerical modeling of three-phase flow	glass	homogen. network	Pereira et al. (1996), Pereira (1999)
	Fluid flow	glass	monolayer of glass beads	Corapcioglu and Fedirchuk (1999)
			homogen. network	Corapcioglu et al. (1997), Soll et al. (1993)
	Capillary rise	glass	triangular network	Bernadiner (1998)
	Development of air bubbles	glass		Li and Yortsos (1995)
	Fracture–matrix interactions	glass	homogen. pore network with fracture	Haghighi et al. (1994), Wan et al. (1996)
Oil exploration	Cementation due to gas hydrates	glass		Tohidi et al. (2001)
	Kinetics of carbonate cementation in wells	glass		Dawe and Zhang (1997)
	Effects of injected polymer gels on the flow of water and oil	glass		Al-Sharji et al. (2001)
	Transport of gas condensate	glass		Jamiolahmady et al. (2000), Coskuner (1997), Wang and Mohanty (2000), Bora et al. (2000)
Colloids	Attachment at the air–water–interface	glass	homogen., heterogen.	Wan and Wilson (1994b), Wan et al. (1996)

(from Baumann& Werth, 2004)

Micro-Model Applications

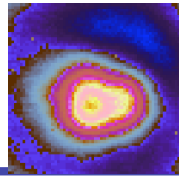
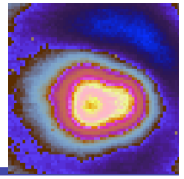


Table 2. Selected Applications of Micromodels for Visualization of Colloidal Transport in Porous Media

Source	Type of Micromodel	Network Characteristics	Pore Dimensions, μm	Visualization Method	Moisture Conditions	Nature of Colloids (Size, μm)	Objective
Wan and Wilson [1994]	etched glass	regular polygon pillars and irregular shapes	200[a]/50[b]; 300[a]/20–100[b]; 4–400	dark-field; epifluorescence	unsaturated	hydrophilic microspheres (0.6, 1.05); hydrophobic microsphere (0.95); bacteria (1.2 × 0.8, 1.0 × 0.8); clay (0.5)	attachment at the air-water interface
Wan et al. [1996]	etched glass	two-domain: fracture-matrix	range of widths 0–600[c]	epifluorescence	saturated	microspheres (1.0)	two-domain flow
Lanning and Ford [2002]	etched glass	regular cylindrical pillars	360–375 × 60–83[c]	light scattering to determine turbidity	saturated	*E. coli*	dispersion of bacteria
Sirivithayapakorn and Keller [2003a]	etched silicon	simulation of natural pore system	2.4 – 30 × 15[c]	epifluorescence	saturated	latex microspheres (0.05, 1.0, 2.0, 3.0); stained bacteriophage	size exclusion and colloid acceleration
Sirivithayapakorn and Keller [2003b]	etched silicon	simulation of natural pore system	2.4 – 30 × 15[c]	epifluorescence	unsaturated	latex microspheres (0.05, 1.0, 2.0, 3.0); stained bacteriophage	dissolution of air-water interface
Auset and Keller [2004]	molded silicon (PDMS[d])	rounded square pillars	10, 20 × 12[c]	epifluorescence	saturated	latex microspheres (2,3,5,7)	colloid dispersion
Baumann and Werth [2004]	etched silicon	regular cylindrical pillars	173[a]/35[b] × 50[c]	epifluorescence	saturated	microspheres (0.691,1.96)	comparison to LB model and filtration theory predictions[e]
Auset et al. [2005]	molded silicon (PDMS[d])	simulation of natural pore system	2.4 – 30 × 12[c]	epifluorescence	cyclical infiltration and draining	DAPI stained bacteria (2 × 1); latex microspheres (5)	Intermittent filtration of bacteria and colloids
Chen and Flury [2005]	etched glass	regular cylindrical pillars	70	bright field	unsaturated	natural colloids(0.348), modified colloids (0.368), kaolinite (0.332), Na-montmorillonite (0.324)	retention of mineral colloid in unsaturated media

(from Ochiai et al., 2006)

What is a micro-model?



*a transparent flow cell that enables direct visualization of fluid motion, chemical reactions, biological behavior and other processes

Etched substrate

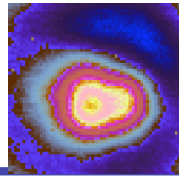
Etched polymer

Mold

Replicas

Optical or X-ray Lithography

Photoresist



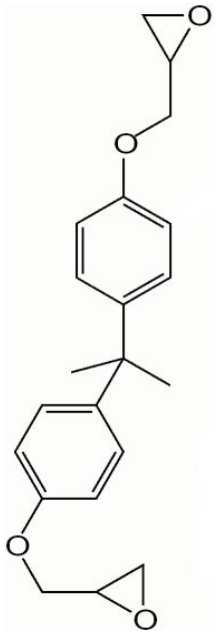
Photoresist: A light sensitive material

PMMA: Polymethylmethacrylate

PMGI: PolyMethylGlutarimide

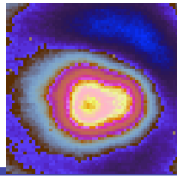
Novolac: phenol formaldehyde resin (PF)

SU-8



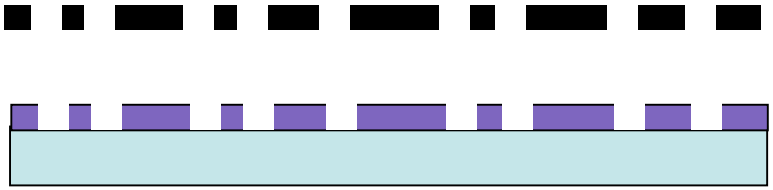
SU-8: epoxy that is a multifunctional glycidyl ether derivate of bisphenol-A novolac. Dissolves in gamma butyrolactone (GBL) to change viscosity & affect film thickness

Photoresist



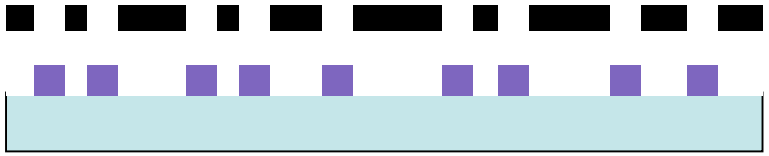
Positive Resist: Regions exposed to UV are washed away upon development.

ex. Shipley 1805 (now Ross & Hass)

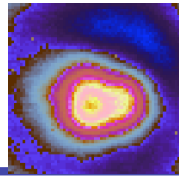


Negative Resist: Regions exposed to UV remain after development

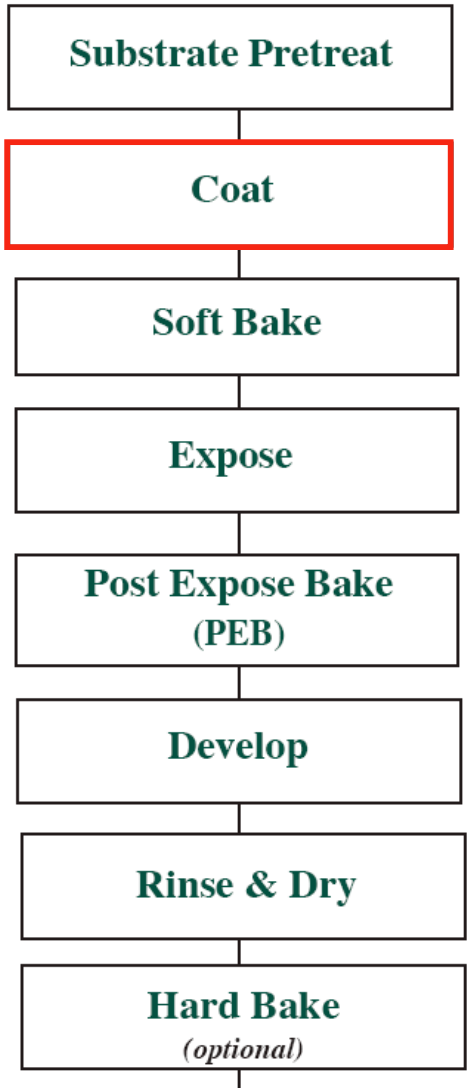
ex. SU-8



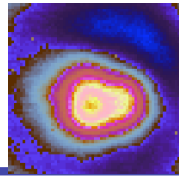
Processing Photoresist



SU-8 Processing Steps

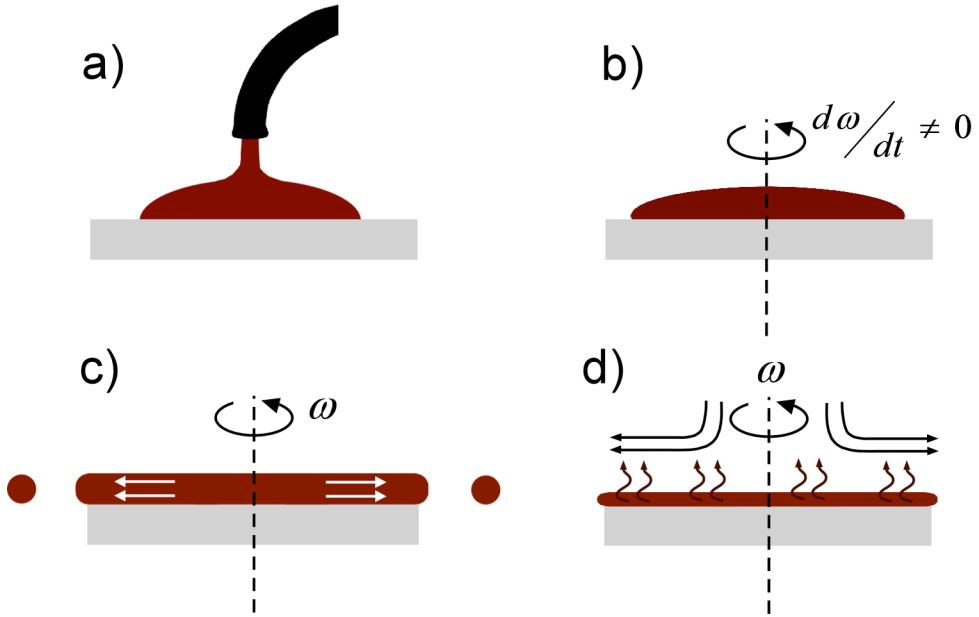


Optical Lithography: Preparation



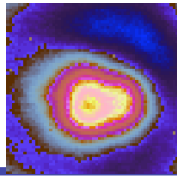
*analogous to darkroom development of photographs

Spin Coating of Disk with a UV-sensitive Polymer

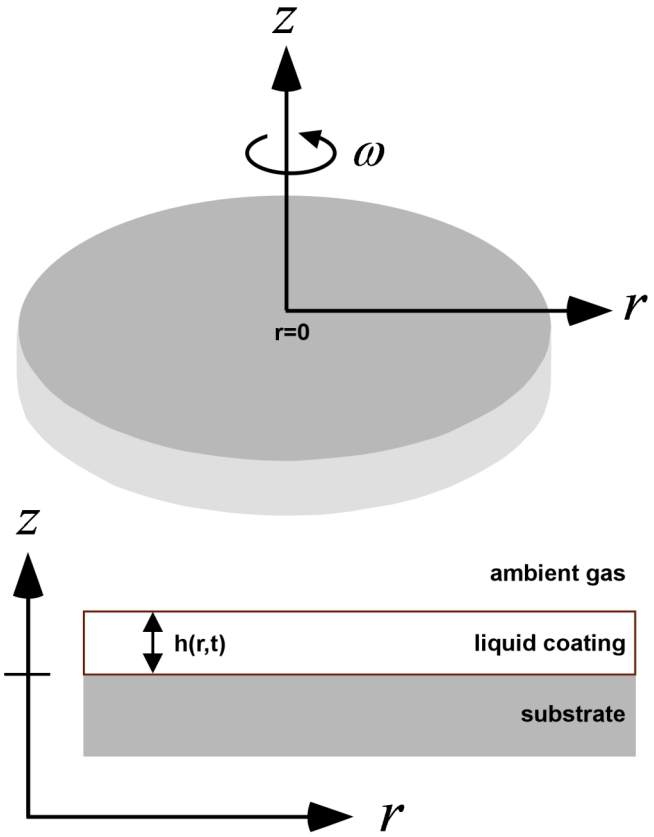


http://large.stanford.edu/courses/ph210/hellstrom1/

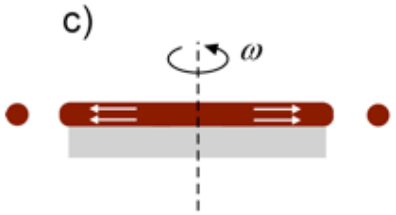
Optical Lithography: Preparation



*analogous to darkroom development of photographs



Assuming No Evaporation

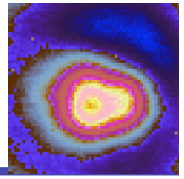


$$h = \frac{h_o}{\sqrt{1 + \frac{4\omega^2 \rho h_o^2 t}{3\eta}}}$$

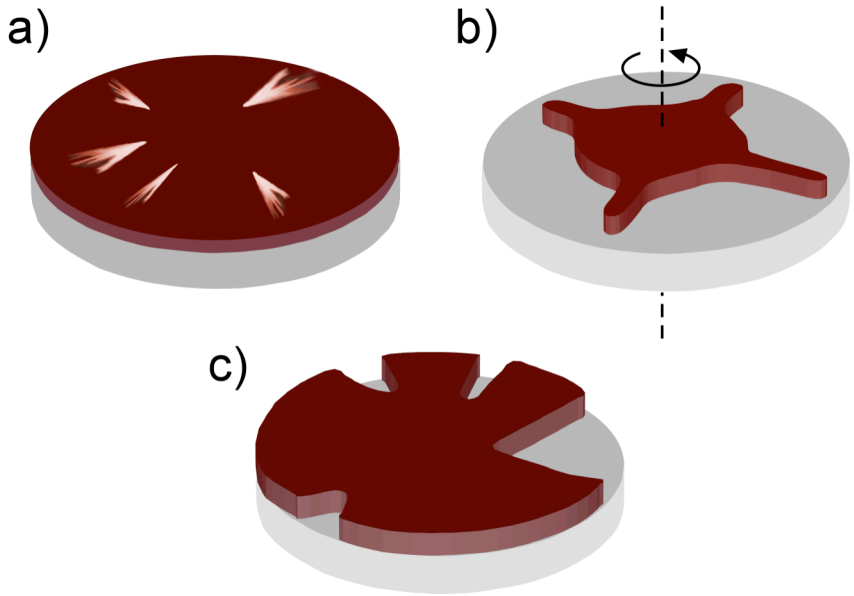
$$r = r_o \sqrt[3/4]{1 + \frac{4\omega^2 \rho h_o^2 t}{3\eta}}$$

http://large.stanford.edu/courses/ph210/hellstrom1/

Optical Lithography: Preparation

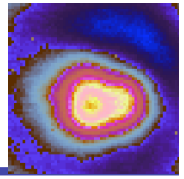


*Care in spin coating

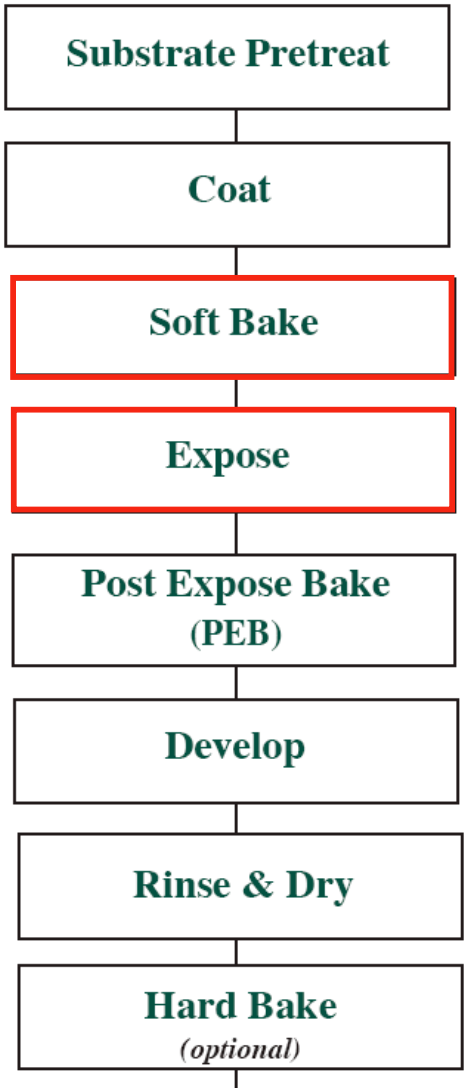


http://large.stanford.edu/courses/ph210/hellstrom1/

Processing Photoresist

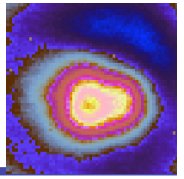


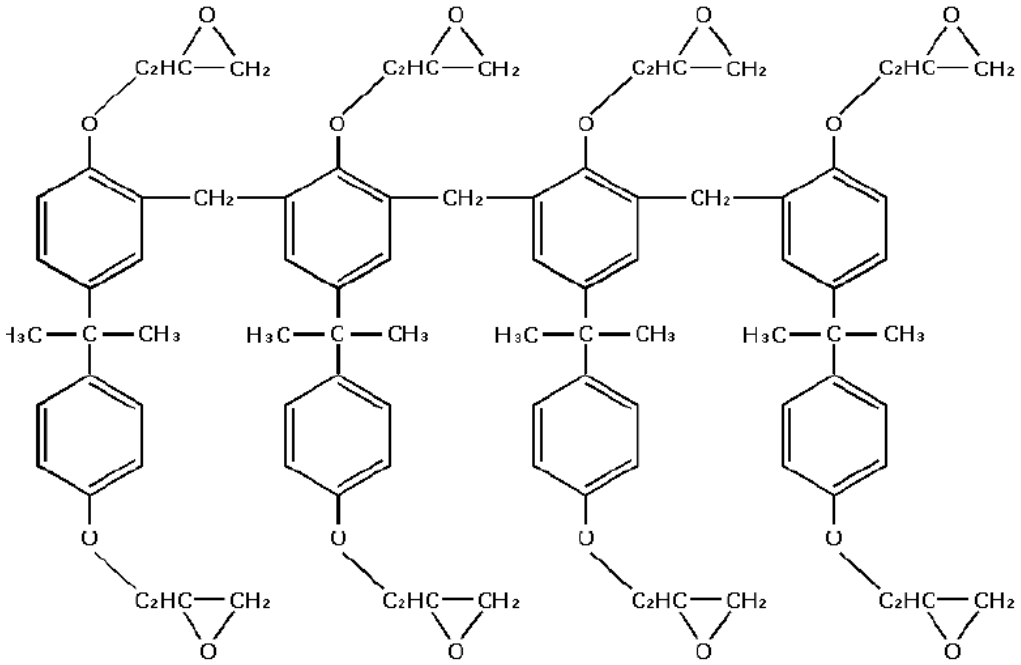
SU-8 Processing Steps



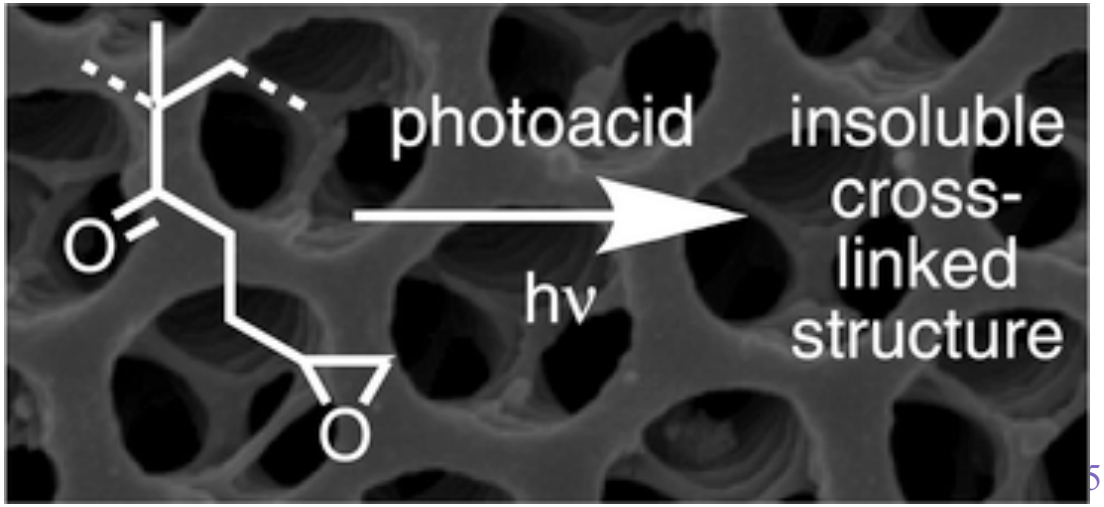
→ Drives off solvents

Photolithography: Exposure Induced Cross-linking

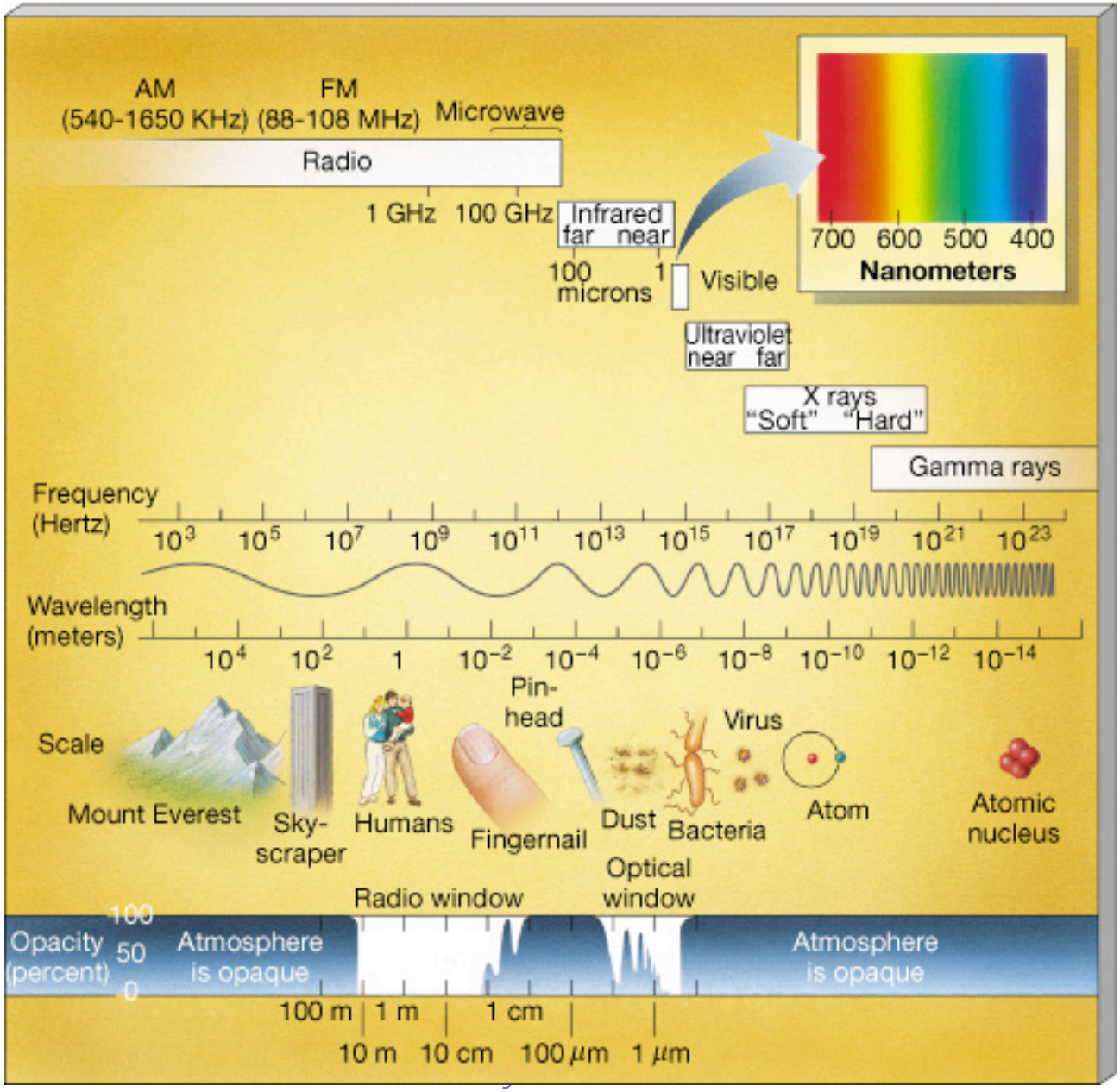




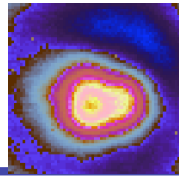
SU-8 molecule



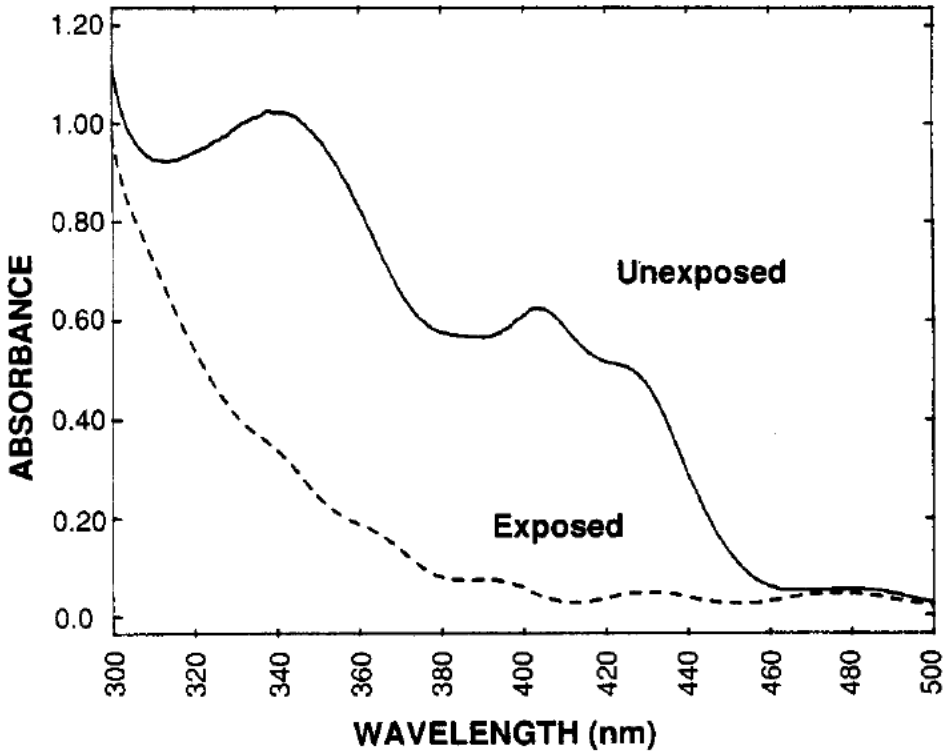
Photolithography: Electromagnetic Spectrum



Photolithography: Wavelength for Exposure



Shipley 1813



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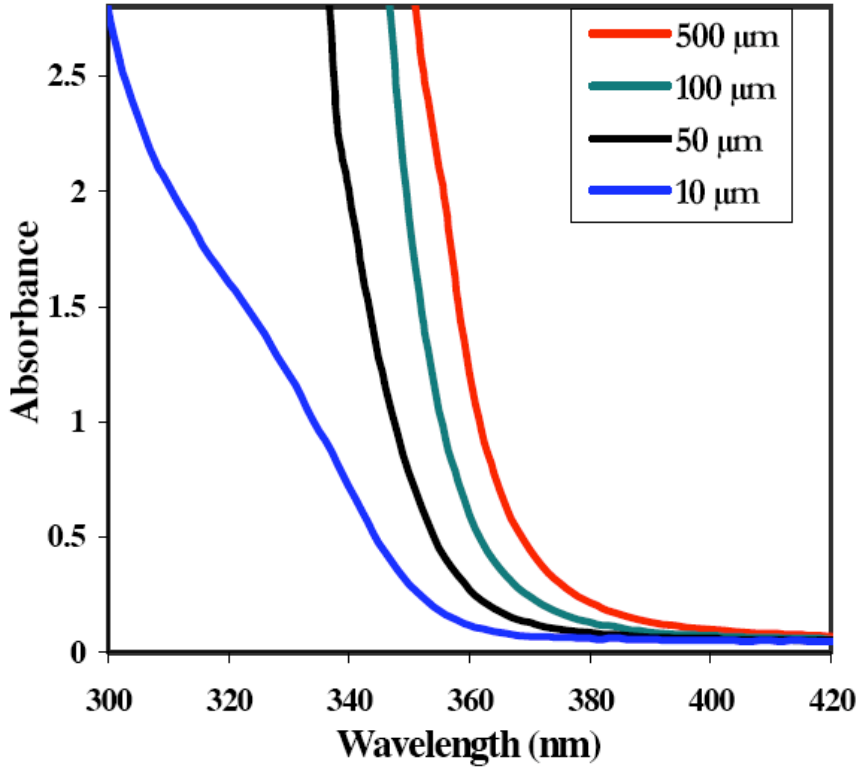
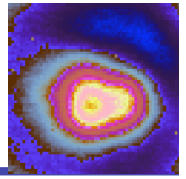
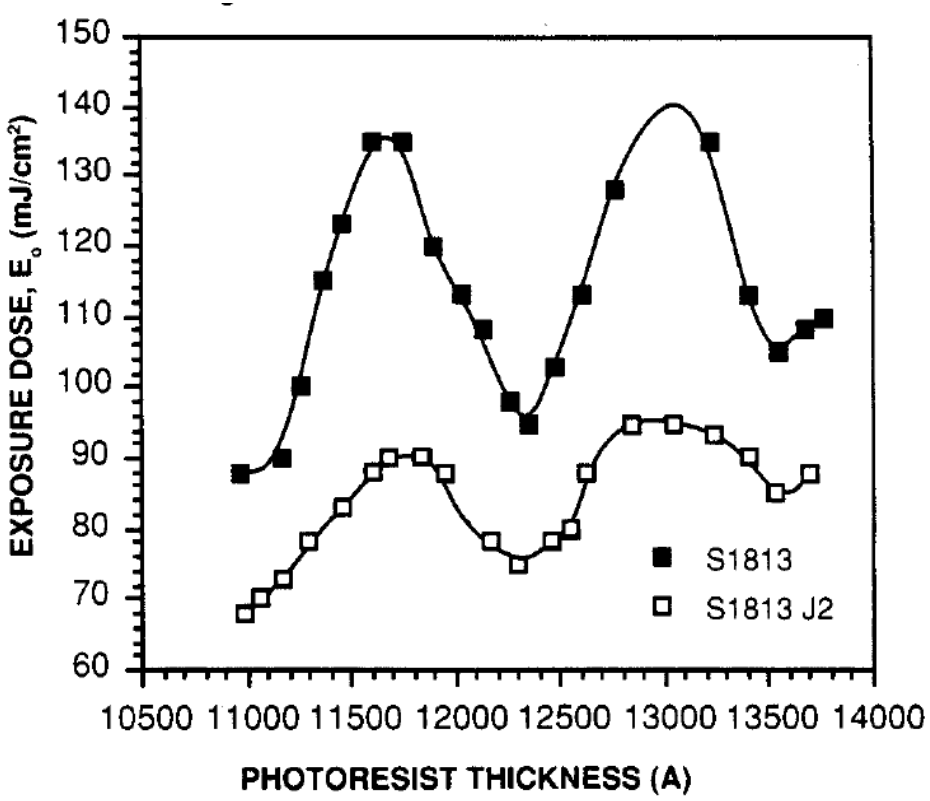


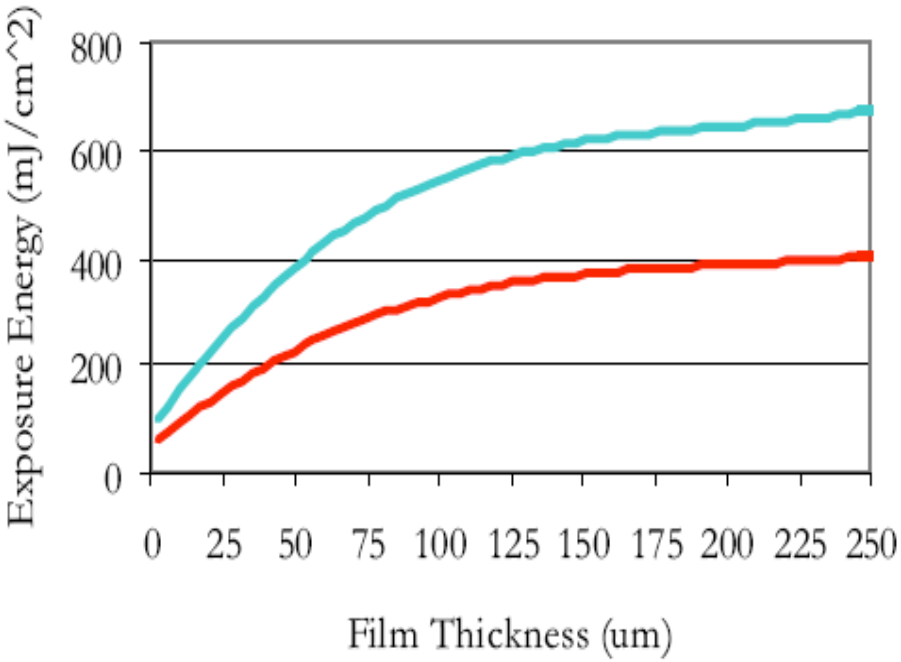
Optical Lithography: Energy Dose for Exposure



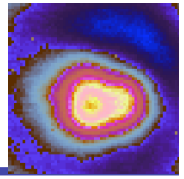
Shipley 1813

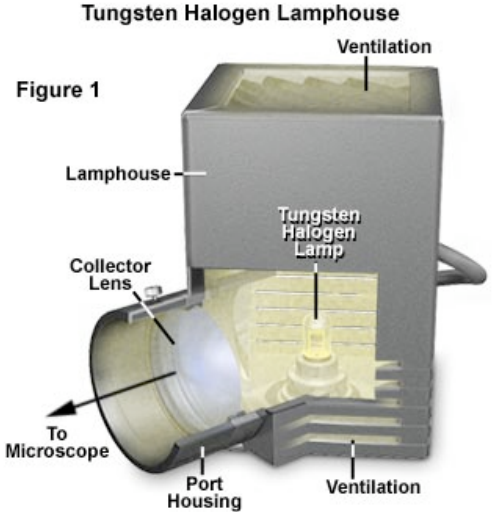


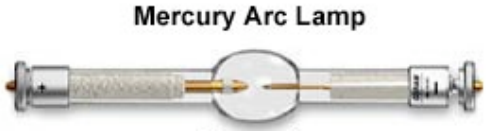
SU-8

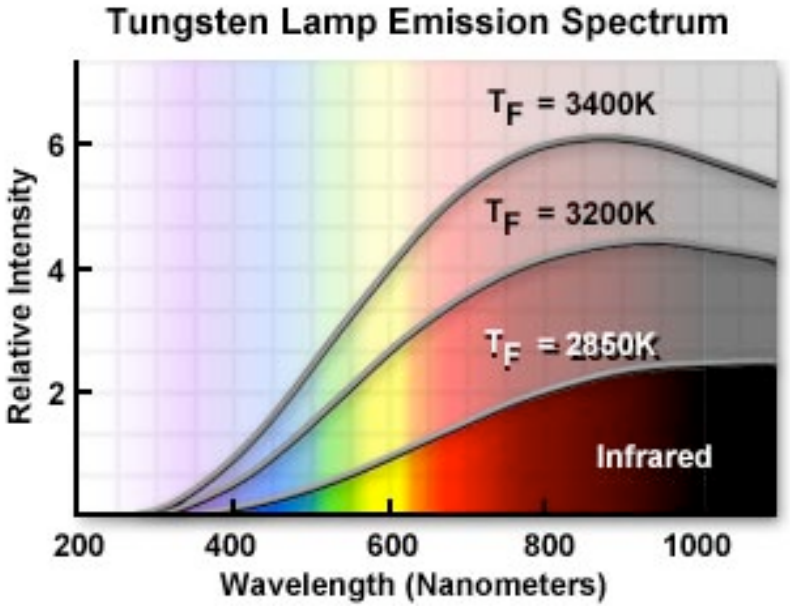


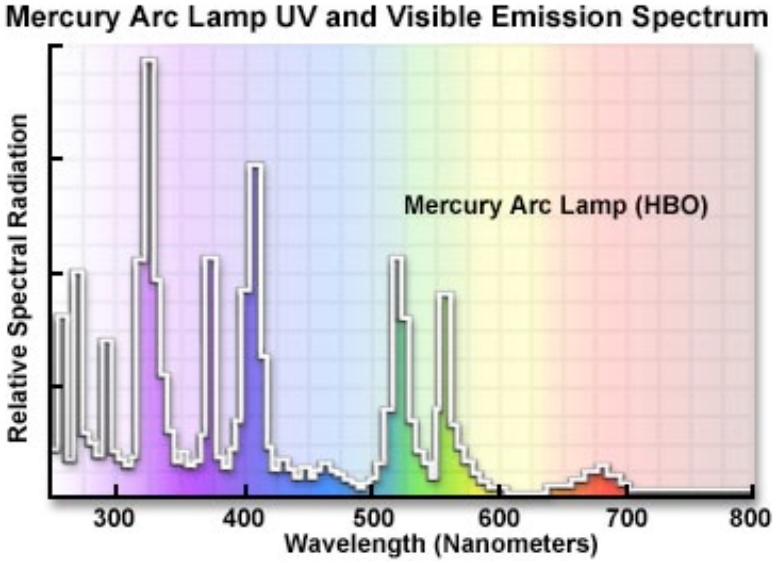
Optical Lithography: Typical Sources



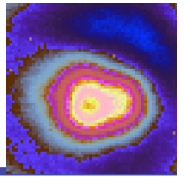








Optical Lithography: Methods



Projection Lithography

Tungsten Light Source

Mask

Lens

Contact Lithography

Mercury Light Source

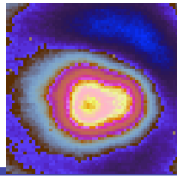
Mask

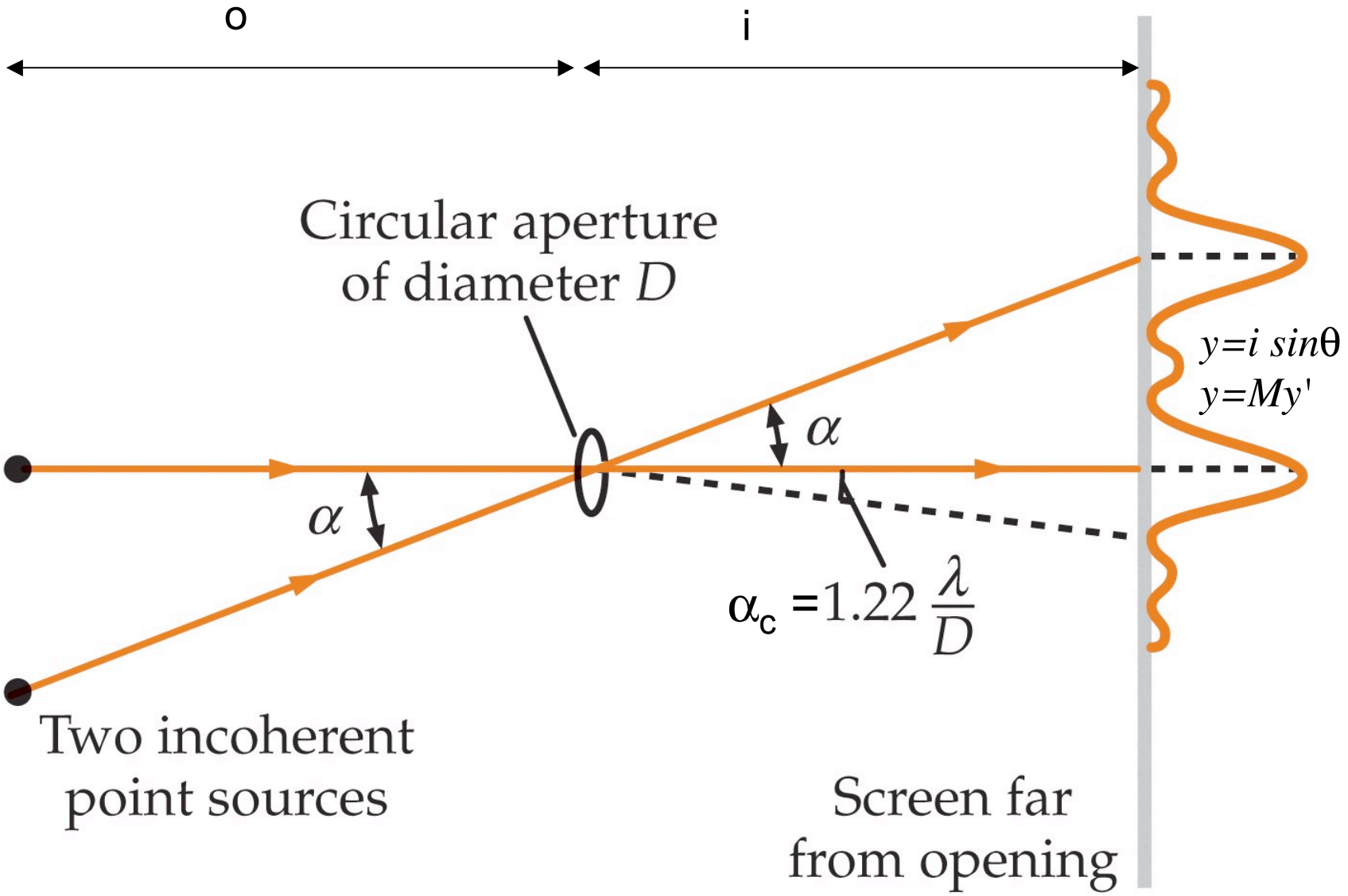
Photoresist

Substrate

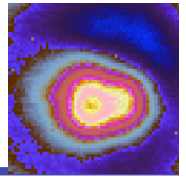
Substrate

Rayleigh Criteria





Rayleigh Criteria



If $\alpha > \alpha_C$ objects can be resolved

If $\alpha < \alpha_R$ objects can not be resolved

To increase our ability to distinguish objects we must minimize the diffraction pattern. Because

$$\alpha_C \approx 1.22\frac{\lambda}{d}$$

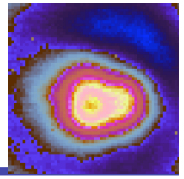
we can :
increase d or
decrease λ

1) Use ultraviolet light

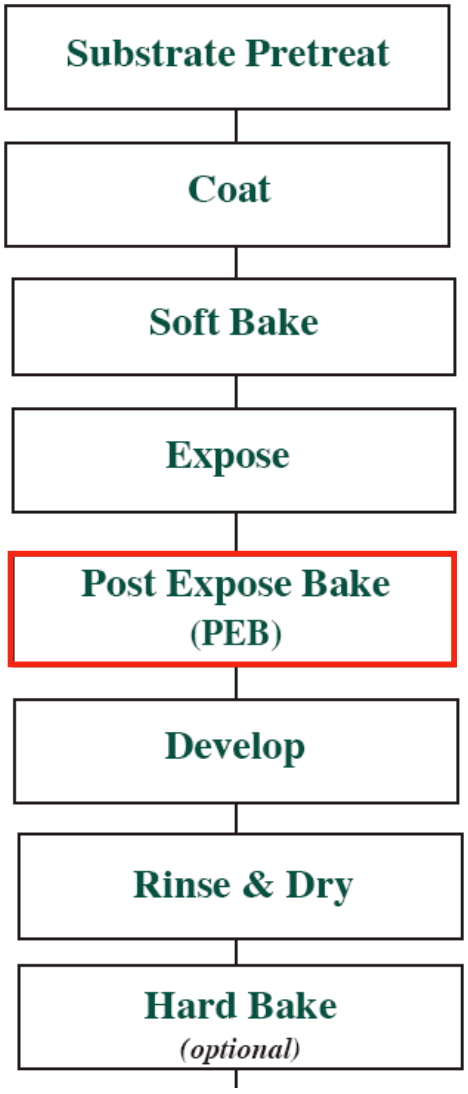
2) e- beam used in Scanning Electron Microscopes (SEM) have $\lambda \approx \lambda(\text{light})/10^5$

3) place object under a microscope in a drop of oil $\lambda_n = \lambda/n$

Processing Photoresist

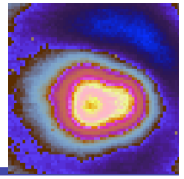


SU-8 Processing Steps

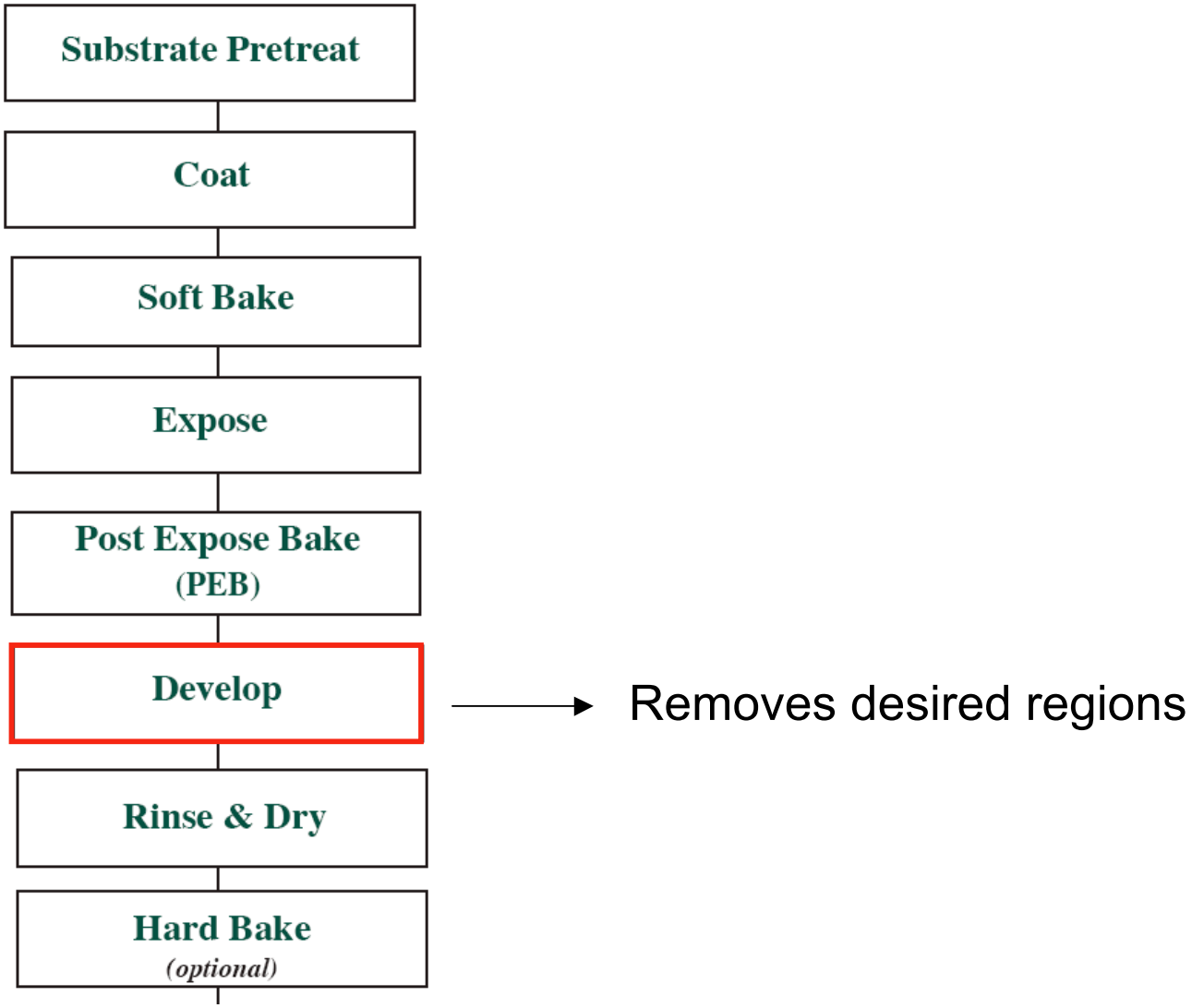


for chemically amplified resists: catalytically performs and completes the photo reaction initiated during exposure. For negative resists, crosslink during PEB and remain after development

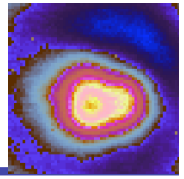
Processing Photoresist



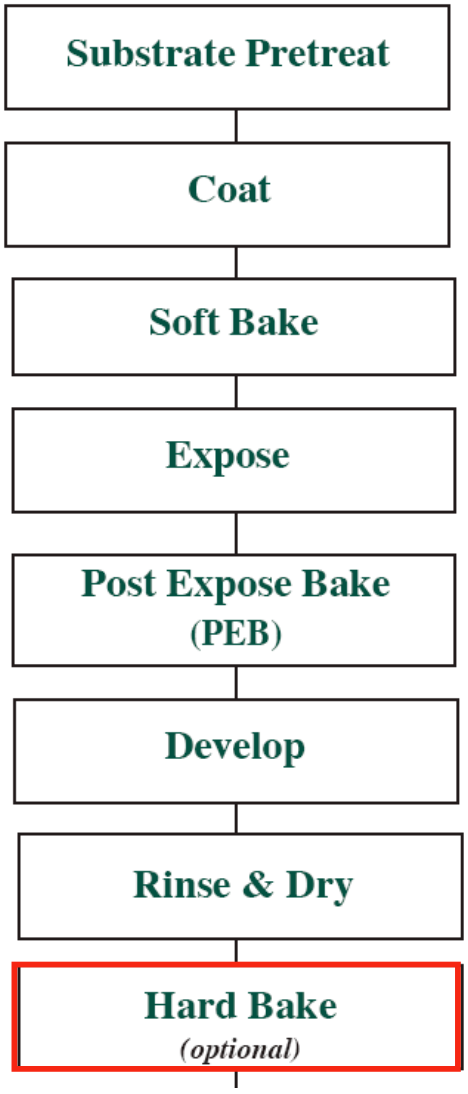
SU-8 Processing Steps



Processing Photoresist

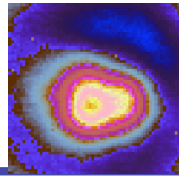


SU-8 Processing Steps

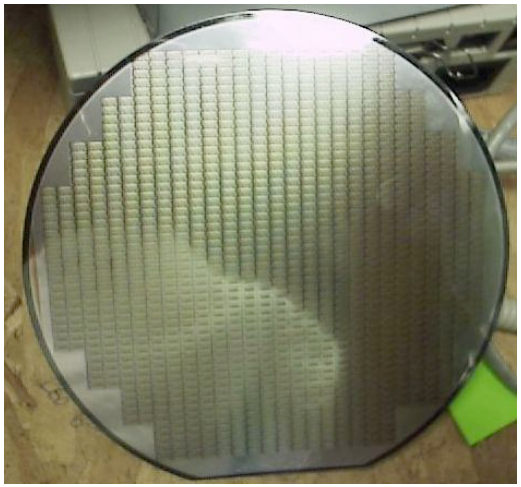


Increases thermal, chemical and physical stability of the structure

Types of Micro-Models: Etched Silicon or Glass

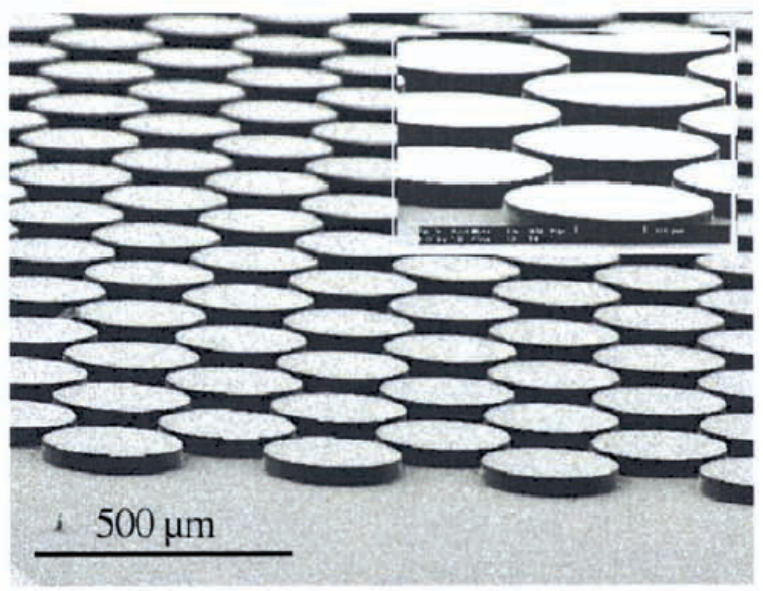


Silicon Wafer

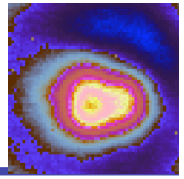


http://www.computermuseum.li/Testpage/SiliconWaferofChips.jpg

Baumann& Werth, 2004



Types of Micro-Models: Etched Silicon or Glass



Baumann& Werth, 2004

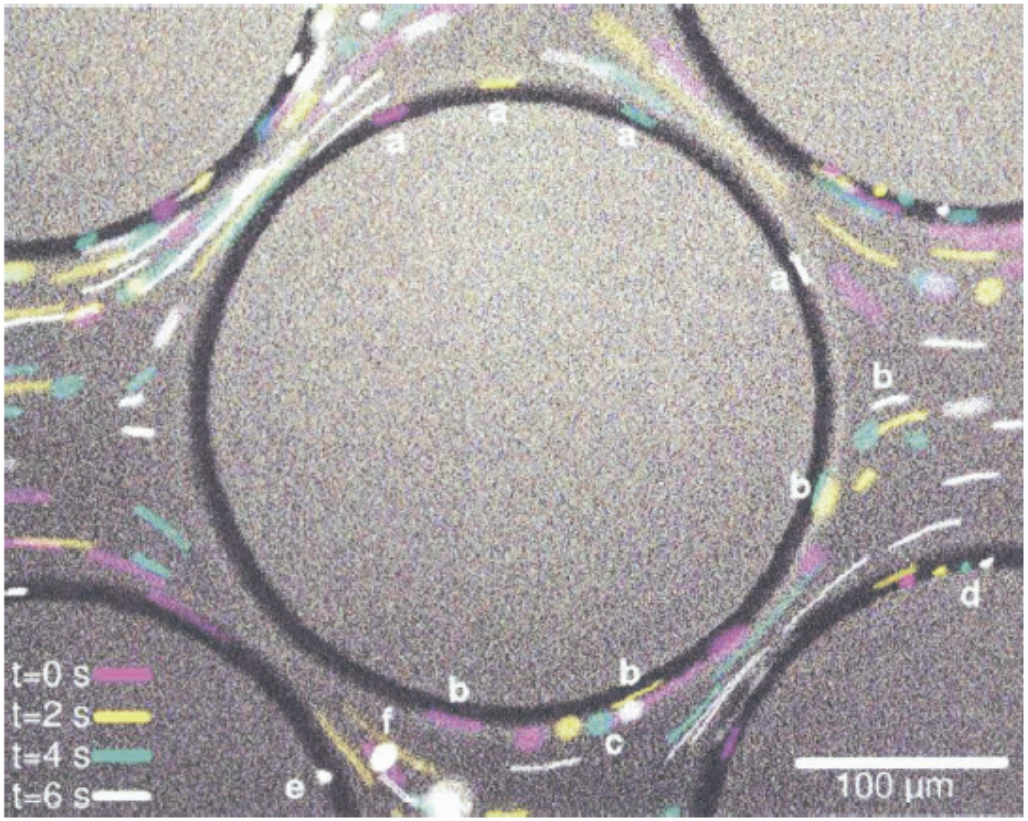
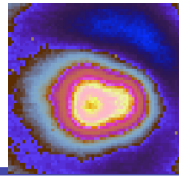
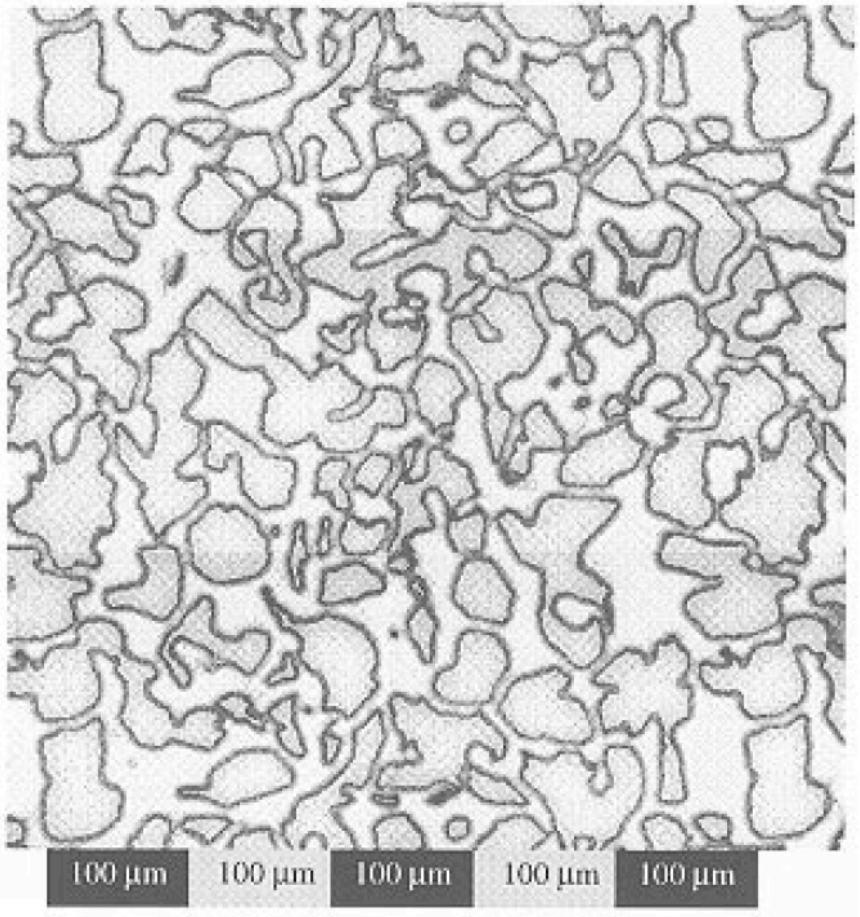


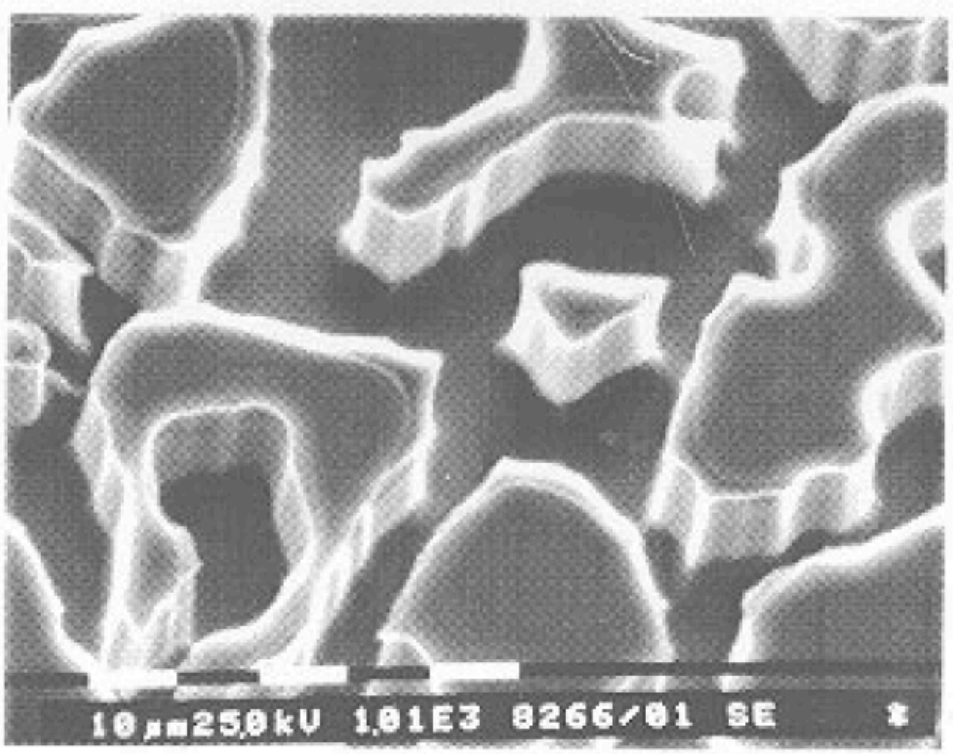
Fig. 4. A composite order image of 691-nm colloids in the homogeneous micromodel. Flow is from left to right at 15 µL h^{-1}. The color code indicates the position of the colloids at time steps 2 s apart.

Types of Micro-Models: Etched Silicon or Glass

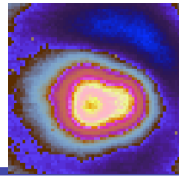


Keller et al., 1997





Types of Micro-Models: Etched Silicon or Glass



Keller et al., 1997

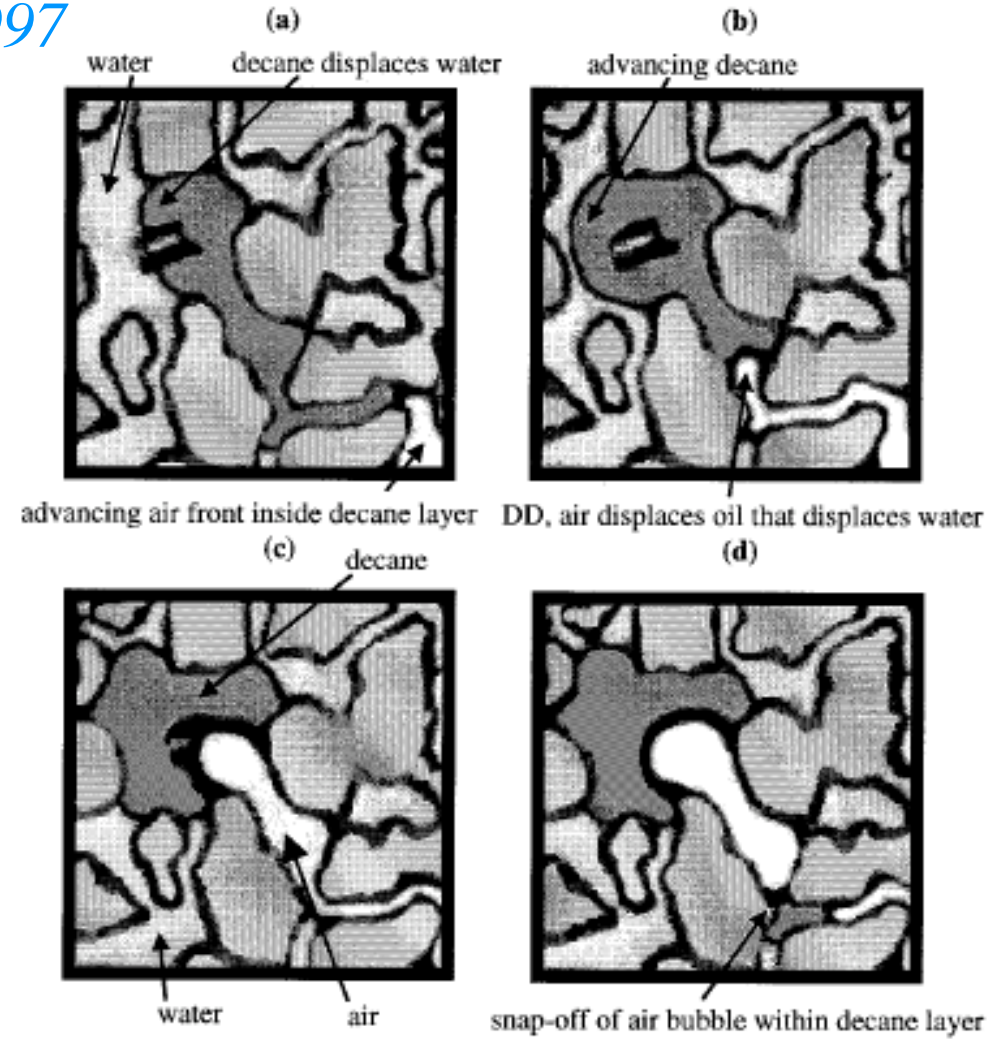
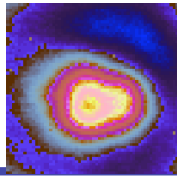
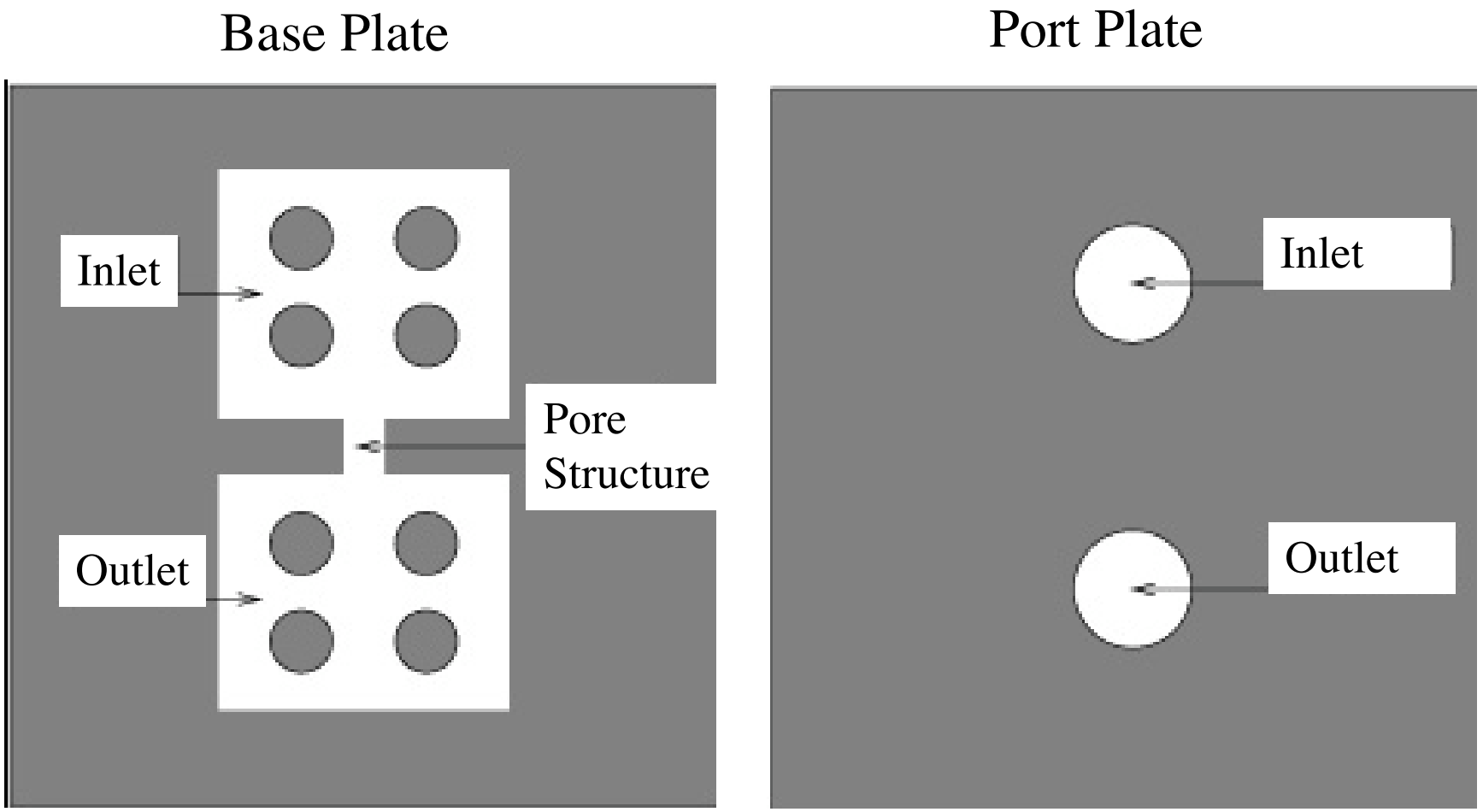


Figure 11. Double drainage sequence, with air displacing decane that displaces water, at the advancing water/decane interface: (a) air surrounded by decane, (b) as the air advances, decane is also forced into the surrounding water – this is double drainage, (c) air displaces decane, (d) snap-off of air front, leaving a disconnected bubble.

Type of Micro-Model: Projection Lithography

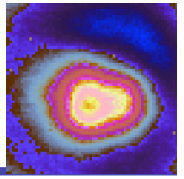


1. Contact Lithography



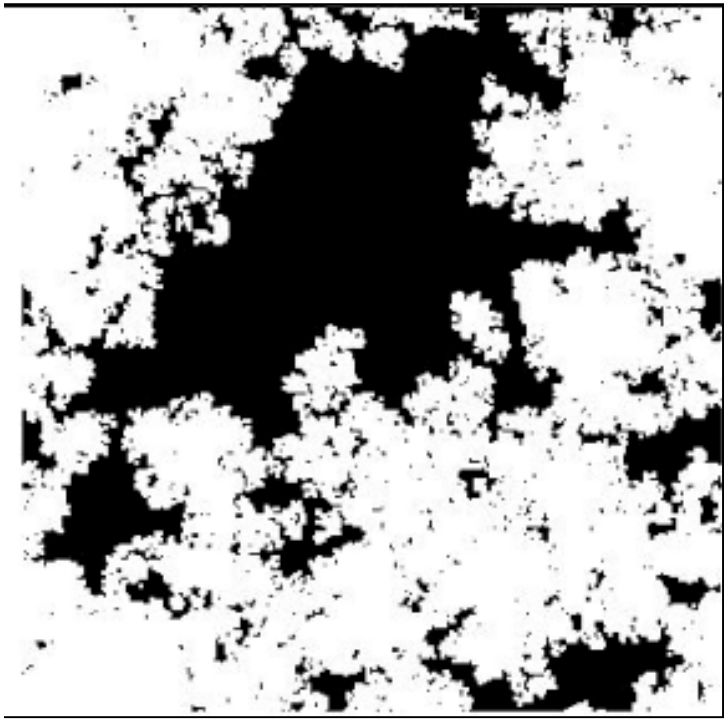
Cheng et al., 2004

Type of Micro-Model: Projection Lithography

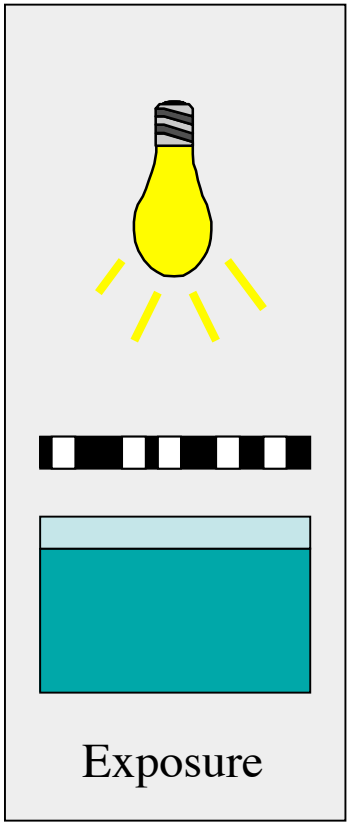


2. Projection Lithography

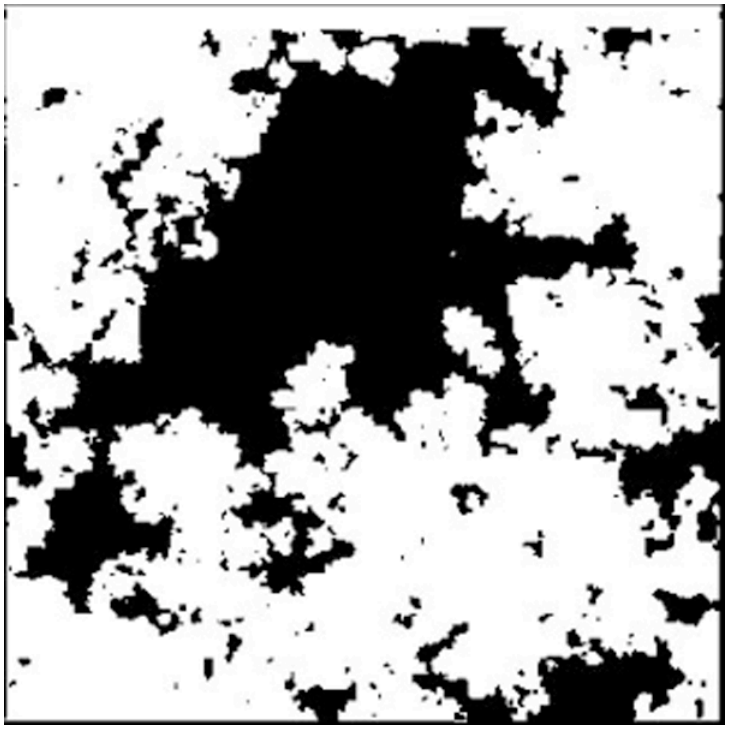
Desired Pattern



Exposure to UV



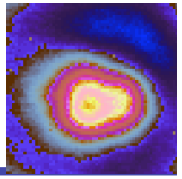
After Development Photoresist Micro-model



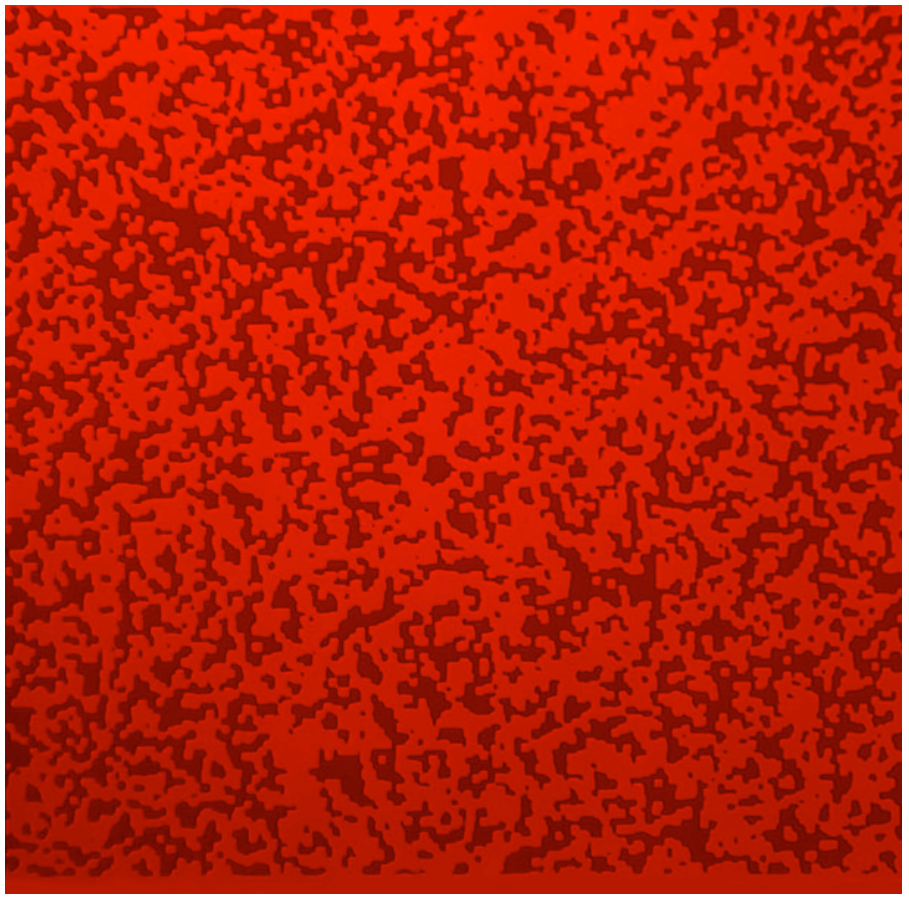
- Photoresist - Glass Slide - Mask

Cheng et al., 2004

Type of Micro-Model: Projection Lithography

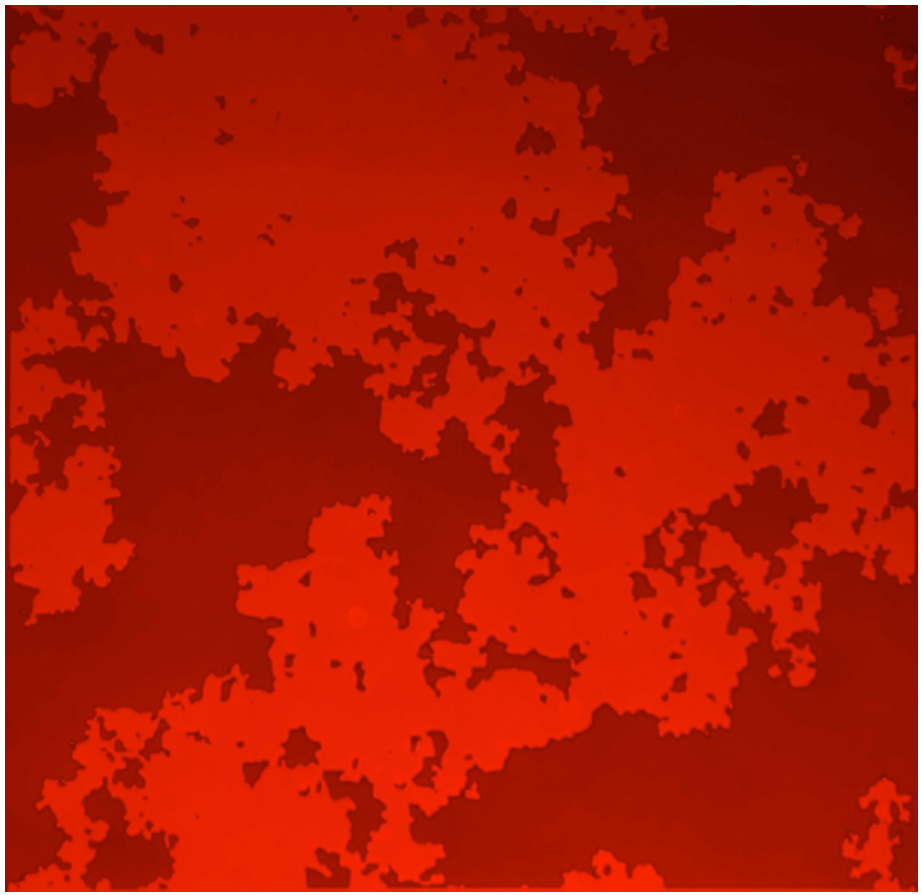


Spatially Uncorrelated



600 μm

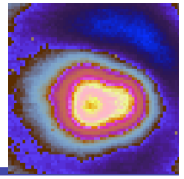
Spatially Correlated



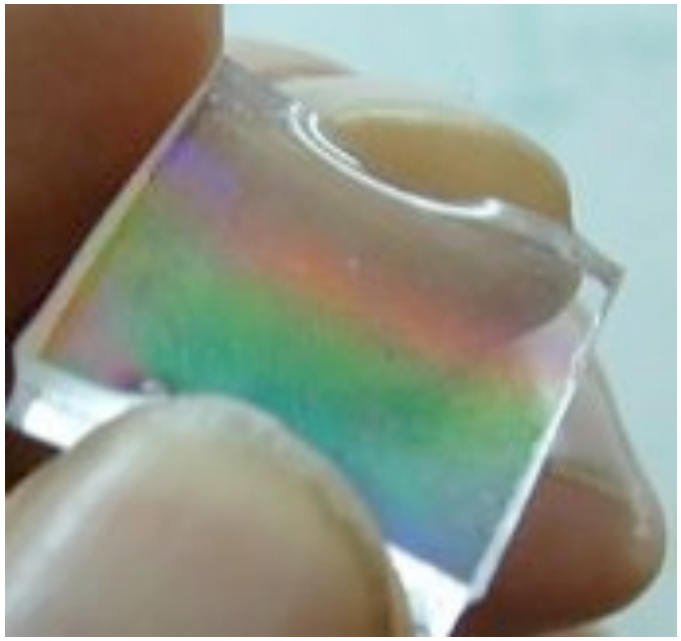
Aperture ~ 1.08 μm

Cheng et al., 2004

Types of Micro-Models: Soft Lithography



"An elastomeric block with patterned relief structures on its surface is the key to soft lithography." (Xia & Whitesides, 1998)



http://www.ws.chemie.tu-muenchen.de/uploads/pics/pdms300_01.jpg

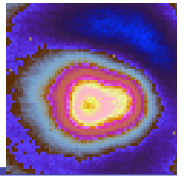
Most Common Elastomer:

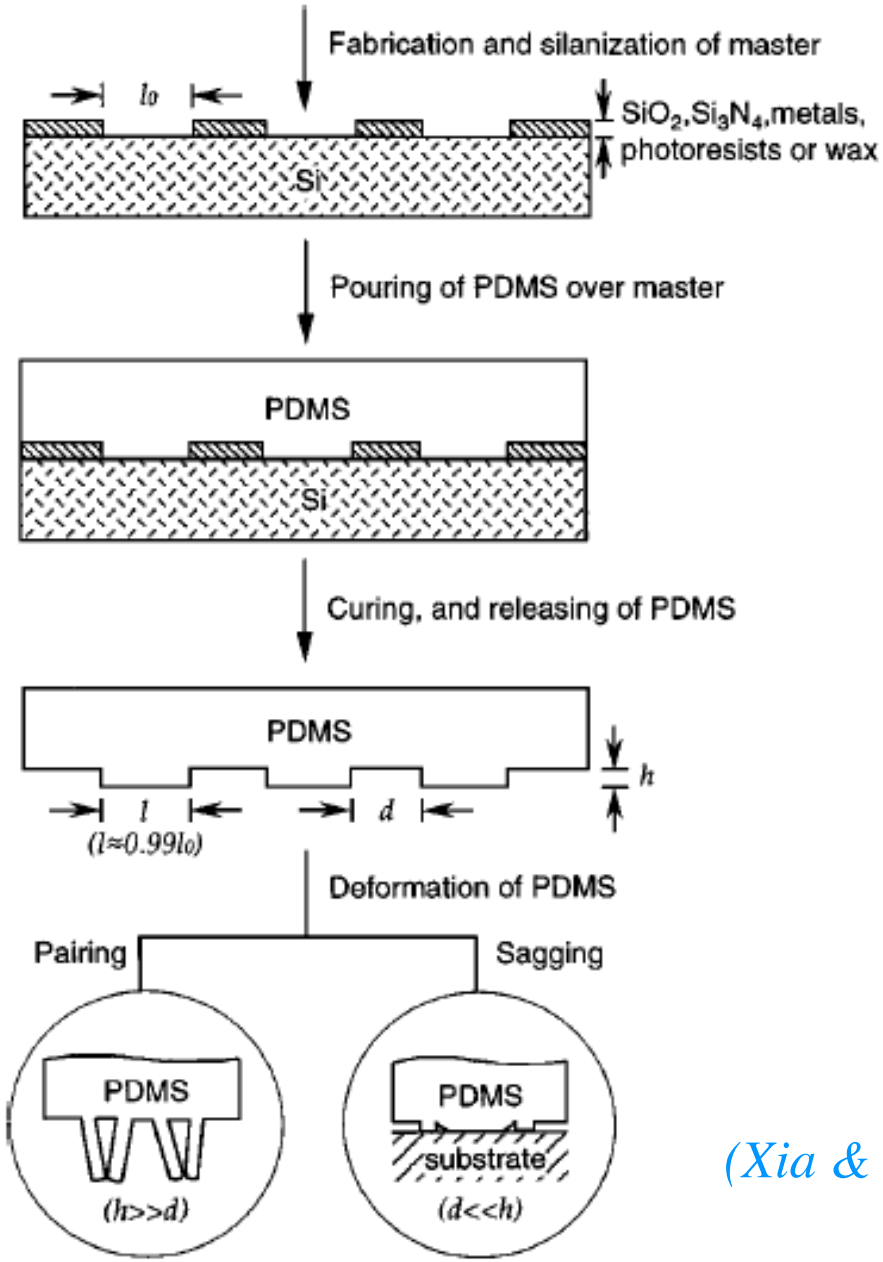
PDMS: Poly(dimethylsiloxane)

Other Elastomers:

polyurethanes, polyimides,
phenol formaldehyde polymer

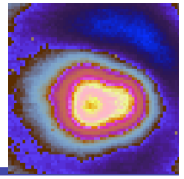
Types of Micro-Models: Soft Lithography

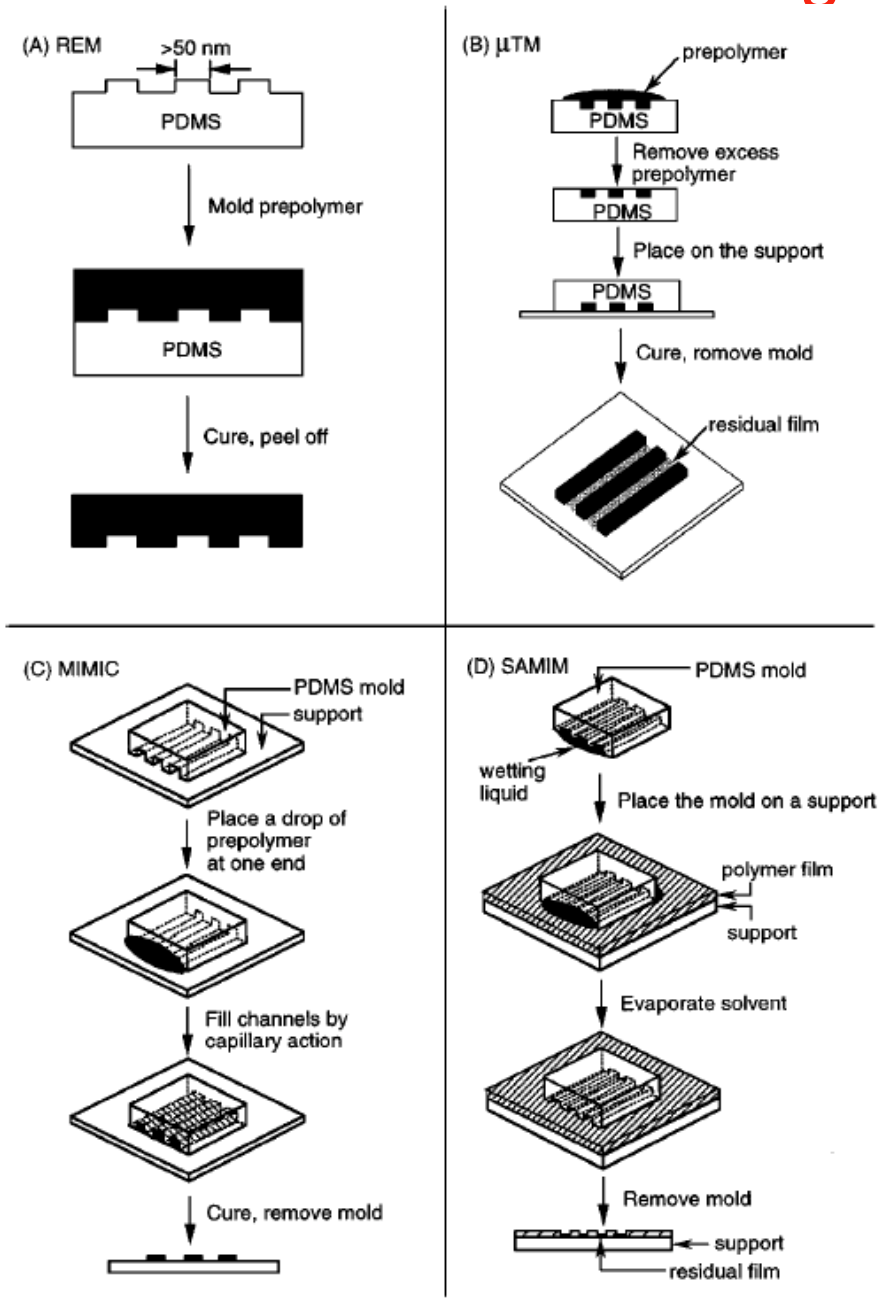




(Xia & Whitesides, 1998)

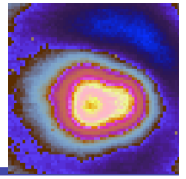
Types of Micro-Models: Soft Lithography



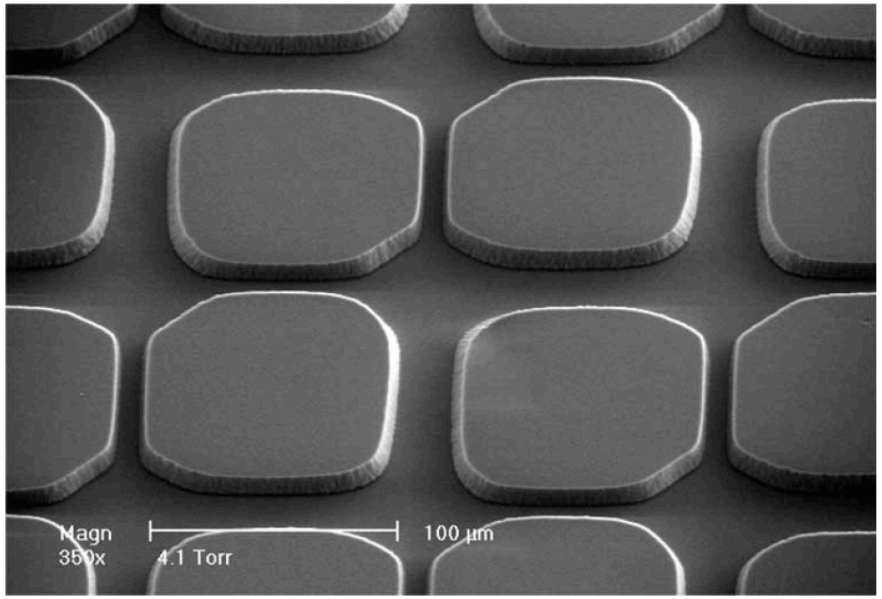


(Xia & Whitesides, 1998)

Types of Micro-Models: Soft Lithography



PDMS: Example from Hydrology Community

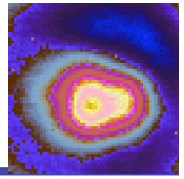


Auset & Keller, 2004

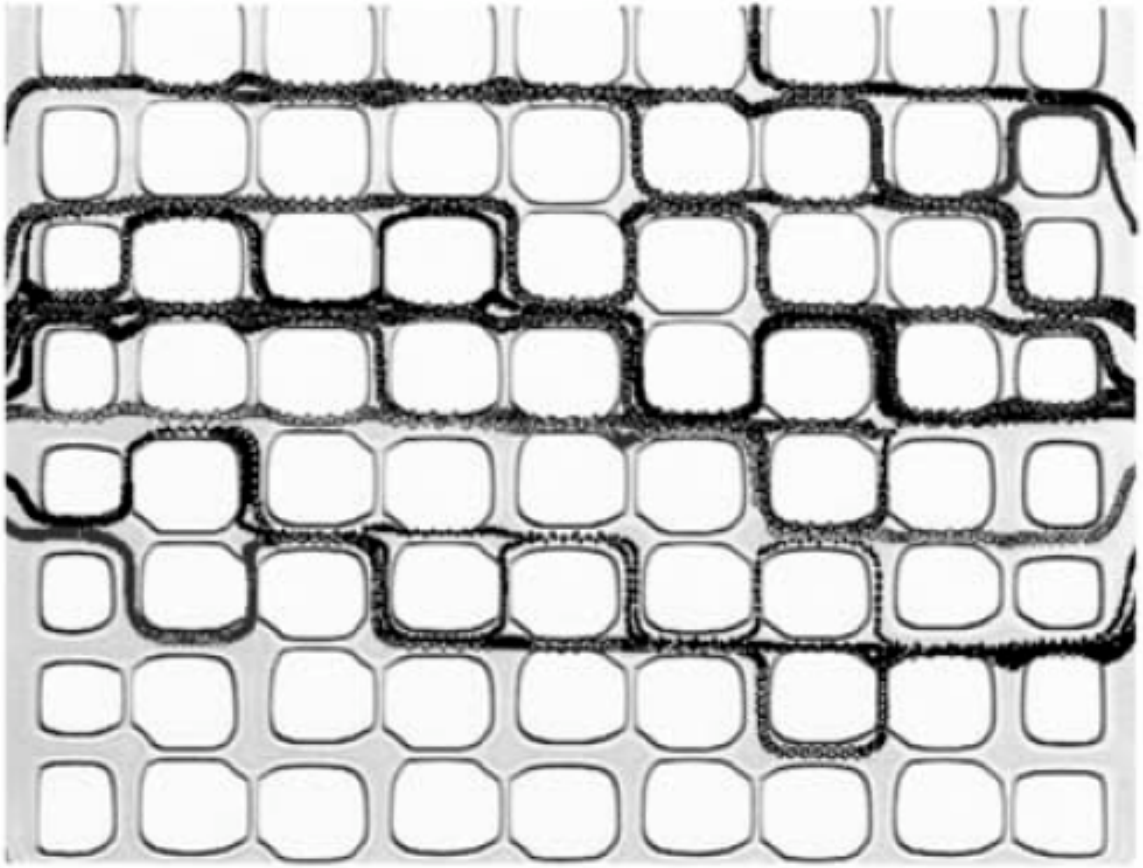
Table 1. Physical and Hydraulic Properties of Micromodels

	Micromodel		
	A	B	C
Length, mm	1	1	1
Width, mm	0.8	0.8	0.8
Porosity	0.228	0.358	0.278
Thickness, mm	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-2}
Pore volume, mm^3	2.7×10^{-3}	4.3×10^{-3}	3.3×10^{-3}
Permeability, mm^2	1.2×10^{-6}	6.2×10^{-6}	2.6×10^{-6}

Types of Micro-Models: Soft Lithography

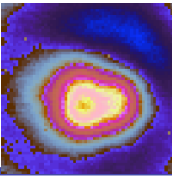


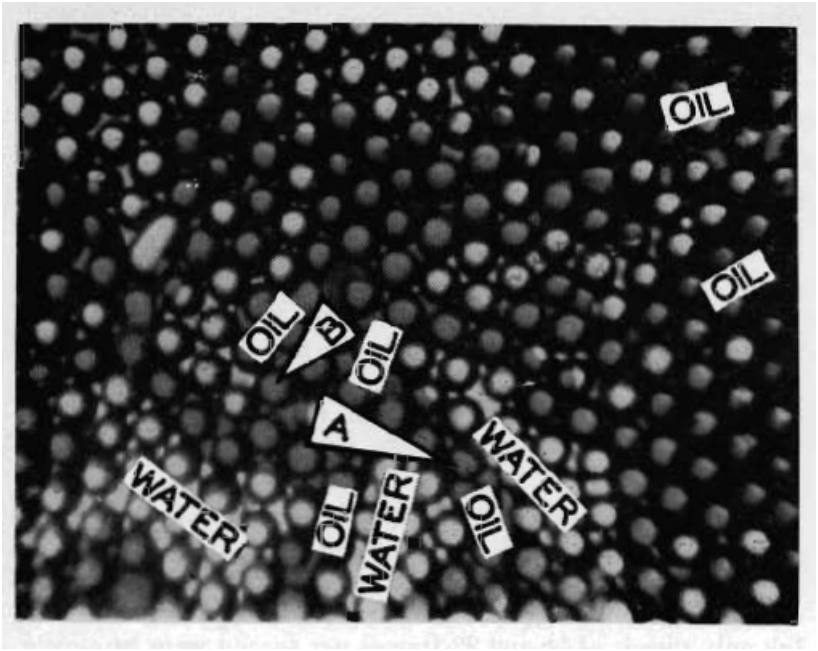
PDMS: Example from Hydrology Community

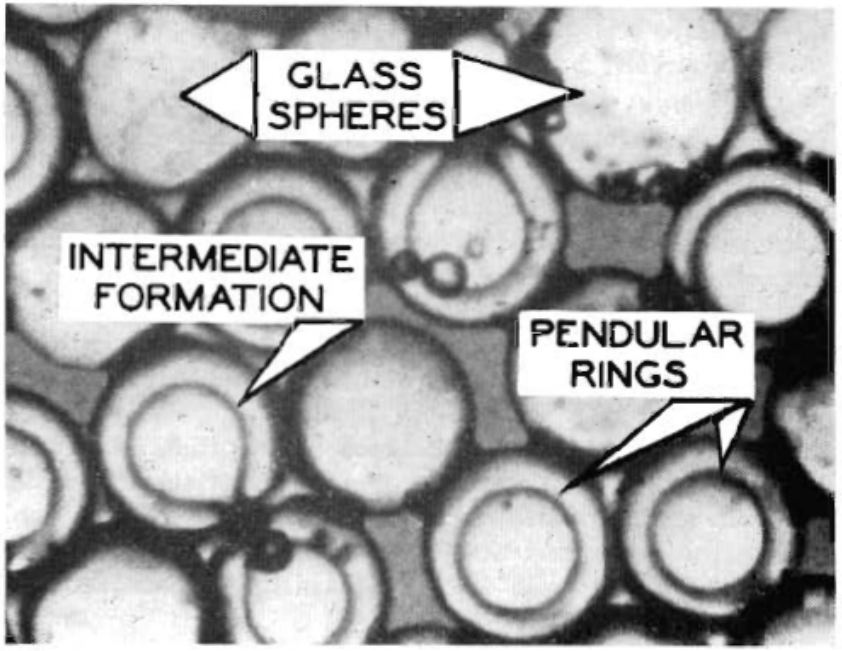


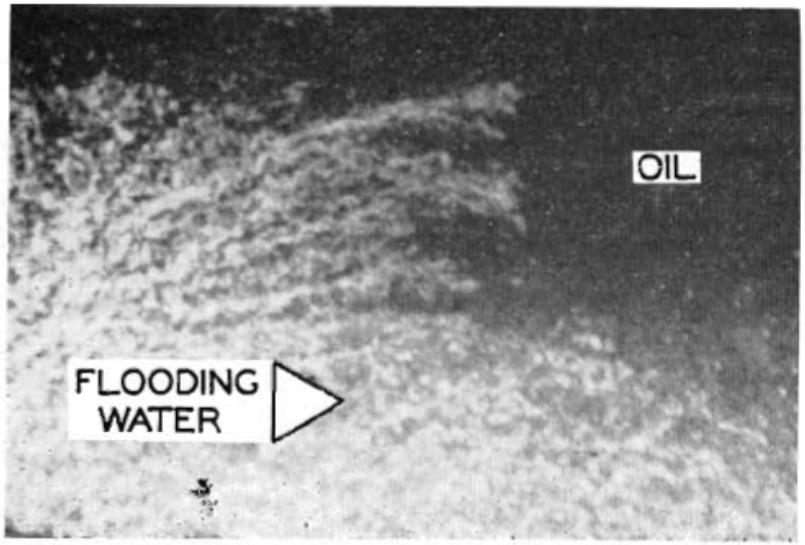
Auset & Keller, 2004

Types of Micro-Models: Glass Beads





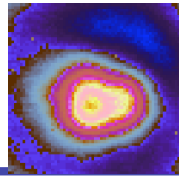




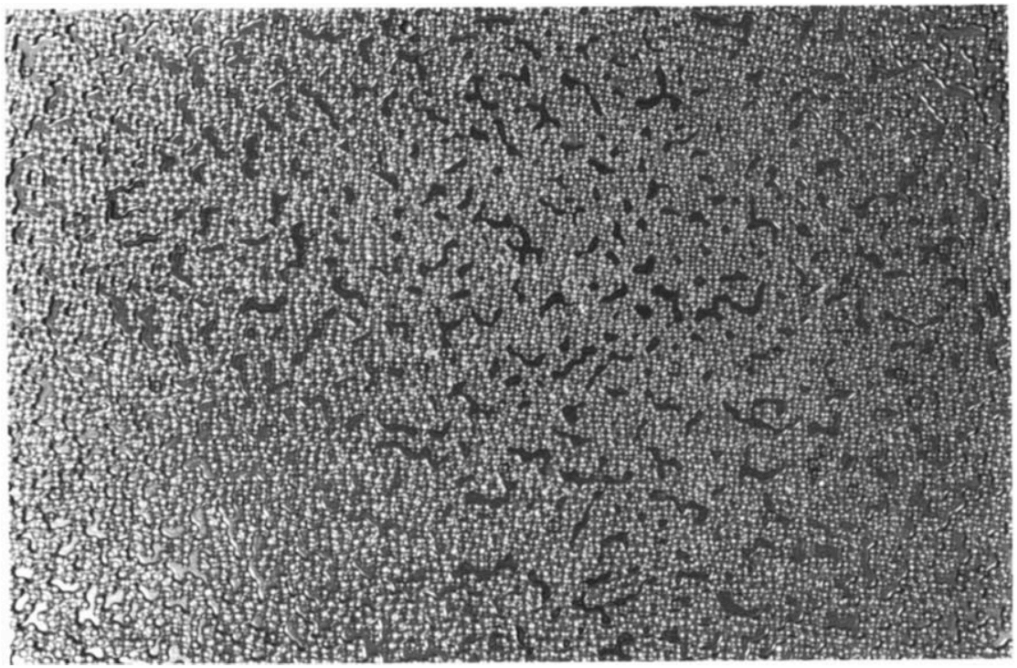
(*Chatenever & Calhoun, 1952*)

One layer of 178 microns in diameter spherical glass beads

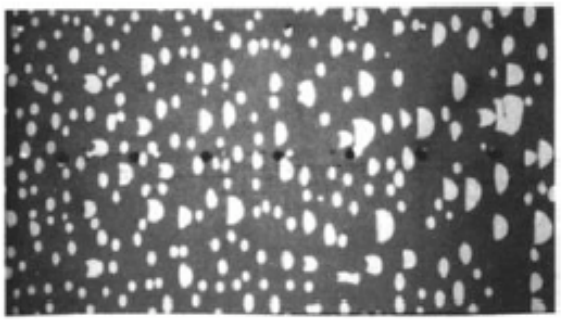
Types of Micro-Models: Glass Beads

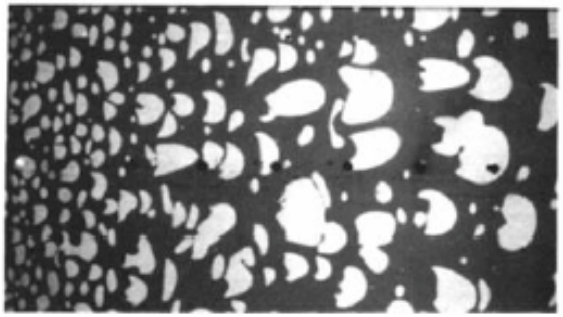


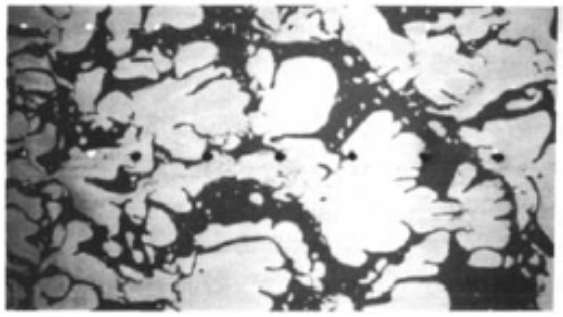
Glass Balls, Fourar et al, 1993



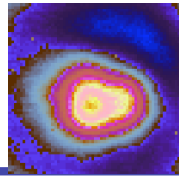
1 mm glass spheres



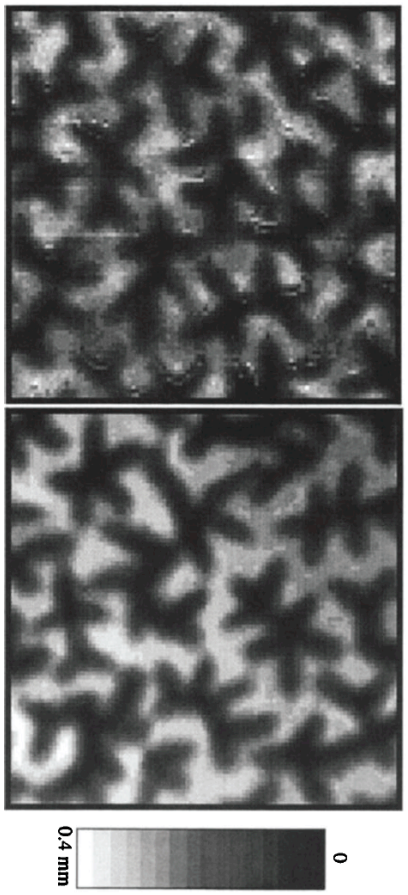


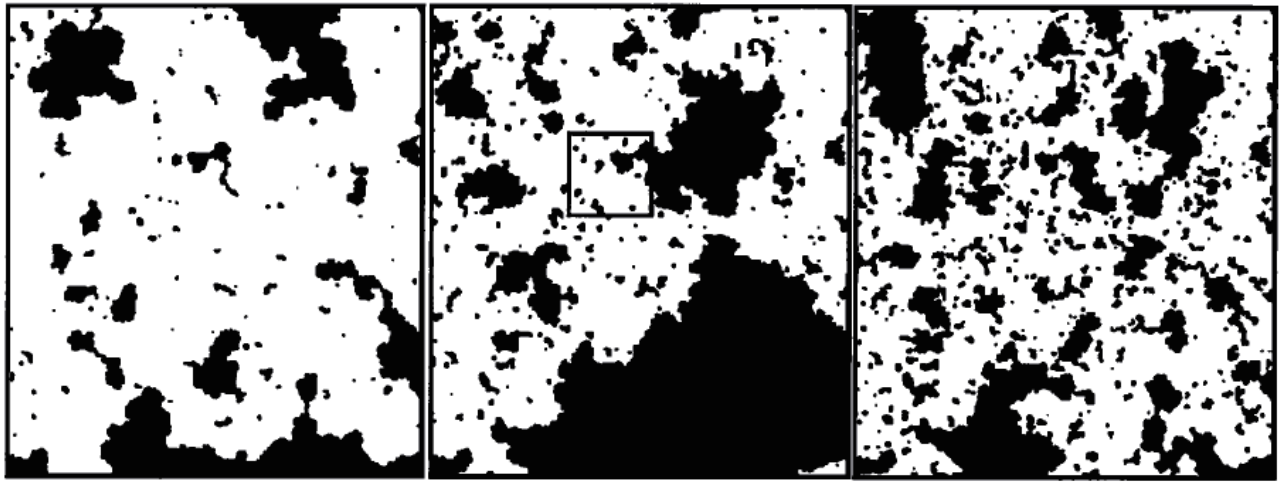


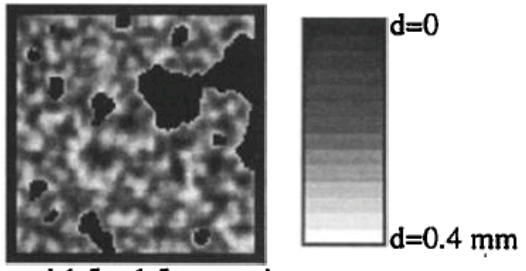
Types of Micro-Models: Simulacrum



Detwiler et al., 1999

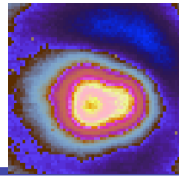






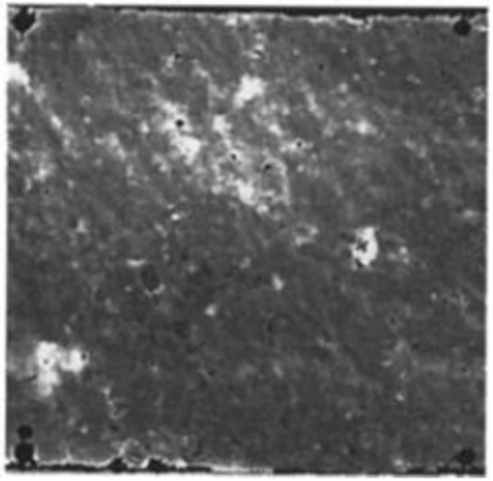
Enlarged 1.5 x 1.5 cm region
of aperture field from optimal field

Types of Micro-Models: Replicas

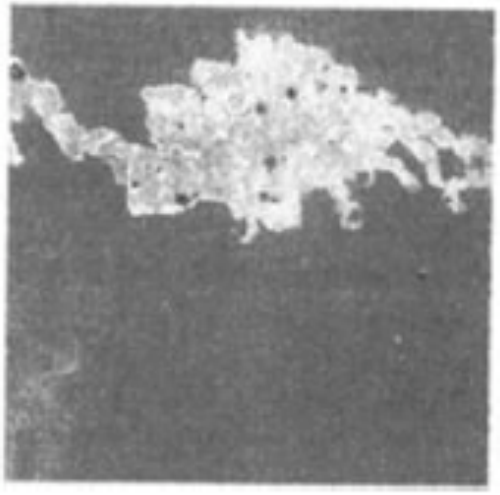


Fracture Casts

Brown et al., 1998

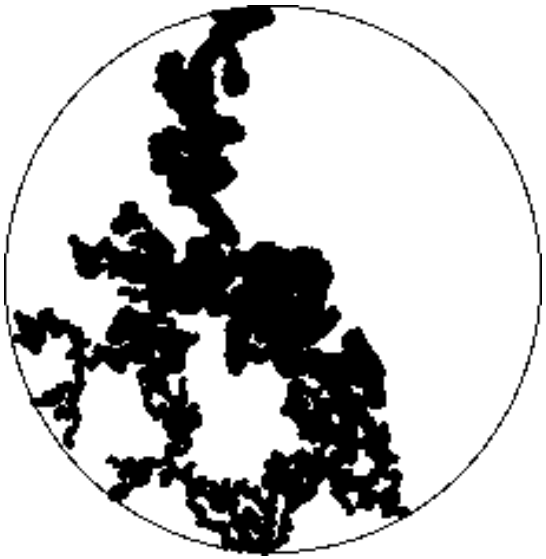


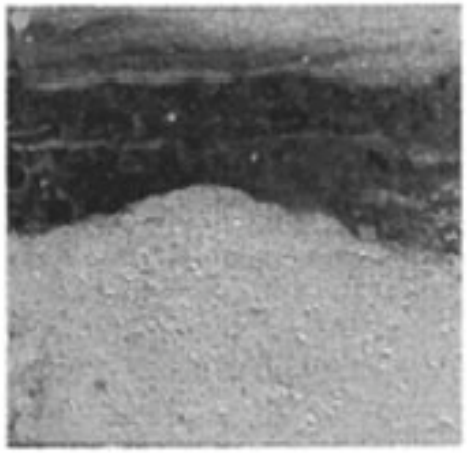
Dry Fracture



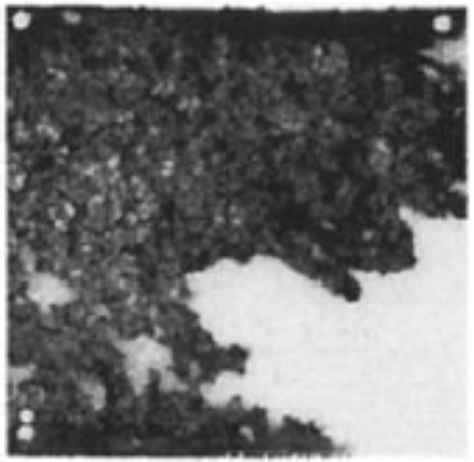
Air Invasion

Pyrak-Nolte et al., 1992



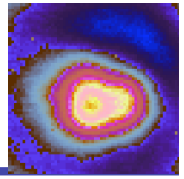


Dye

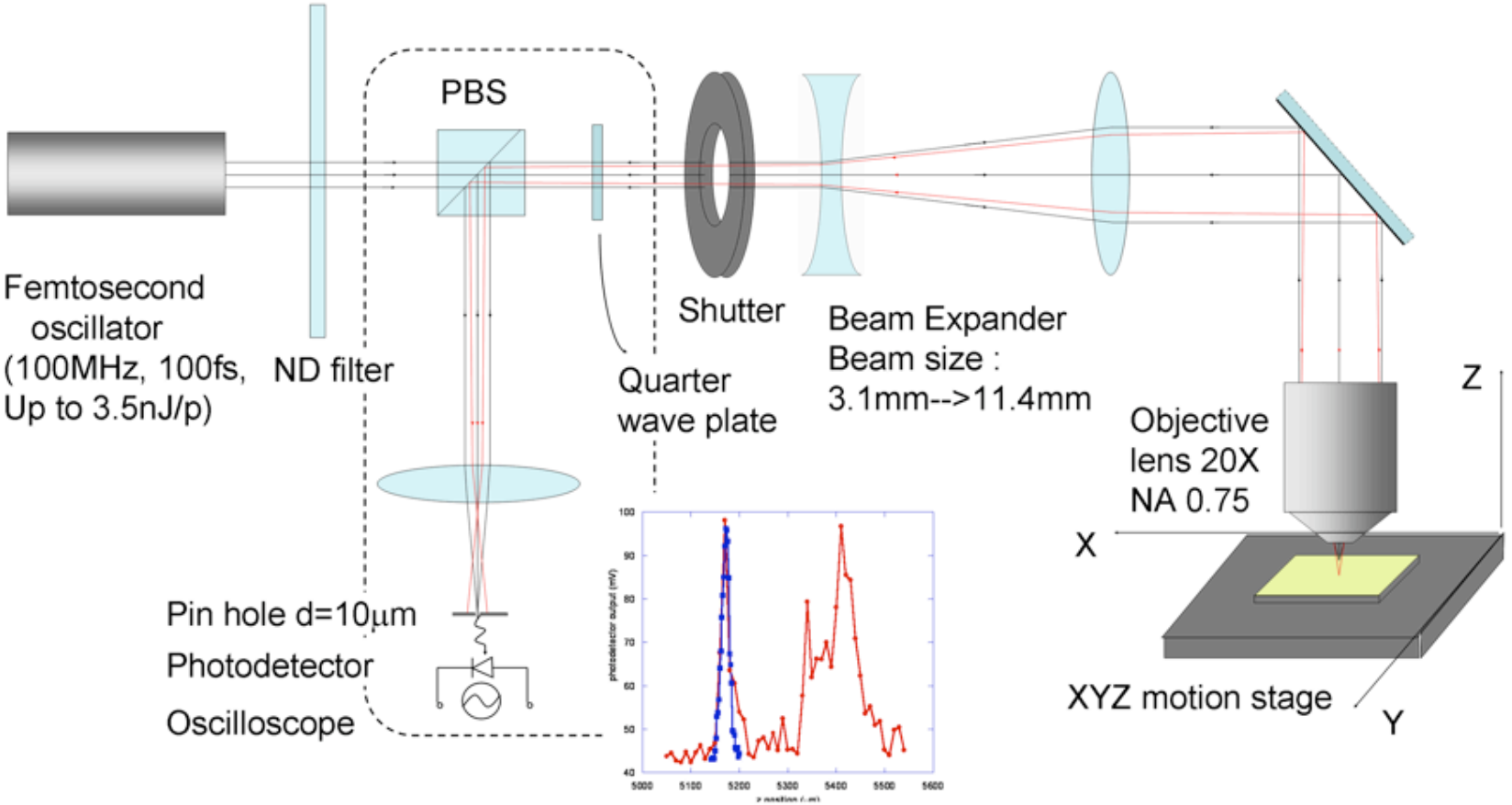


Water Invasion

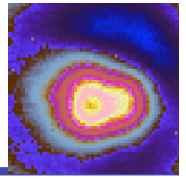
Micro-Models: Toward Three-Dimensions



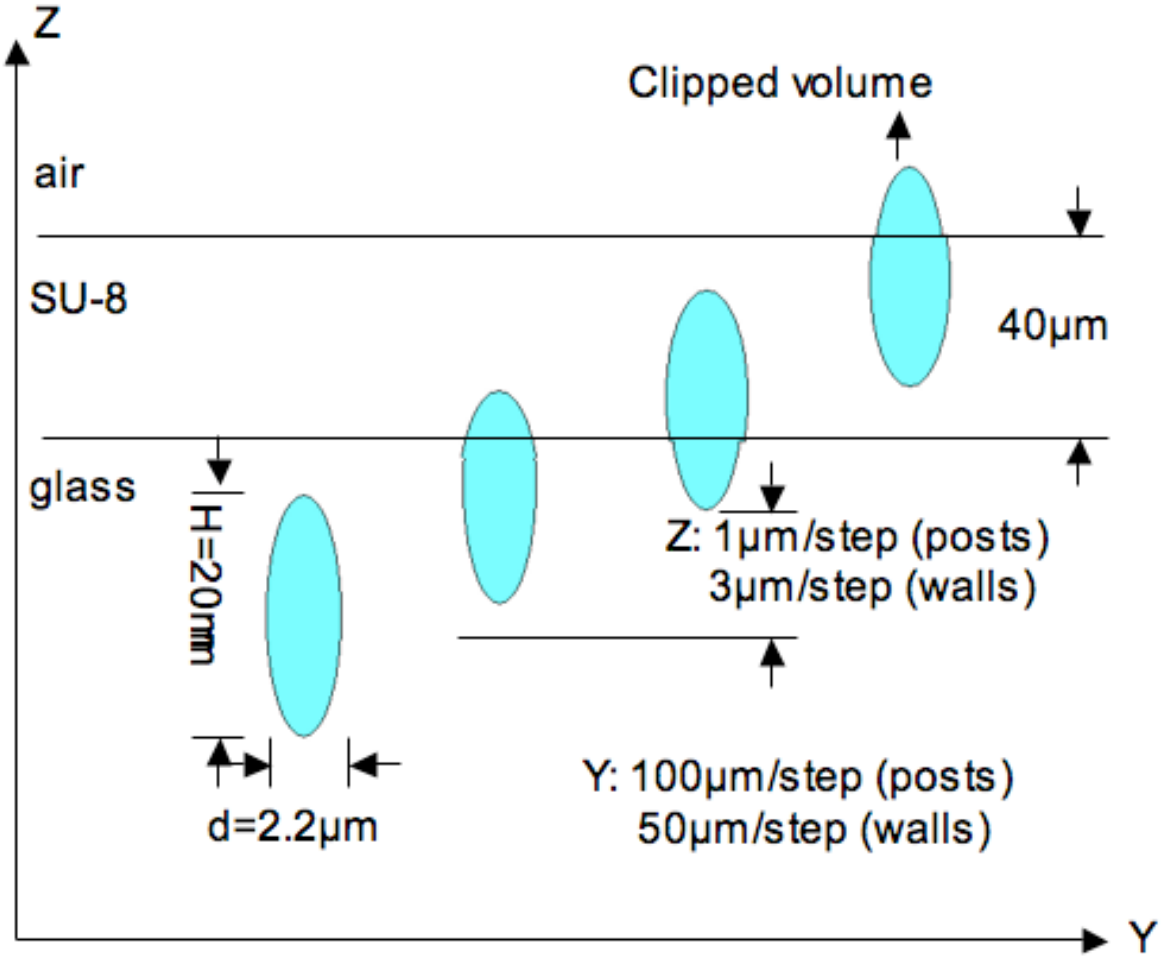
*Two Photon Adsorption Lithography

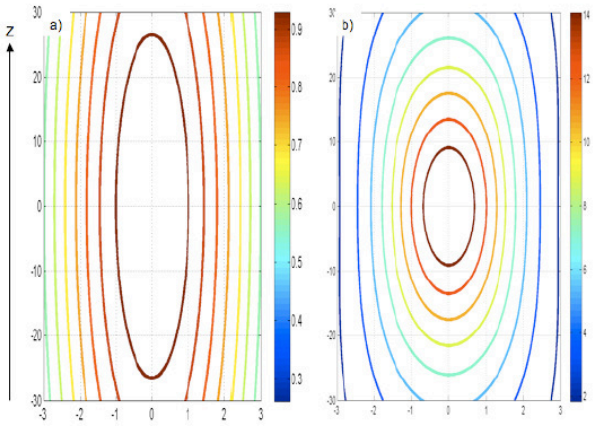


Micro-Models: Toward Three-Dimensions



*Two Photon Adsorption Lithography



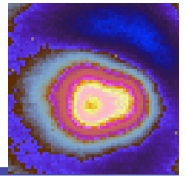


$$I^2 \beta \tau \upsilon t \geq F_{th}$$

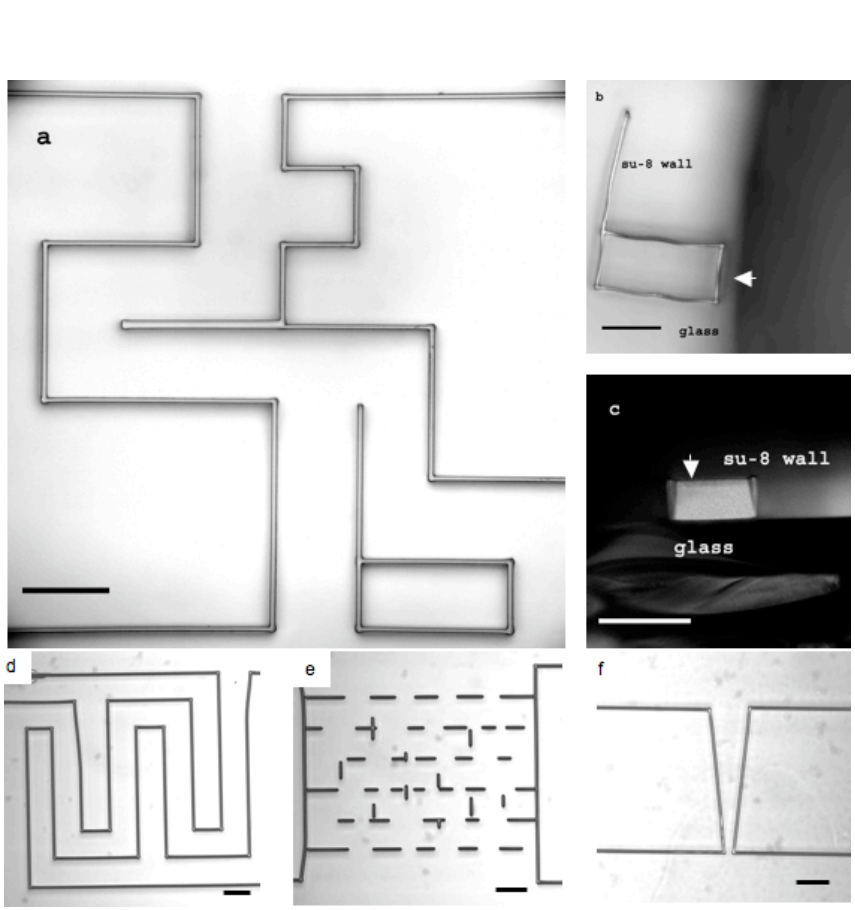
$$d = w_o \sqrt{\ln\left(\frac{I_o^2 t \beta \tau \upsilon}{F_{th}}\right)}$$

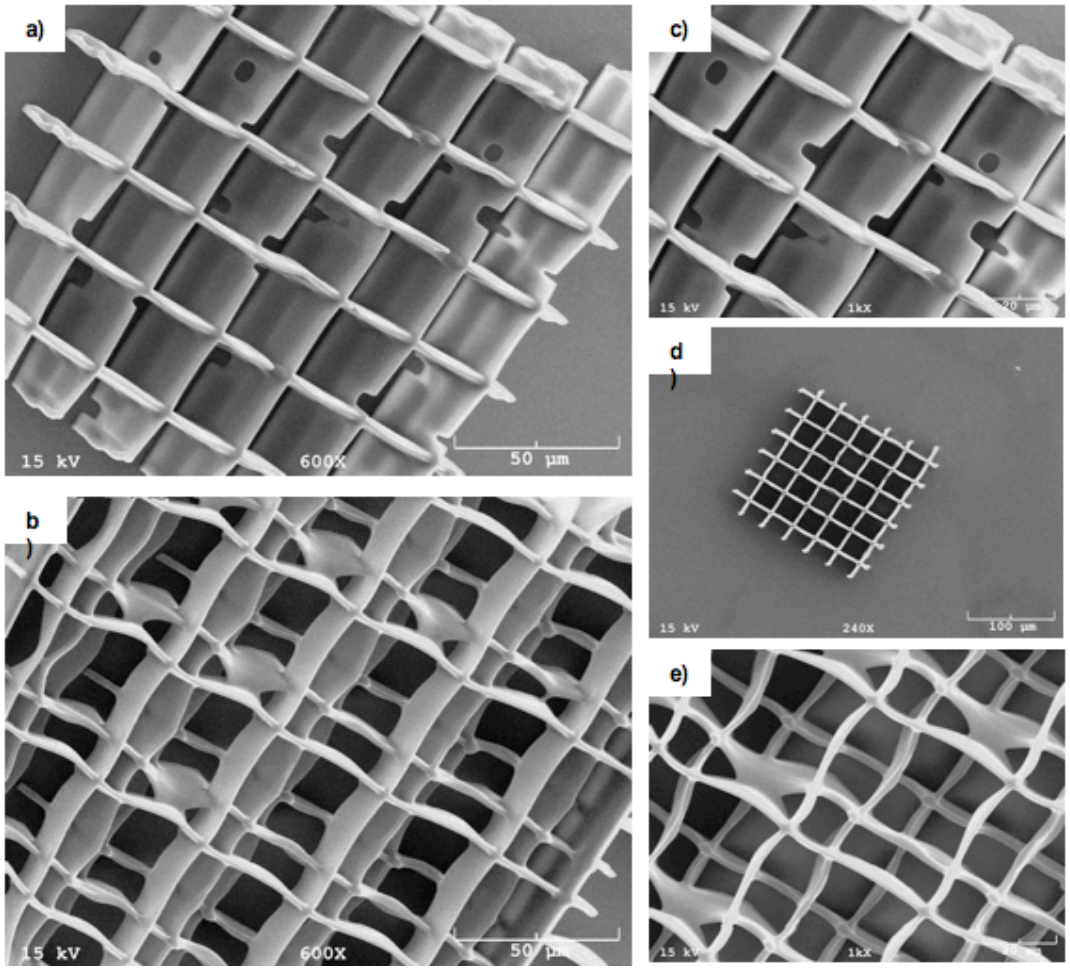
$$H = \frac{2 z_r}{n} \sqrt{\exp\left(\frac{1}{2}\frac{d^2}{w_o^2}\right) - 1}$$

Micro-Models: Toward Three-Dimensions

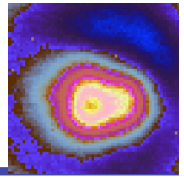


*Two Photon Adsorption Lithography

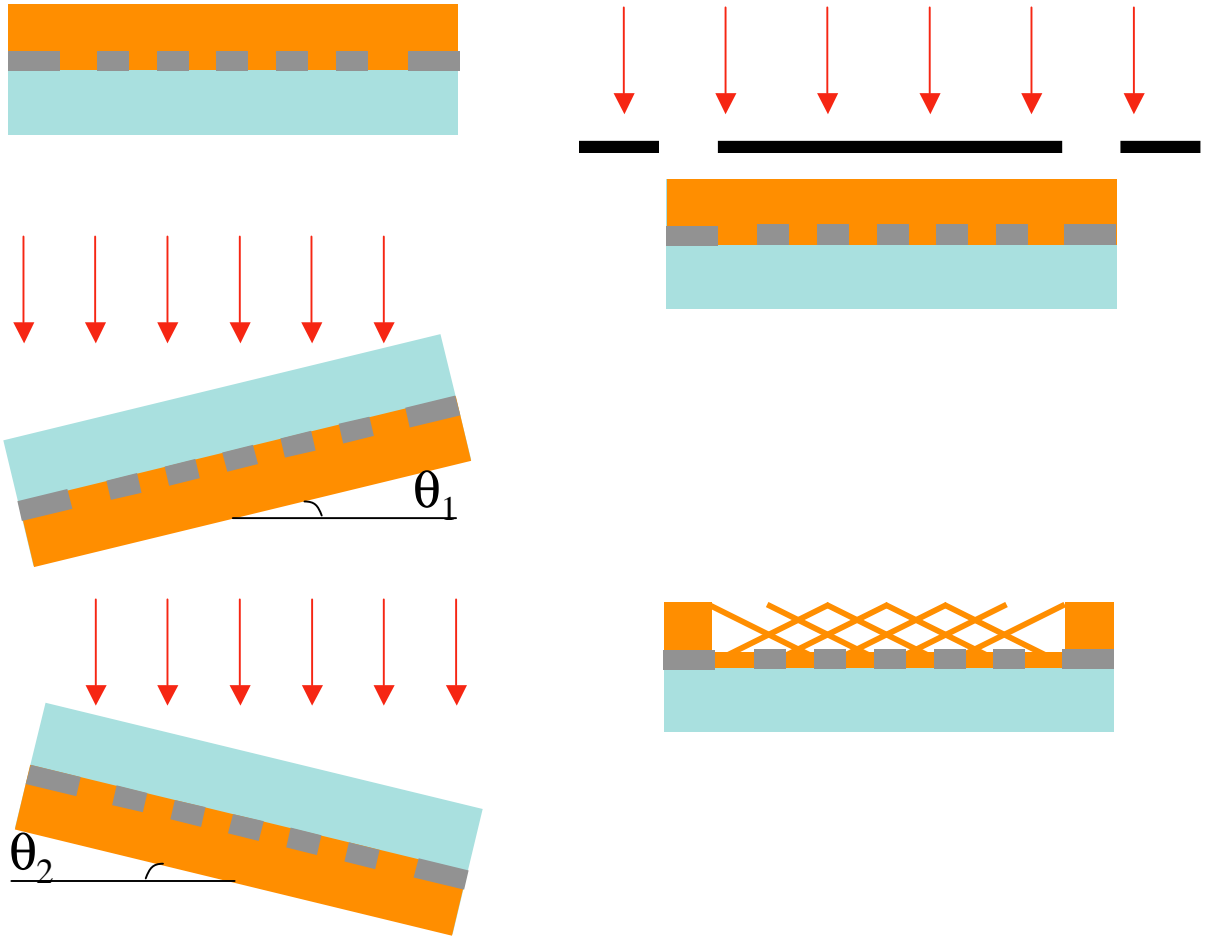




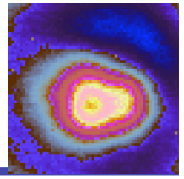
Micro-Models: Three-Dimensions



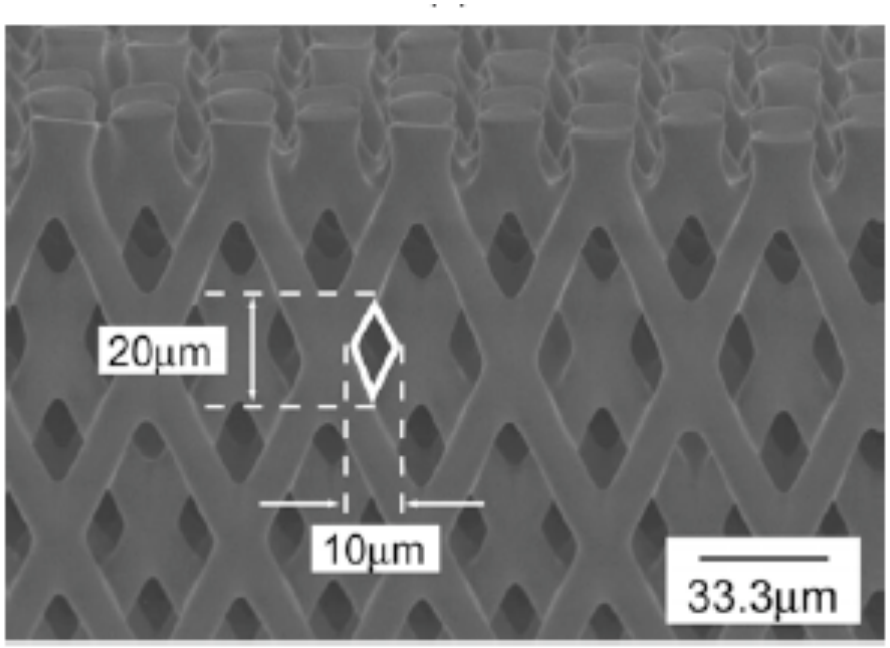
*High Angle Exposure



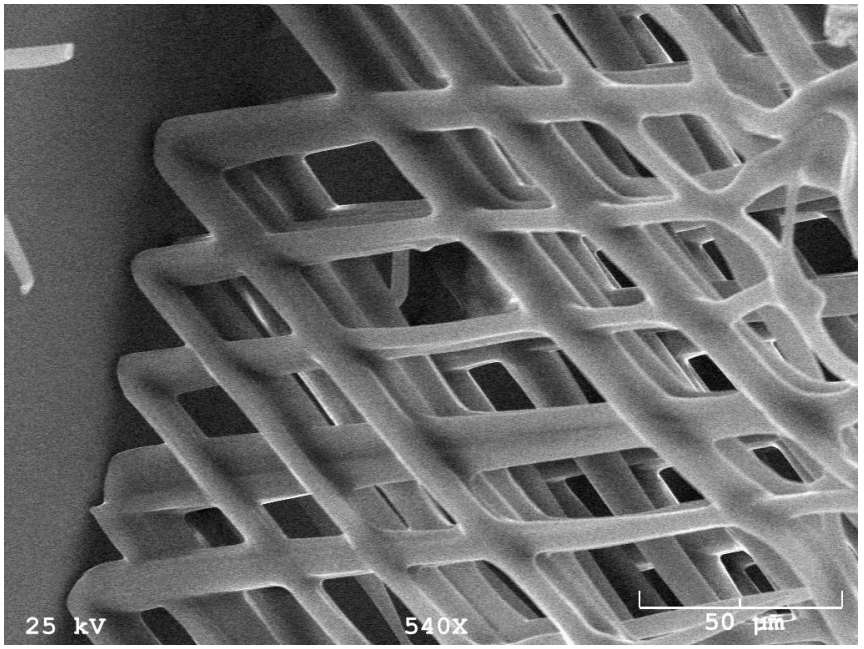
Micro-Models: Three-Dimensions



*High Angle Exposure

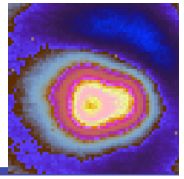


(Sato et al., 2003)



(Liu 2009-2010 in progress)

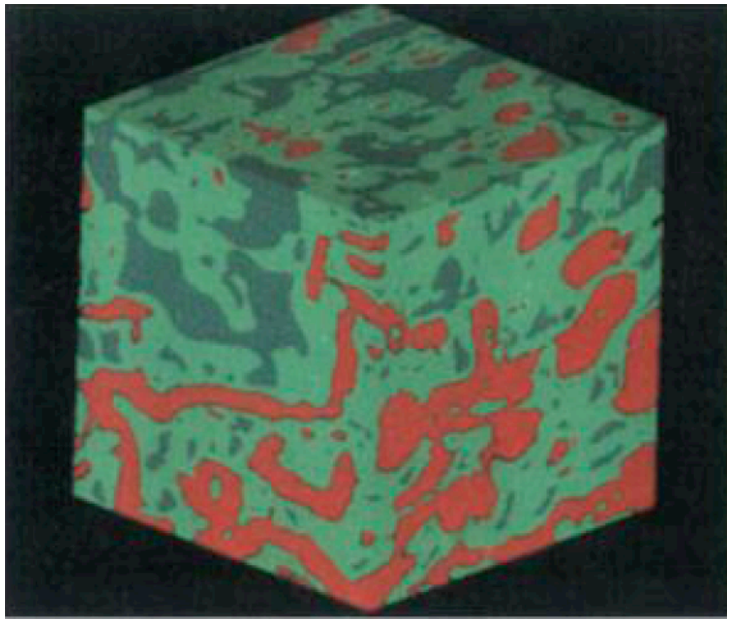
Micro-Models: Three-Dimensional

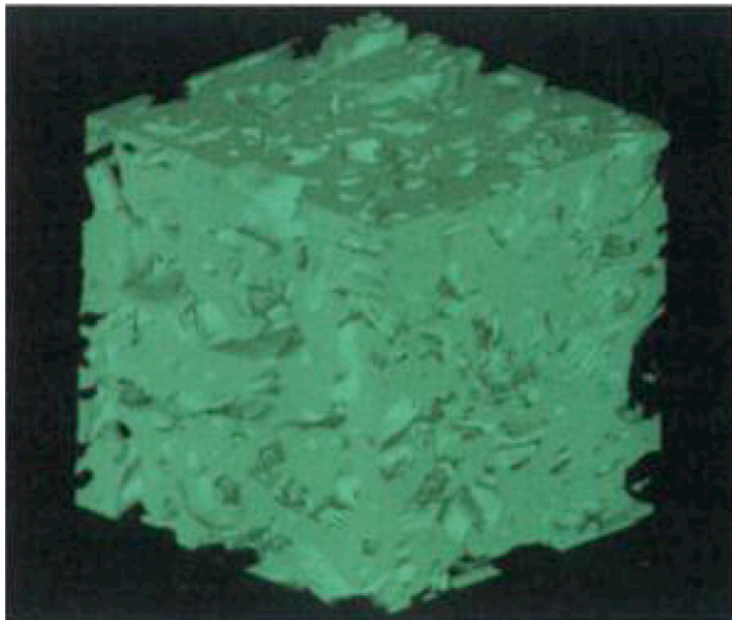


*Optical quality glass sand

*Index matched fluids

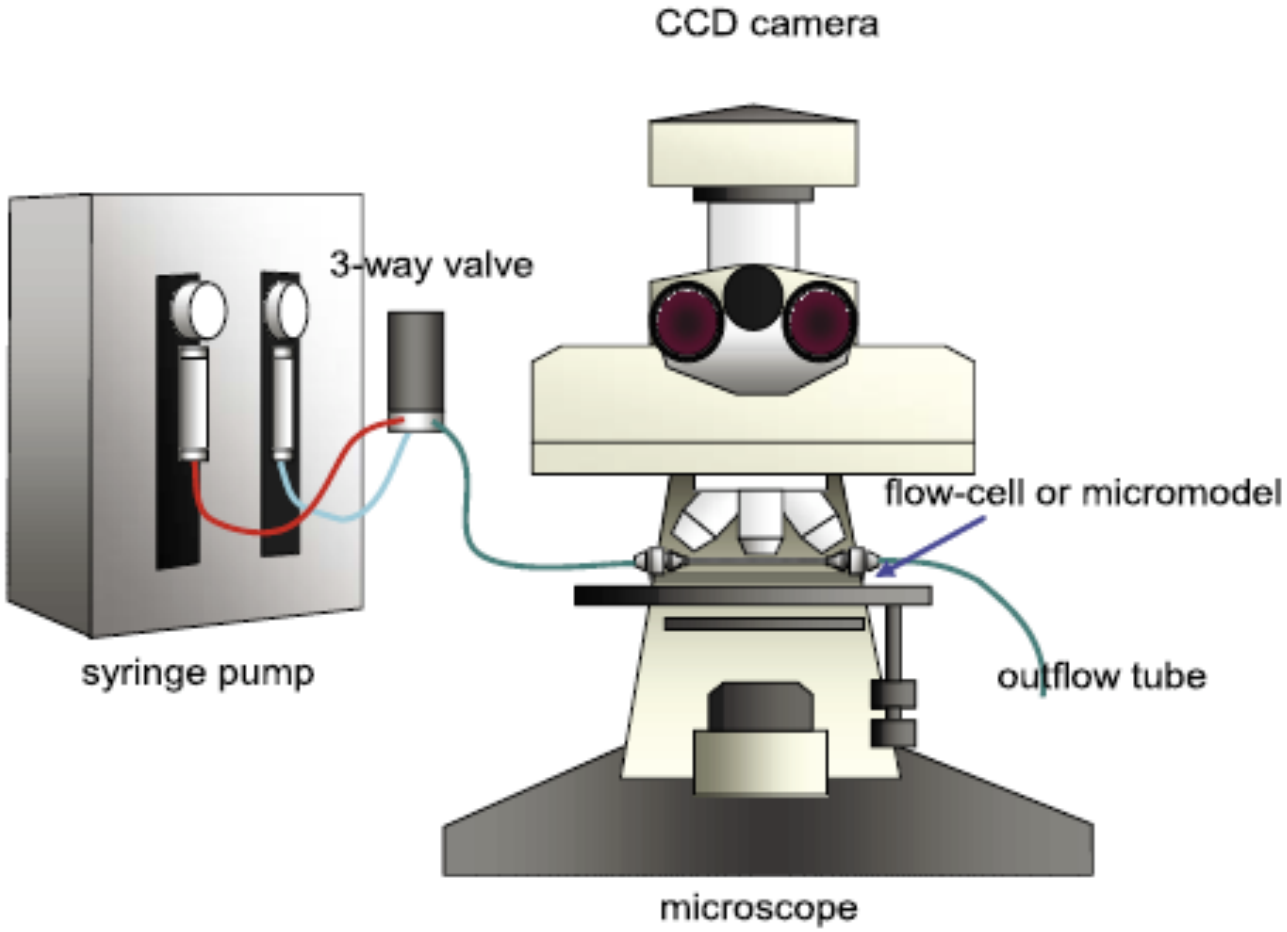
*Fluorophores





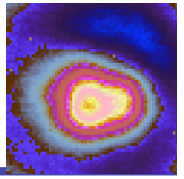
Montemagno & Gray, 1995

Imaging Systems: Optical Microscope



(from Ochiai et al., 2006)

Imaging Systems: Visualization Chambers



*Sand packs, fracture replicas

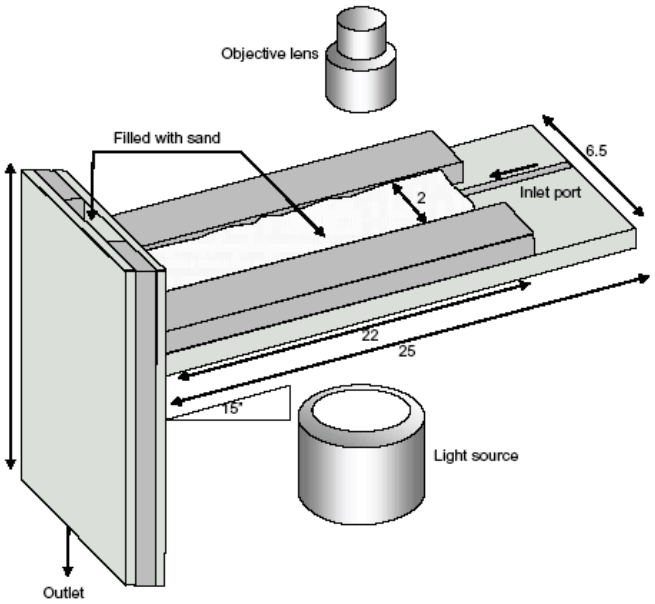


Figure 5. Schematic of tilted, open-faced visualization chamber utilized by *Crist et al.* [2004, 2005] and *Zevi et al.* [2005], showing chamber dimensions and positioning of video magnification lens and light source. Adapted with permission from *Zevi et al.* [2005] Copyright 2005 American Chemical Society.

(from Ochiai et al., 2006)

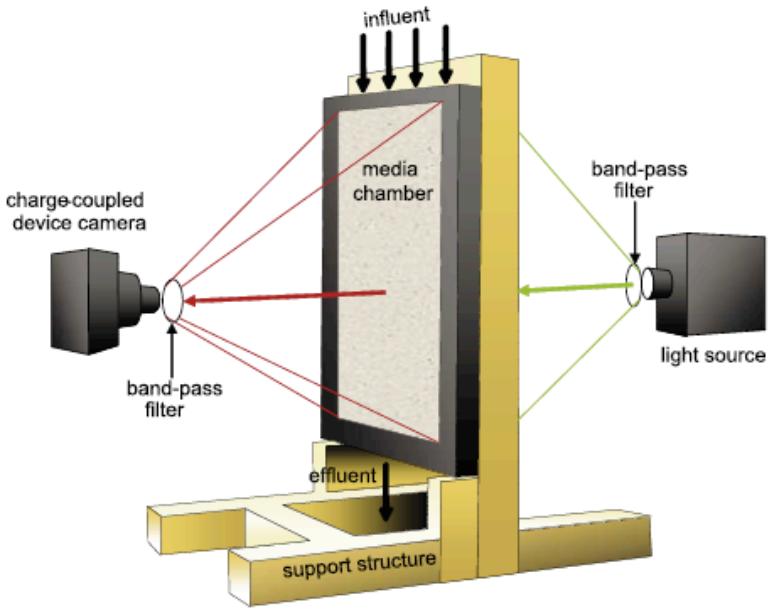
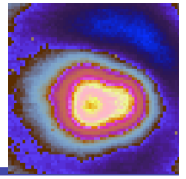
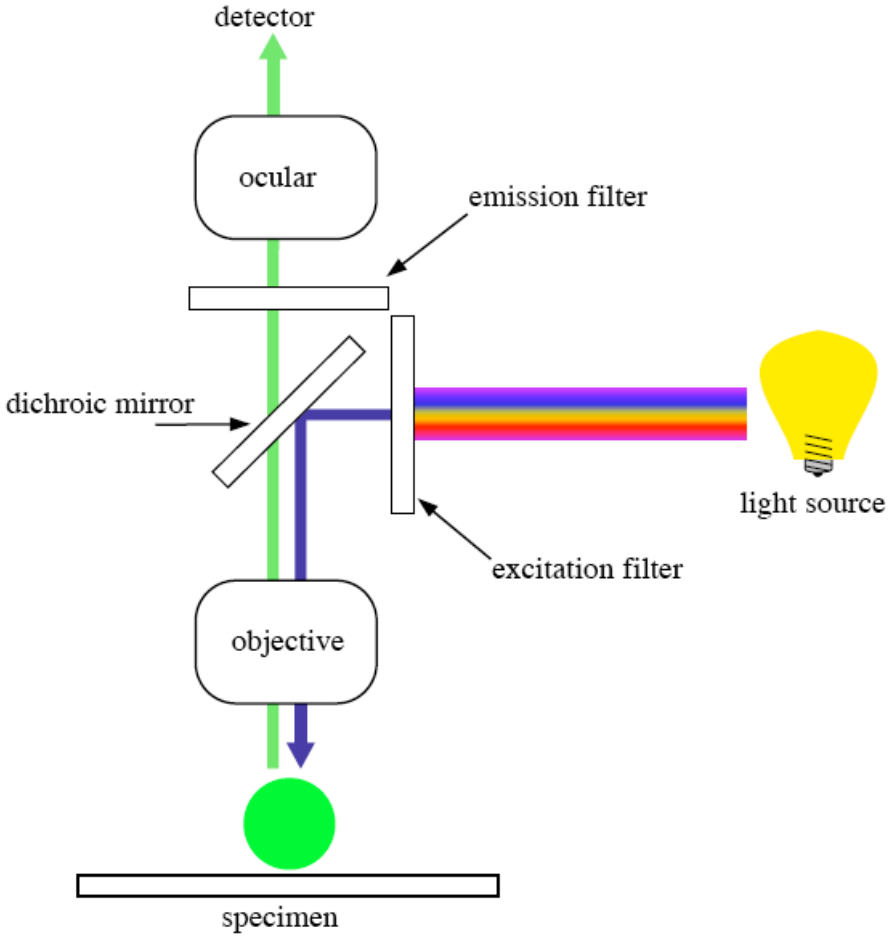


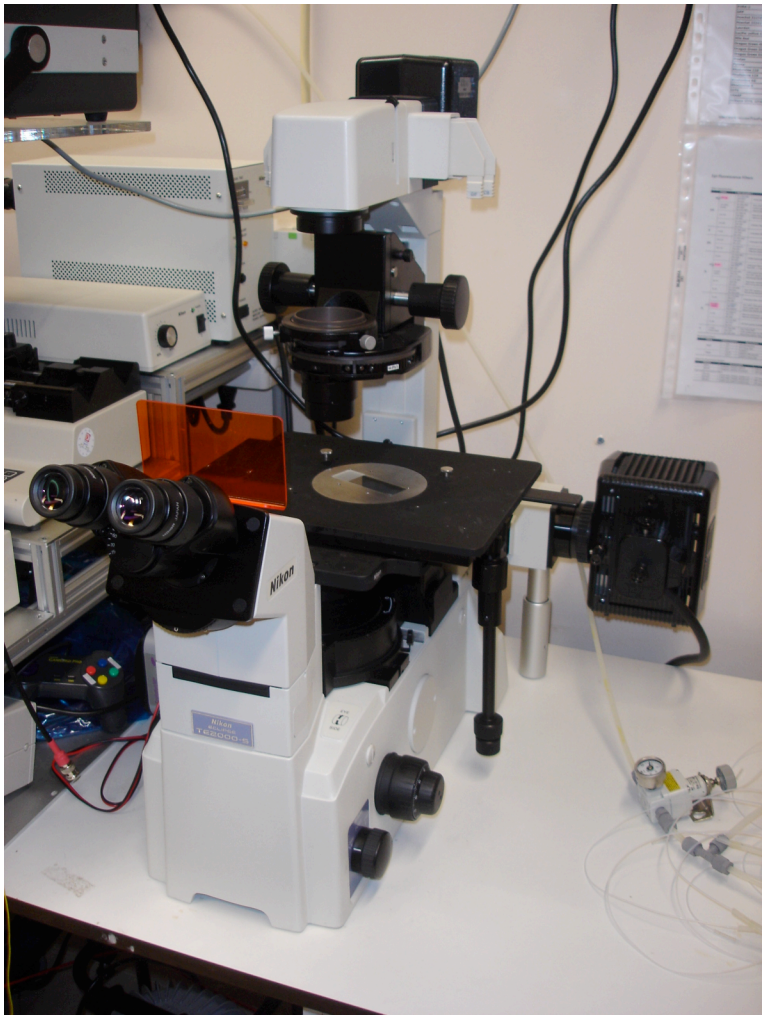
Figure 9. Schematic of mesoscale light transmission visualization under development by *Kraft and Selker* [2005], showing arrangement of optical components and media chamber. Note: not drawn to scale.

Imaging Systems: Epifluorescence Microscope

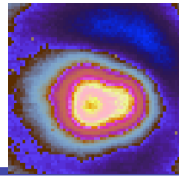


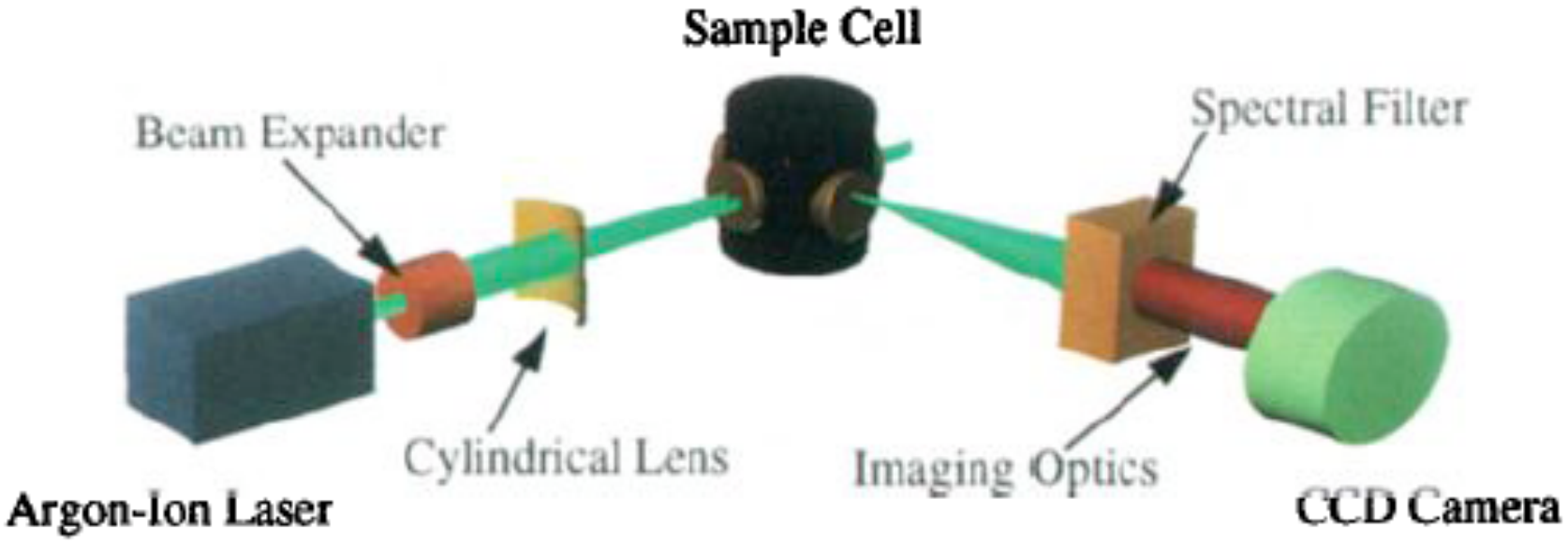


Example: Nikon TE2000



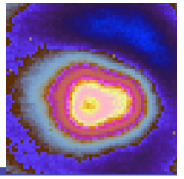
Imaging Systems: PVI

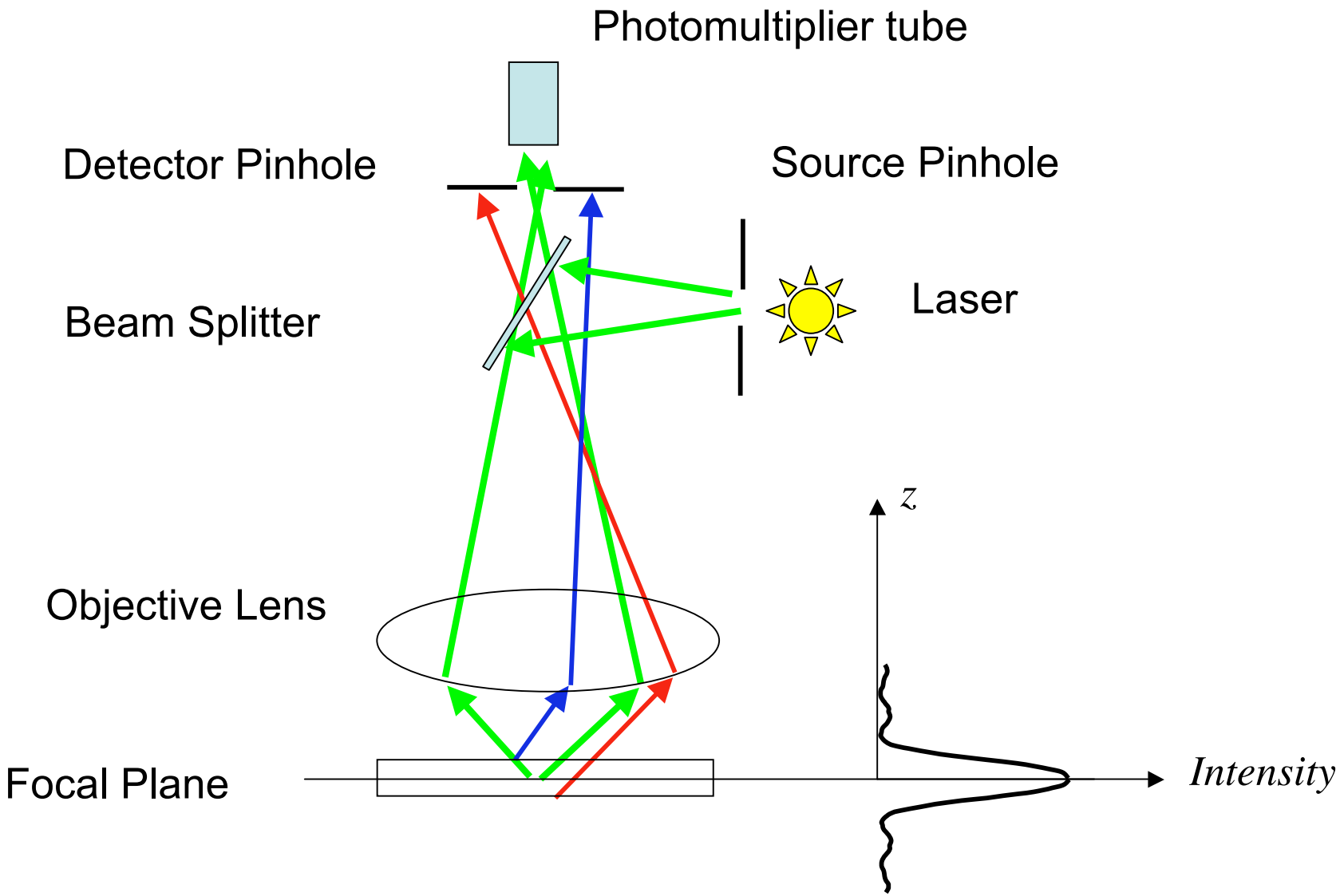




Montemagno & Gray, 1995

Imaging Systems: Laser Confocal Microscopy





(after Fredrich & Wong, 1995; Fredrich, 1999)

Laser Confocal Microscopy

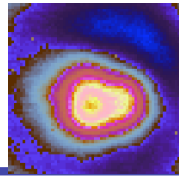
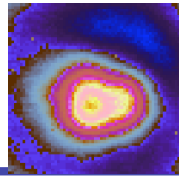


Table 1. Lateral resolution R (Eq. 1) and optical section thickness at λ=514 nm for various settings of the confocal aperture

Objective		R (µm)	Section thickness (µm)			
M	*NA*		Open	1/3	2/3	Closed
×10	0.45	0.71	38	25	13	7.0
×20	0.75	0.42	14	10	6.7	5.0
×40	1.0	0.31	6.1	4.2	2.6	1.4
×60	1.4	0.22	3.7	2.0	1.0	0.7

(Fredrich & Wong, 1995; Fredrich, 1999)

Imaging Systems: Laser Confocal Microscopy



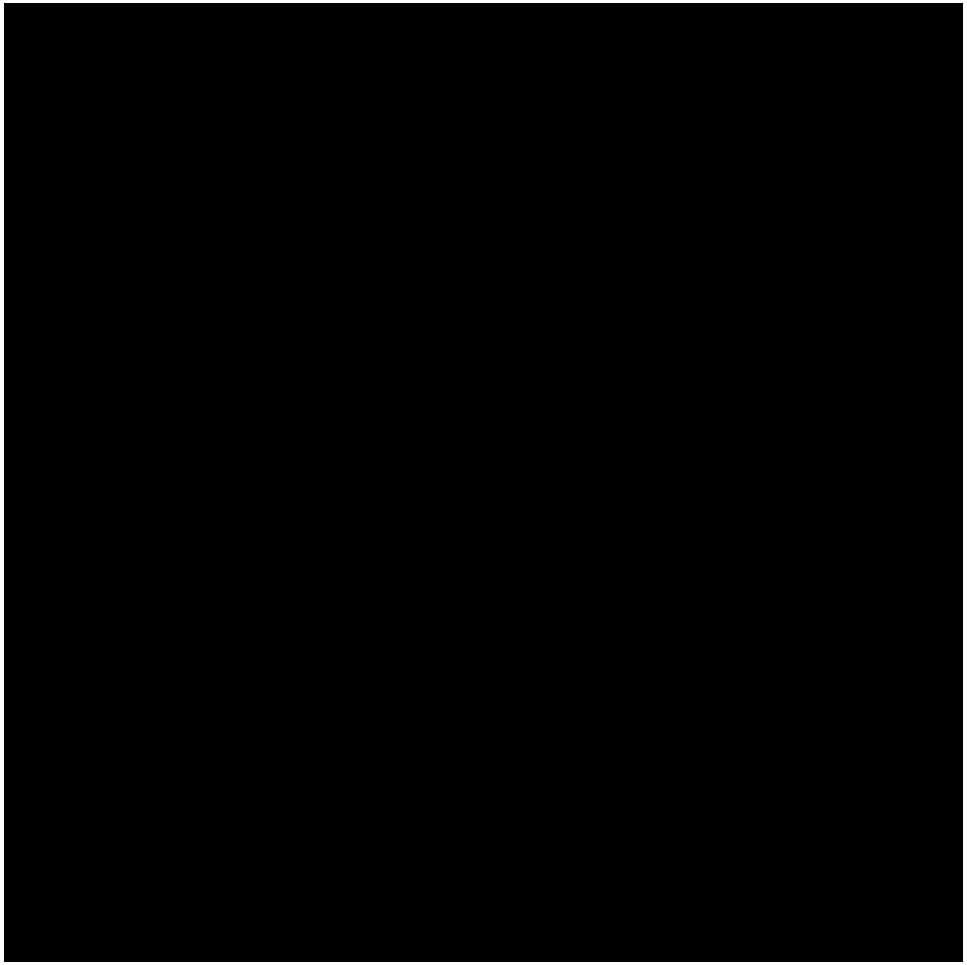
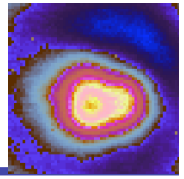


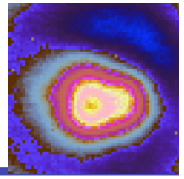
Image Analysis



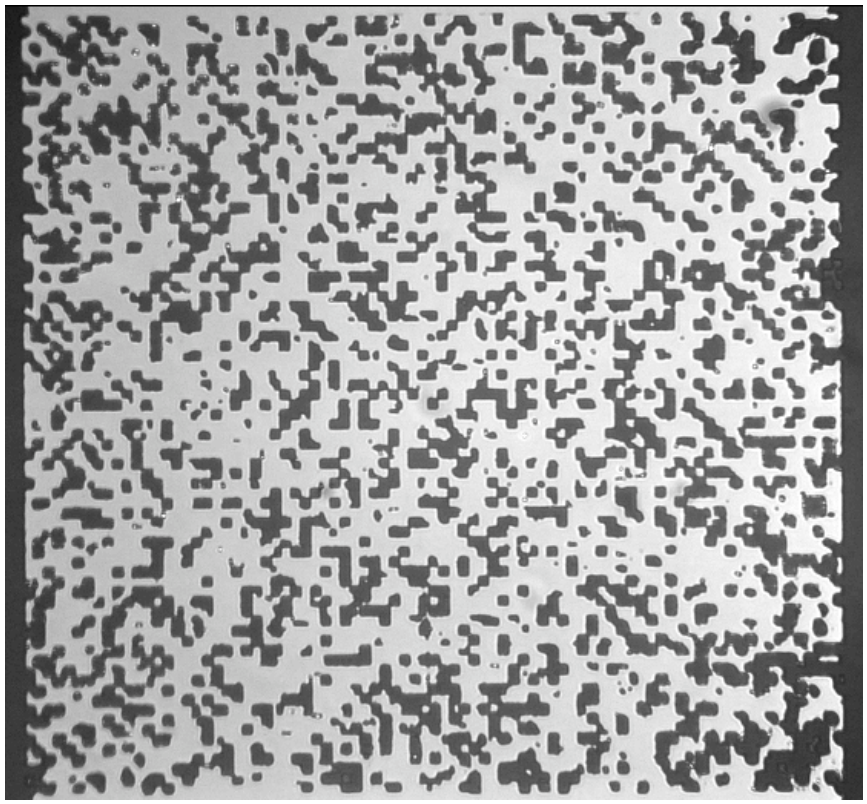
From Image Analysis:

- Saturation
- Interfacial Length
- Curvature
- Normals to Interfaces

Image Analysis: Phase Identification



Non-Uniform Lighting



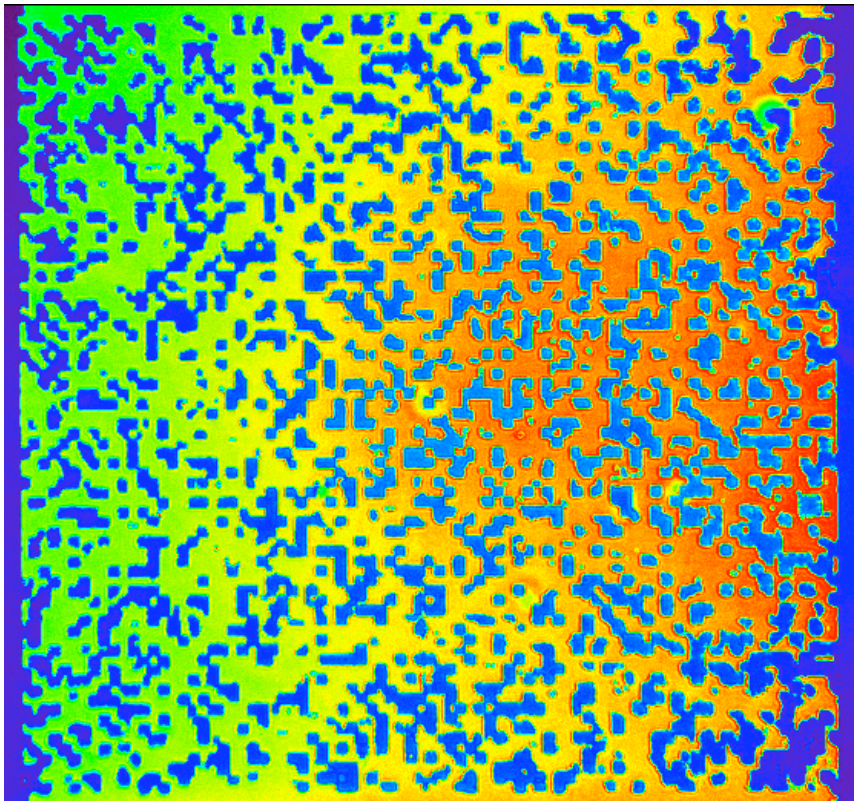
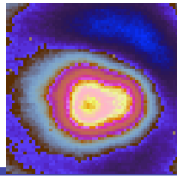
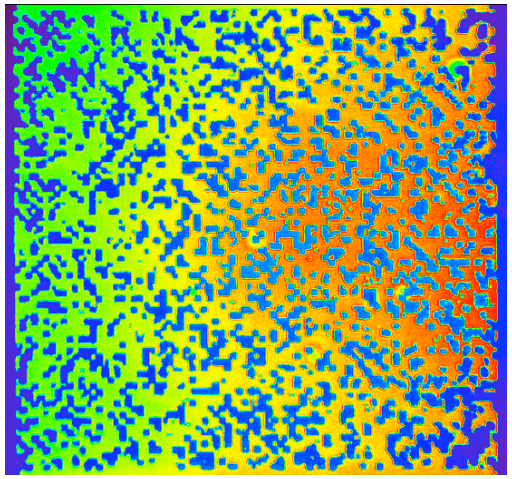


Image Analysis: Phase Identification



$$function = a * (x - x_{ic})^2$$

$$Newimage = image + function$$



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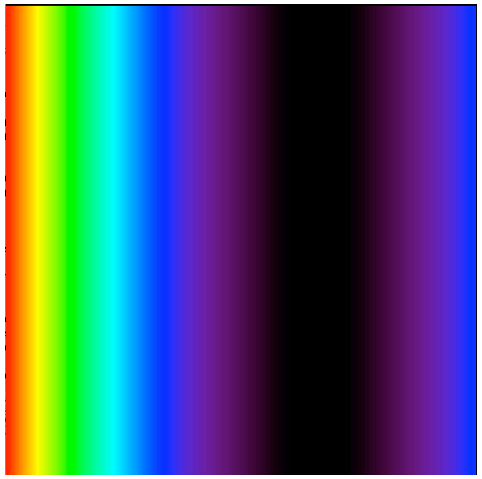

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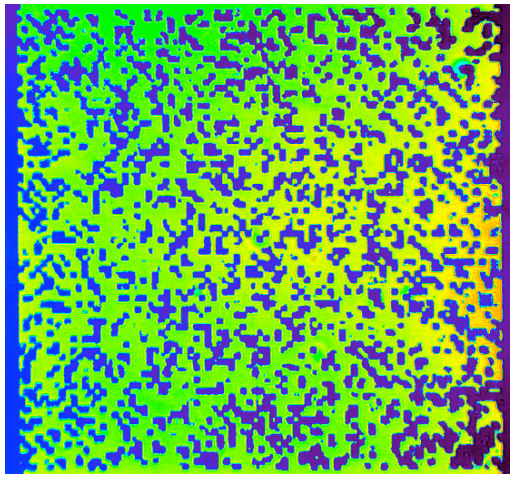
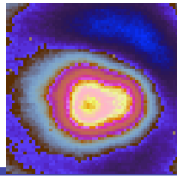
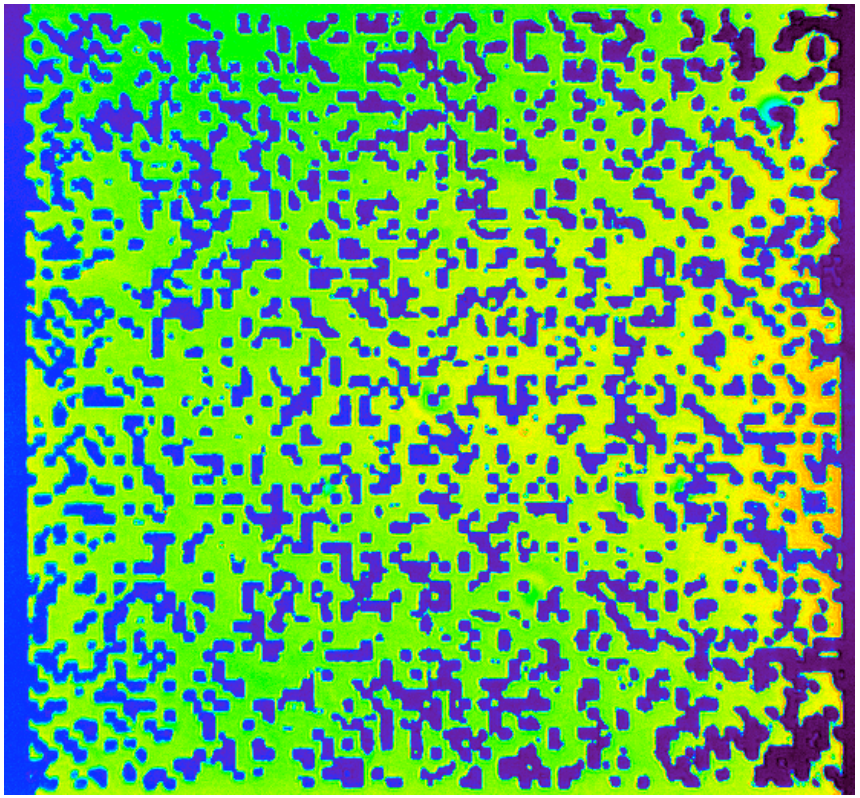
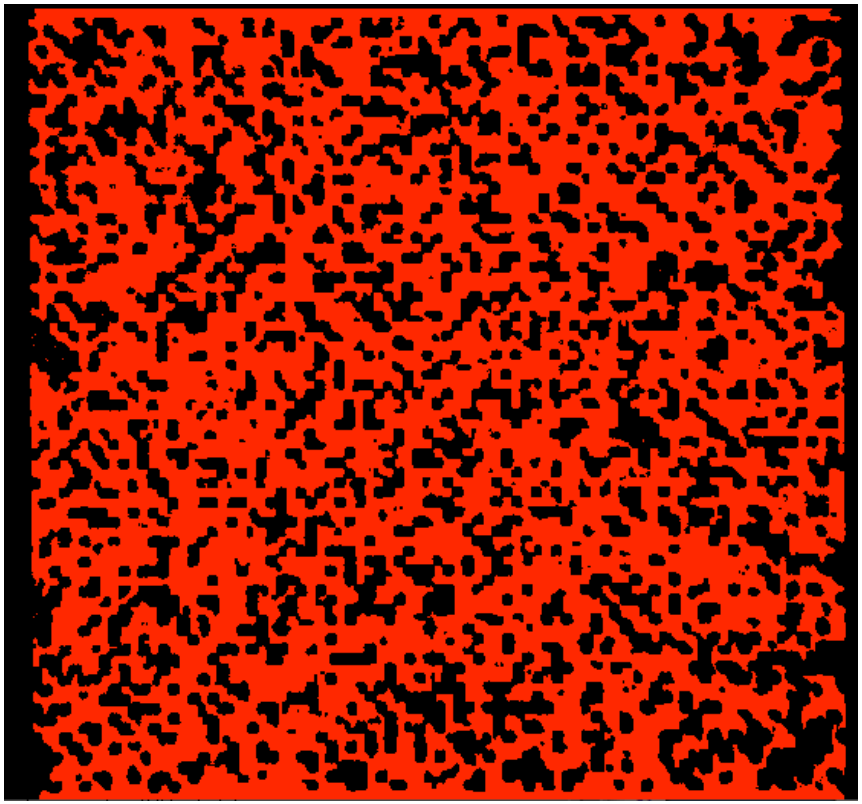


Image Analysis: Connected Path

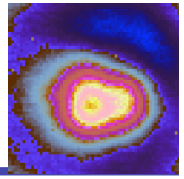




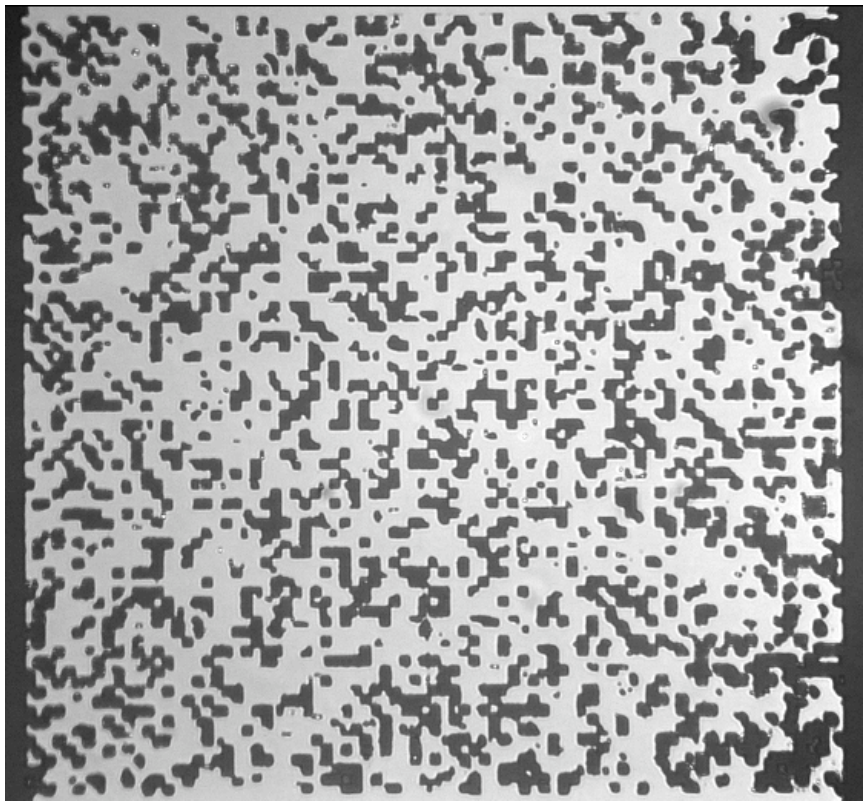


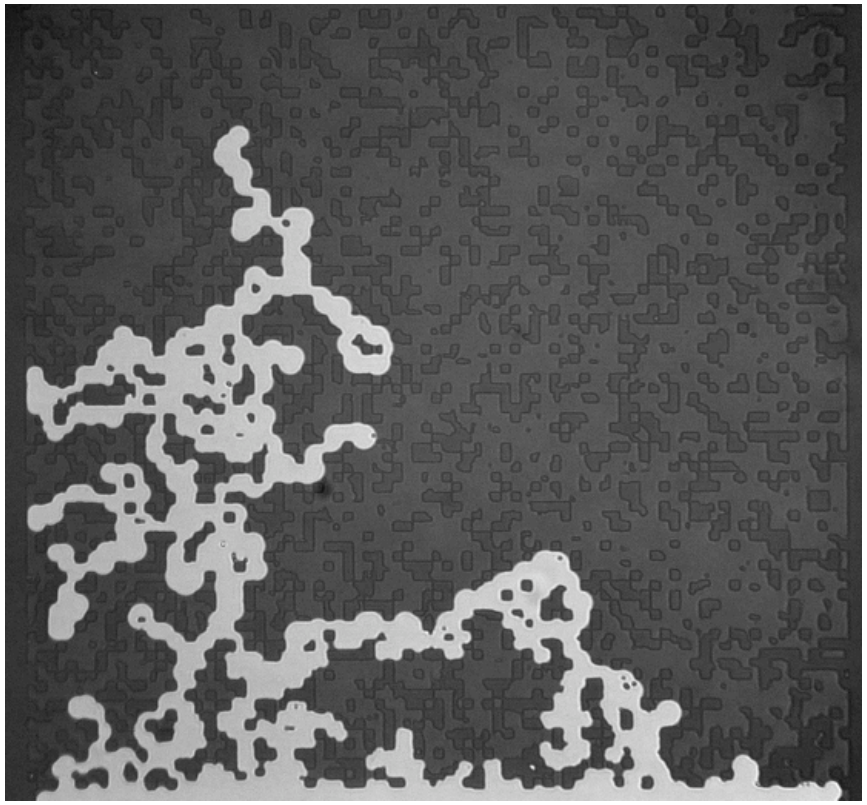
s70_sum04_Q

Image Registration: Cross-Correlation



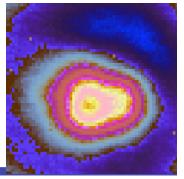
$$S_2(x,y) = \frac{1}{A}\int_A f_{mask}(u,v) f_{image}(u-x, v-y)\,du\,dv$$



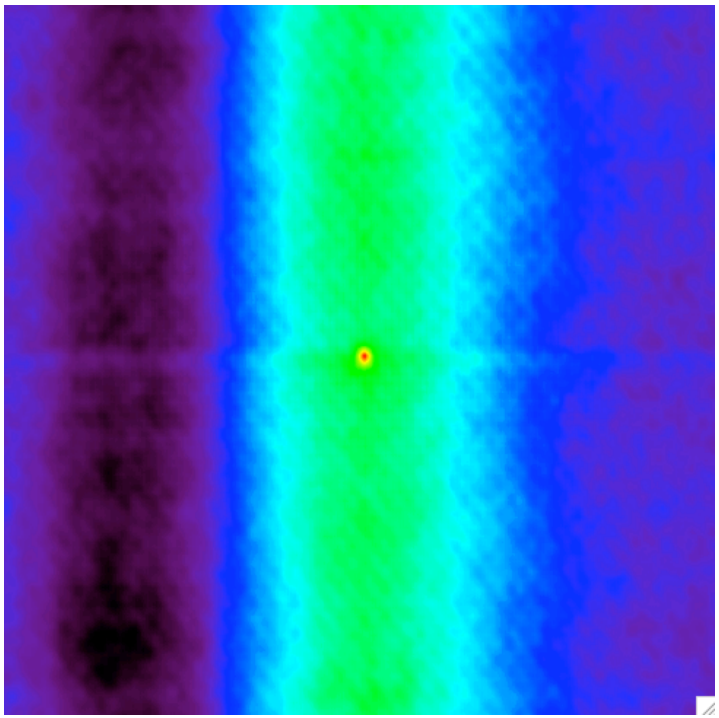


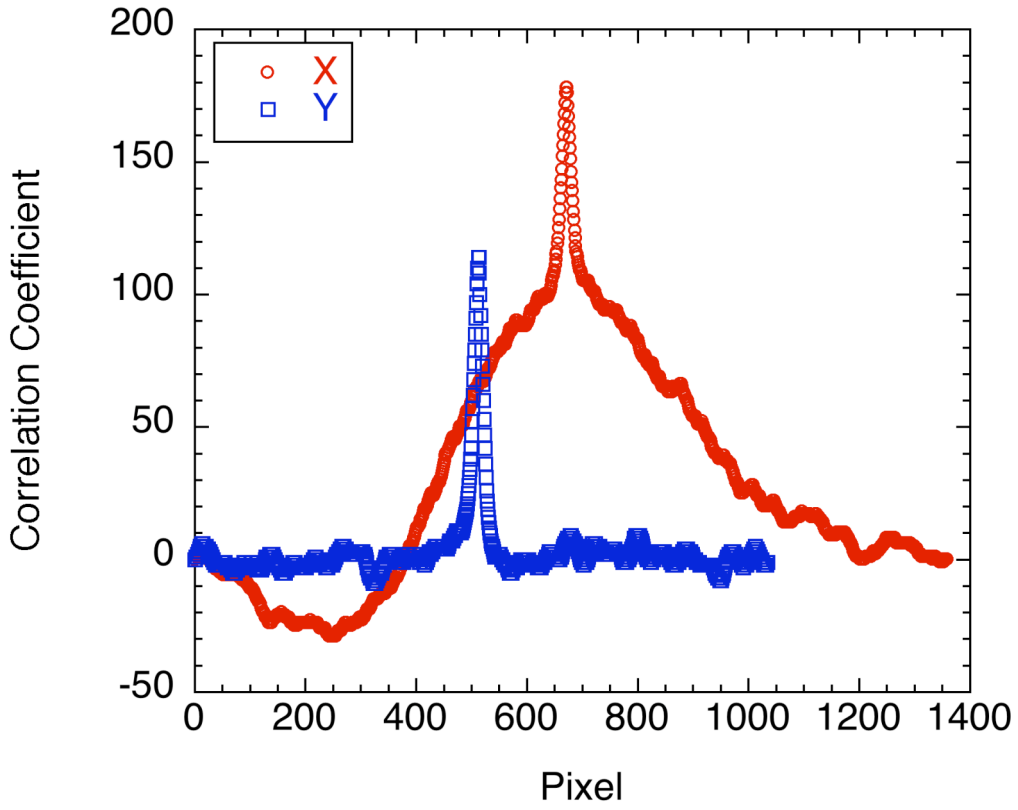
s70_sum04_Q

Image Registration: Cross-Correlation



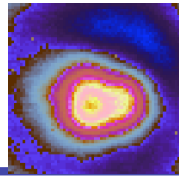
$$S_2(x,y) = \frac{1}{A}\int_A f_{mask}(u,v) f_{image}(u-x, v-y)\,du\,dv$$

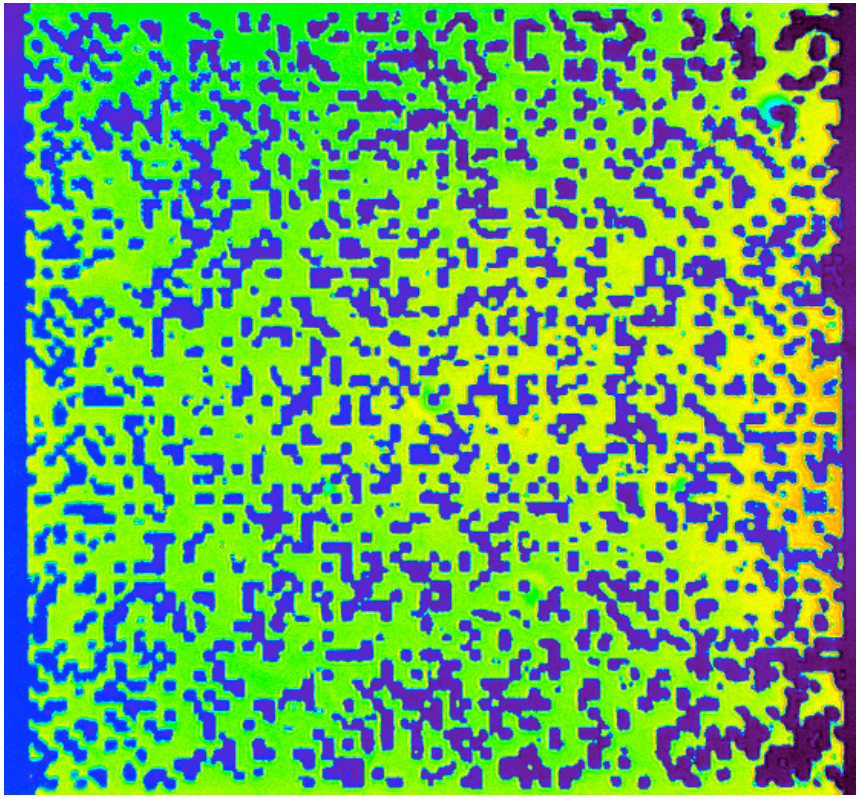


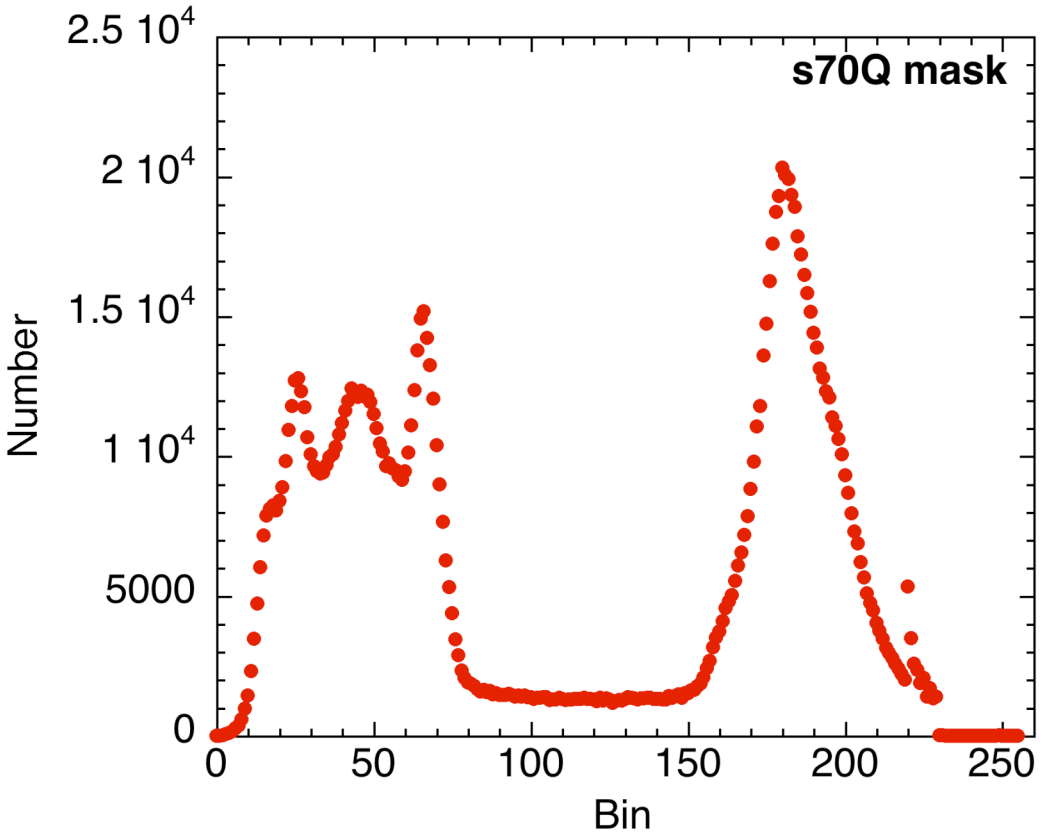


s70_sum04_Q

Image Analysis: Threshold

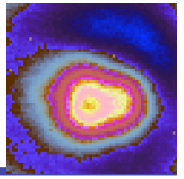




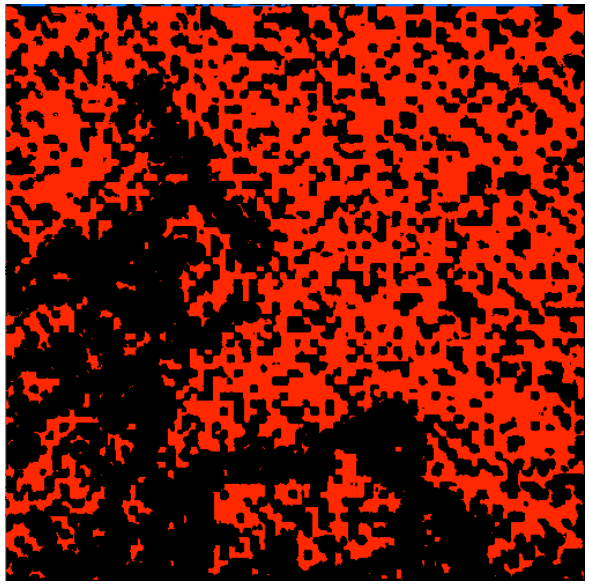


s70_sum04_Q

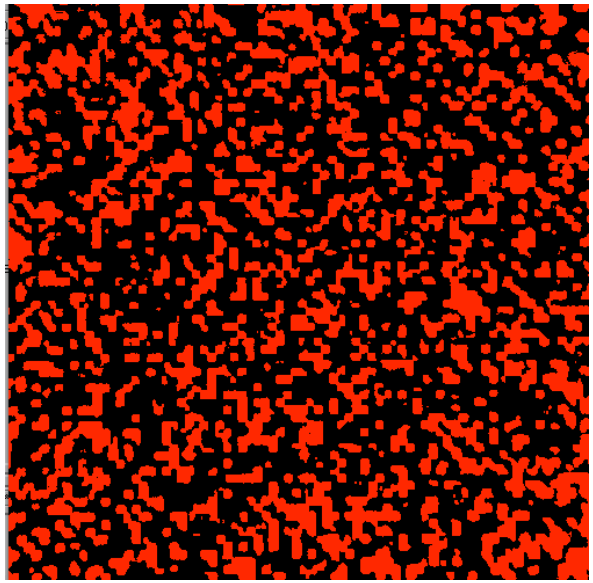
Phase Identification



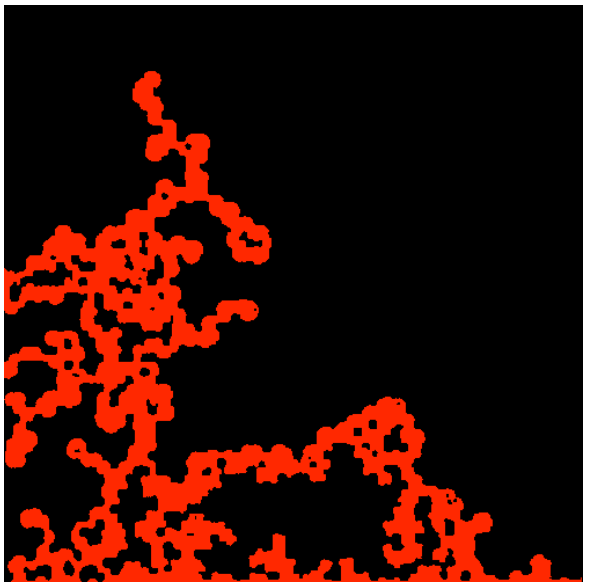
Decane



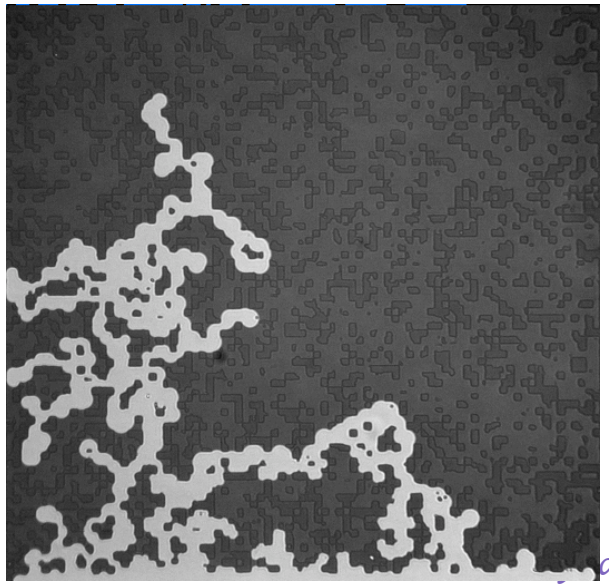
Photoresist

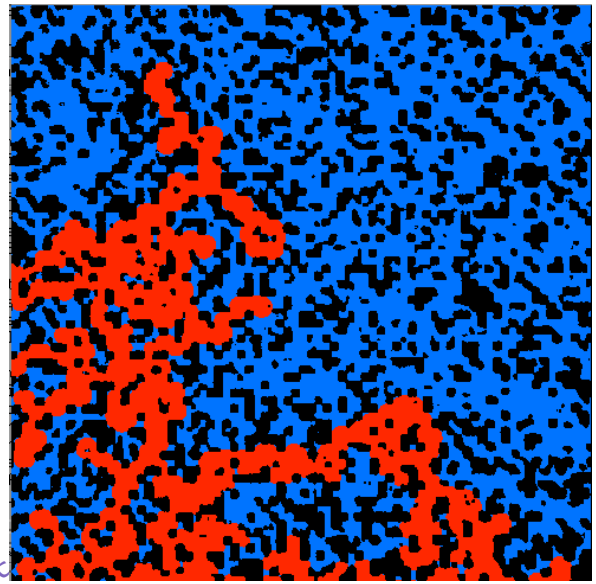


Nitrogen



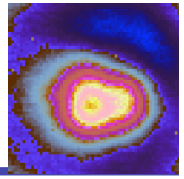
Raw Image





False Color Image

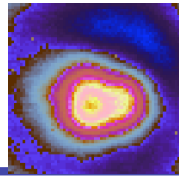
Image Analysis



From Image Analysis:

- Saturation
- Interfacial Length
- Curvature
- Normals to Interfaces

Image Analysis: Convolution Kernels



Image

I_{11}	I_{12}	I_{13}	I_{14}	I_{15}	I_{16}	I_{17}	I_{18}	I_{19}
I_{21}	I_{22}	I_{23}	I_{24}	I_{25}	I_{26}	I_{27}	I_{28}	I_{29}
I_{31}	I_{32}	I_{33}	I_{34}	I_{35}	I_{36}	I_{37}	I_{38}	I_{39}
I_{41}	I_{42}	I_{43}	I_{44}	I_{45}	I_{46}	I_{47}	I_{48}	I_{49}
I_{51}	I_{52}	I_{53}	I_{54}	I_{55}	I_{56}	I_{57}	I_{58}	I_{59}
I_{61}	I_{62}	I_{63}	I_{64}	I_{65}	I_{66}	I_{67}	I_{68}	I_{69}

Kernel

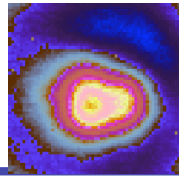
K_{11}	K_{12}	K_{13}
K_{21}	K_{23}	K_{33}

http://homepages.inf.ed.ac.uk/rbf/HIPR2/convolve.htm

$$O(i,j) = \sum_{k=1}^{m} \sum_{l=1}^{n} I(i+k-1, j+l-1) K(k,l)$$

$$O_{57} = I_{57}K_{11} + I_{58}K_{12} + I_{59}K_{13} + I_{67}K_{21} + I_{68}K_{22} + I_{69}K_{23}$$

Edge Detection



Sobel

-1	0	+1
-2	0	+2
-1	0	+1

Gx

+1	+2	+1
0	0	0
-1	-2	-1

Gy

Roberts

+1	0
0	-1

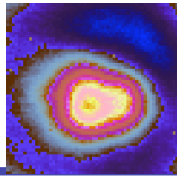
Gx

0	+1
-1	0

Gy

http://homepages.inf.ed.ac.uk/rbf/HIPR2/convolve.htm

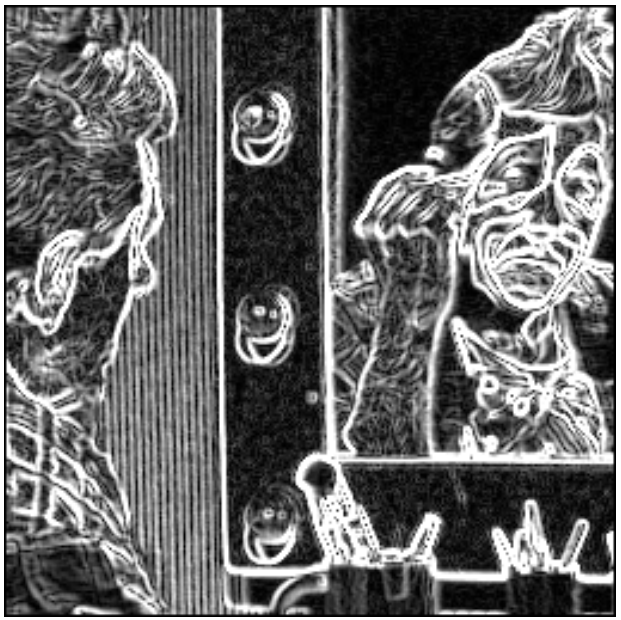
Edge Detection

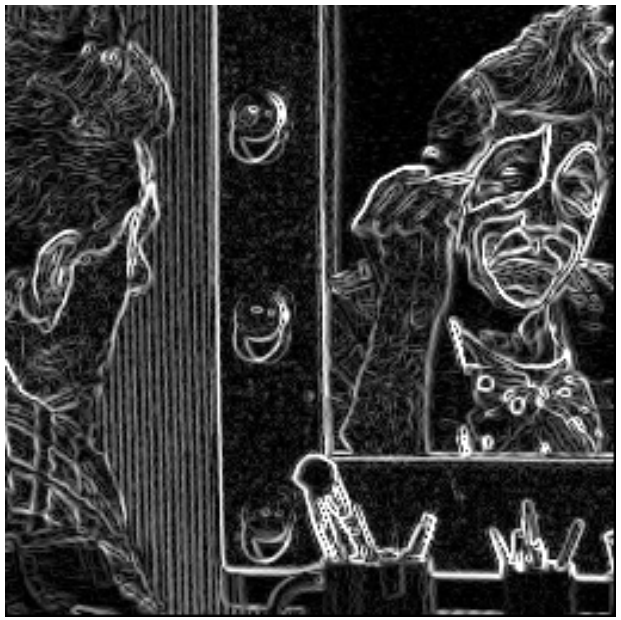


Image

Sobel

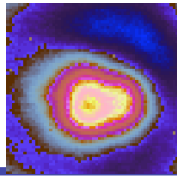
Roberts

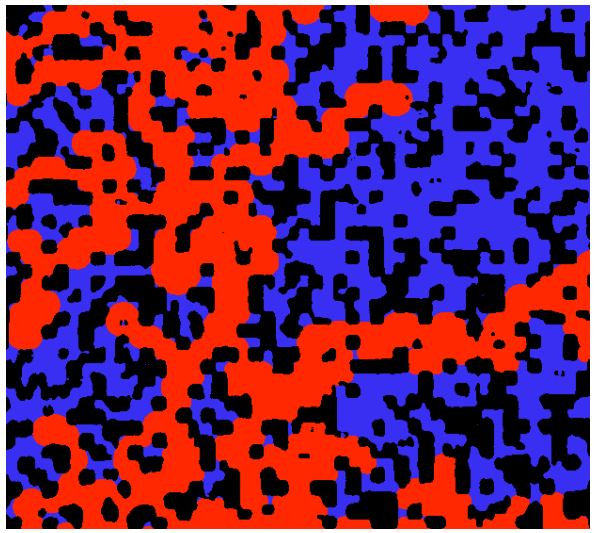




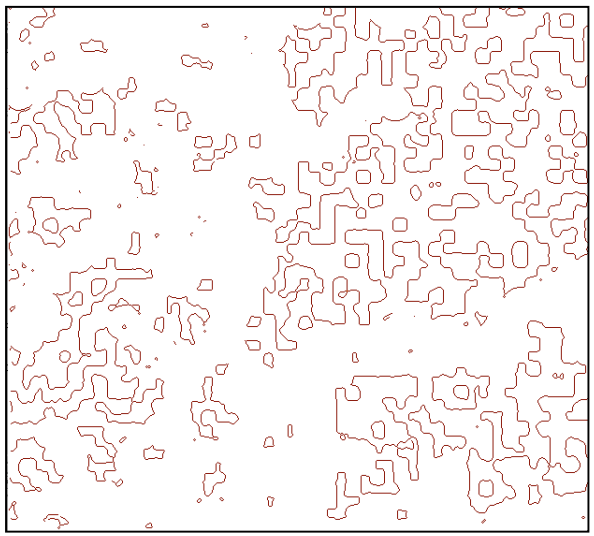
http://homepages.inf.ed.ac.uk/rbf/HIPR2/sobel.htm

Image Analysis: Edge Detection

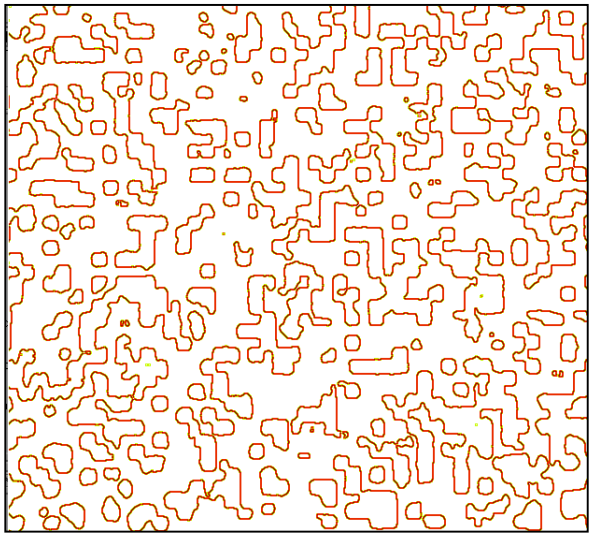




Decane Interfaces



Photoresist Interfaces



Nitrogen Interfaces

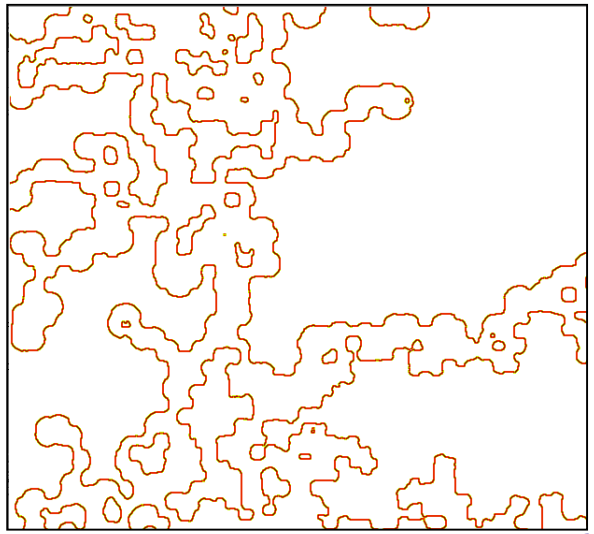
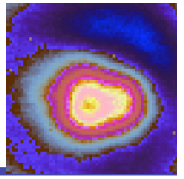
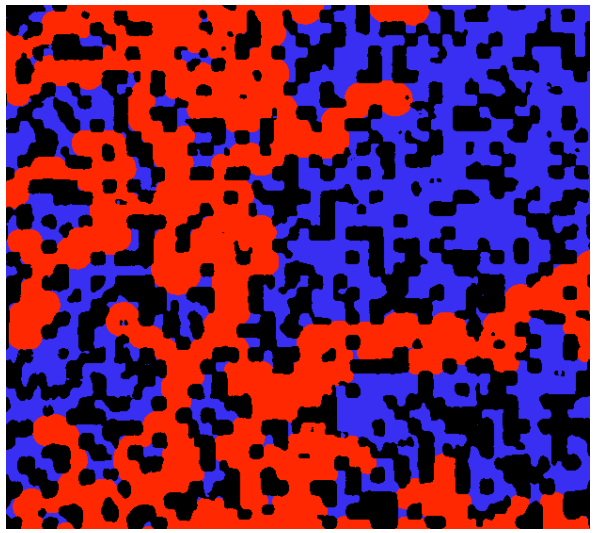


Image Analysis: Interfaces





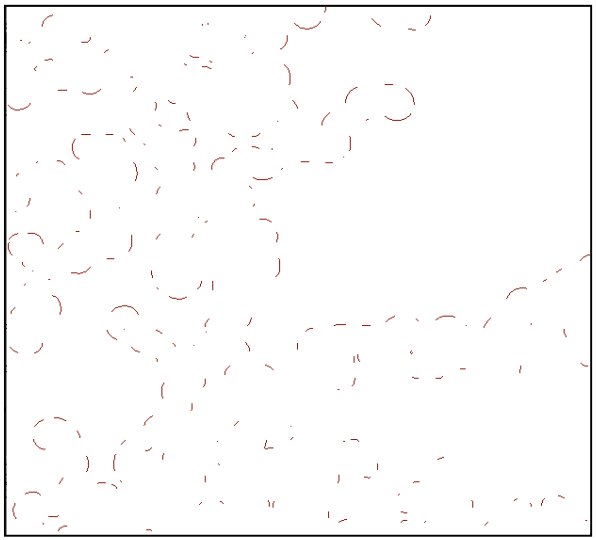
Interfacial Length

$$L_{wn} = (L_n + L_w - L_s)/2$$

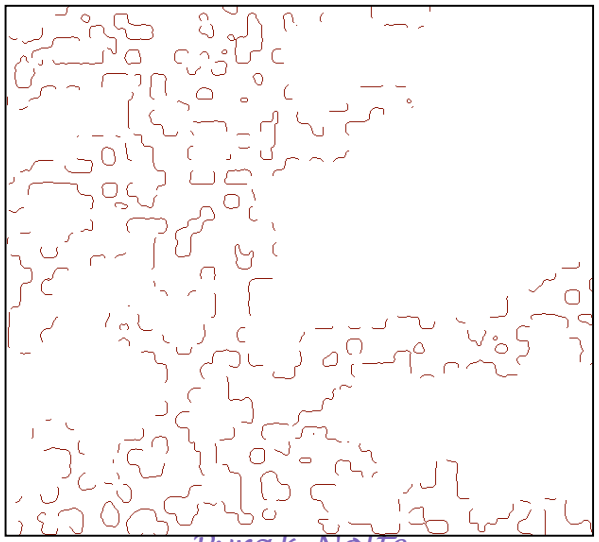
$$L_{ns} = (L_n + L_s - L_w)/2$$

$$L_{ws} = (L_w + L_s - L_n)/2$$

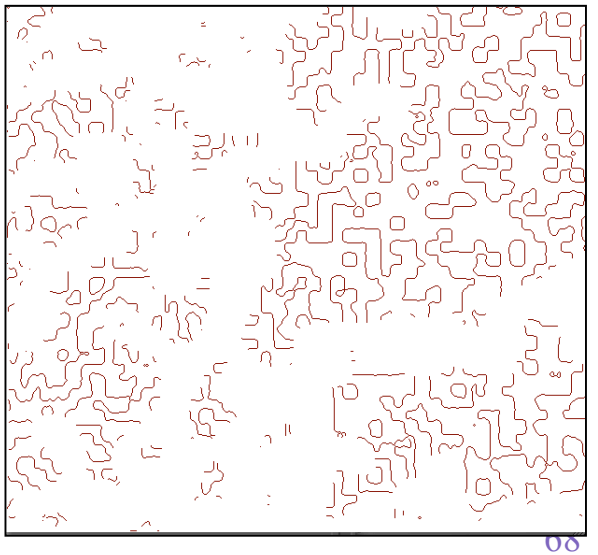
wn interfaces



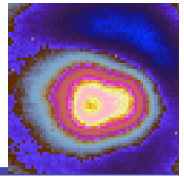
ns interfaces



ws interfaces



Curvature: Kernel Approach



$$K = \frac{\Phi_y^2 \Phi_{xx} - 2\Phi_x \Phi_y \Phi_{xy} + \Phi_x^2 \Phi_{yy}}{(\Phi_x^2 + \Phi_y^2)^{3/2}}$$

$$\Phi_x = [-0.5, 0, 0.5]$$

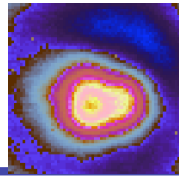
$$\Phi_y = transpose[\Phi_x]$$

$$\Phi_{xx} = [1.0, -2.0, 1.0]$$

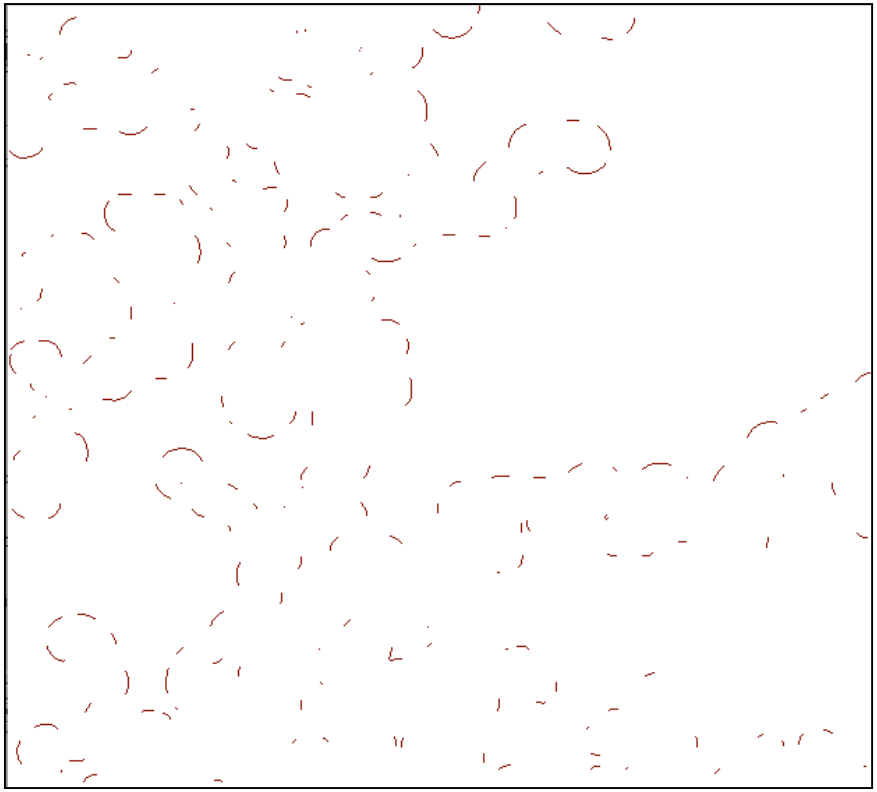
$$\Phi_{yy} = transpose[\Phi_{xx}]$$

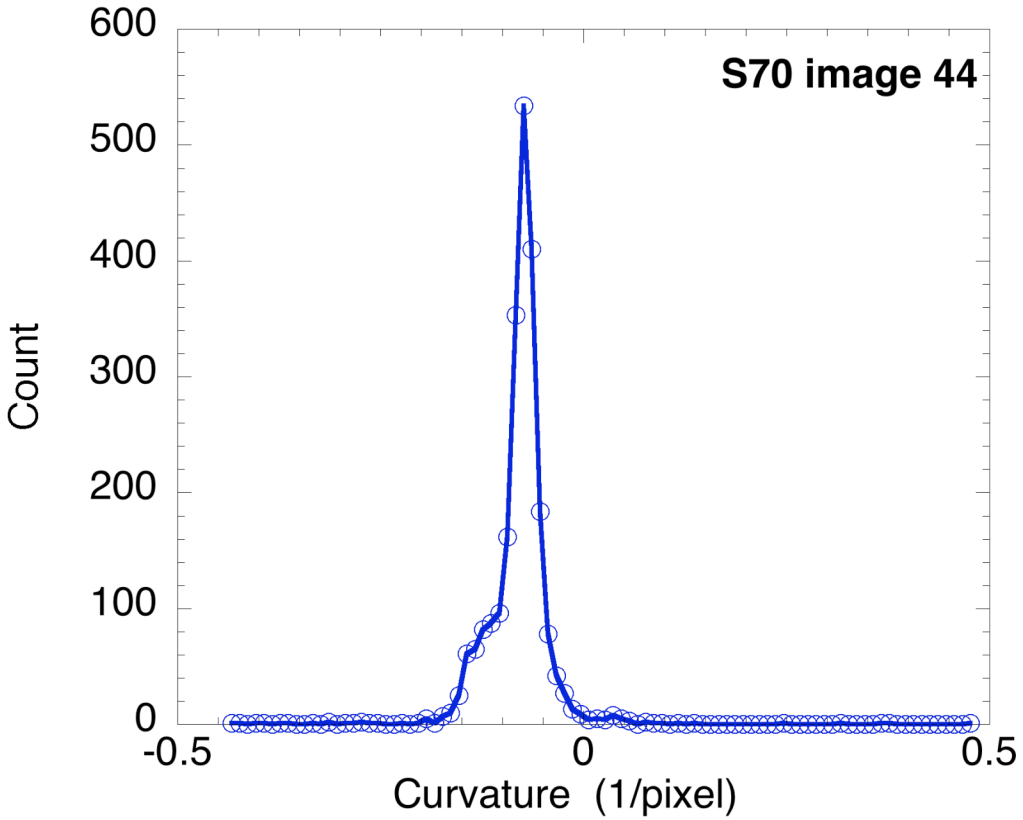
$$\Phi_{xy} = \begin{bmatrix} 0.25 & 0 & -0.25 \\ 0 & 0 & 0 \\ 0.25 & 0 & -0.25 \end{bmatrix}$$

Curvature of wn Interfaces

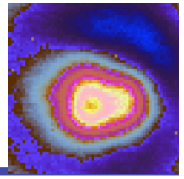


wn interfaces

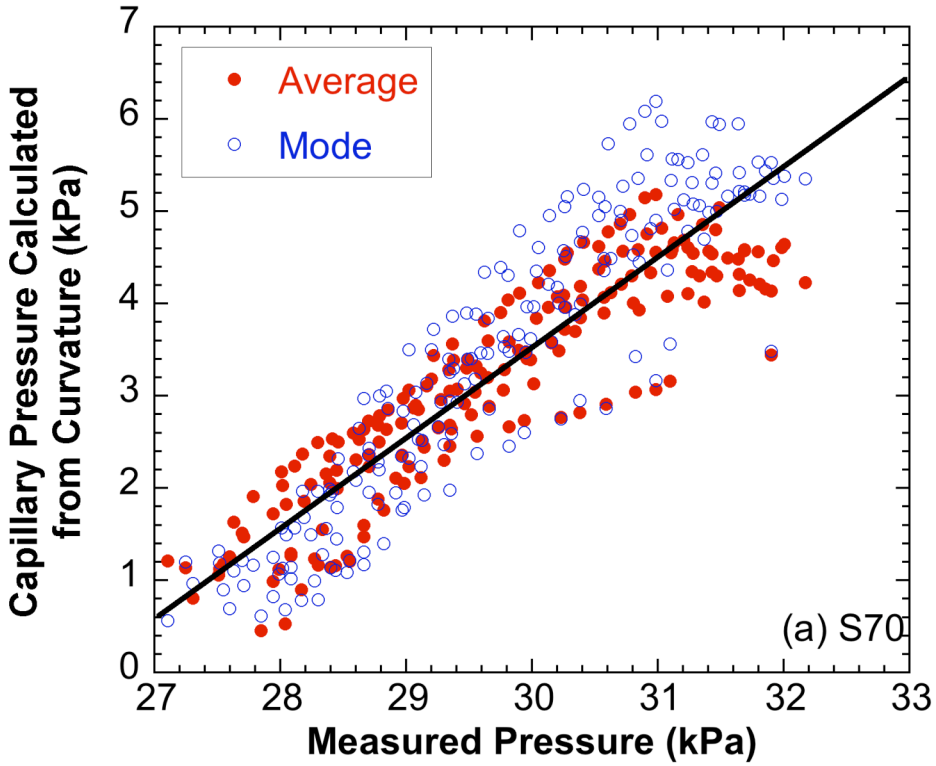


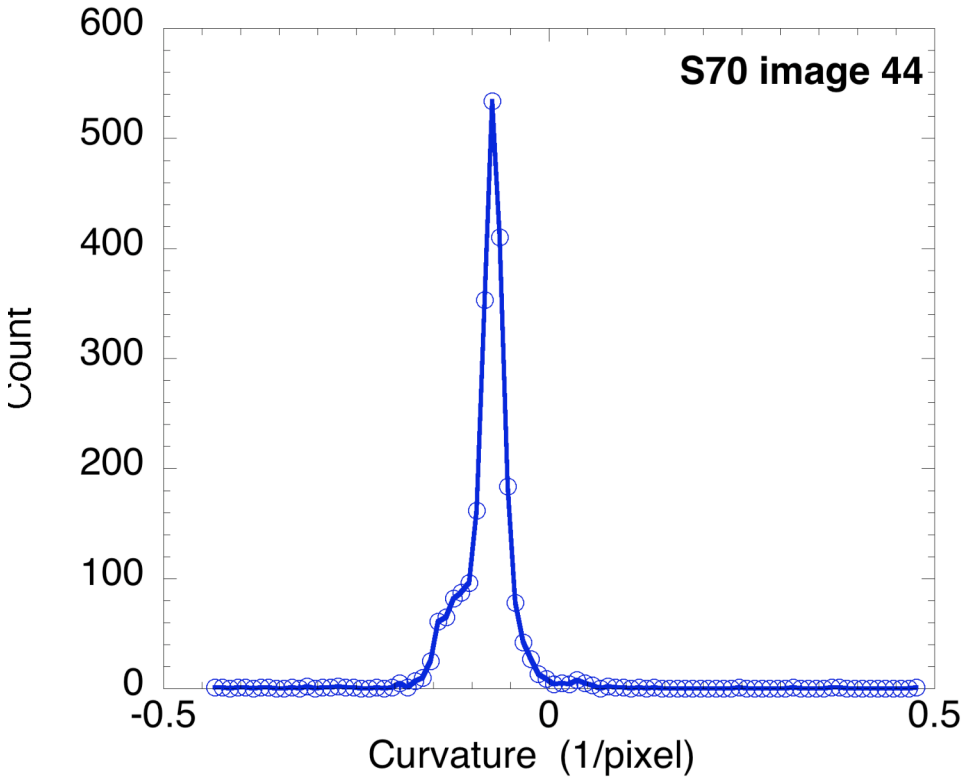


Mode versus Average

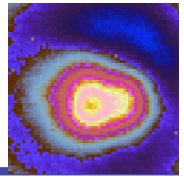


wn interfaces





Normals



$$n_x = \frac{\Phi_x}{\sqrt{\Phi_x^2 + \Phi_y^2}}$$

$$n_y = \frac{\Phi_y}{\sqrt{\Phi_x^2 + \Phi_y^2}}$$

$$n_{xx} = \text{Image} * n_x n_x$$

$$n_{yy} = \text{Image} * n_y n_y$$

$$n_{xy} = \text{Image} * n_x n_y$$

Thank you!