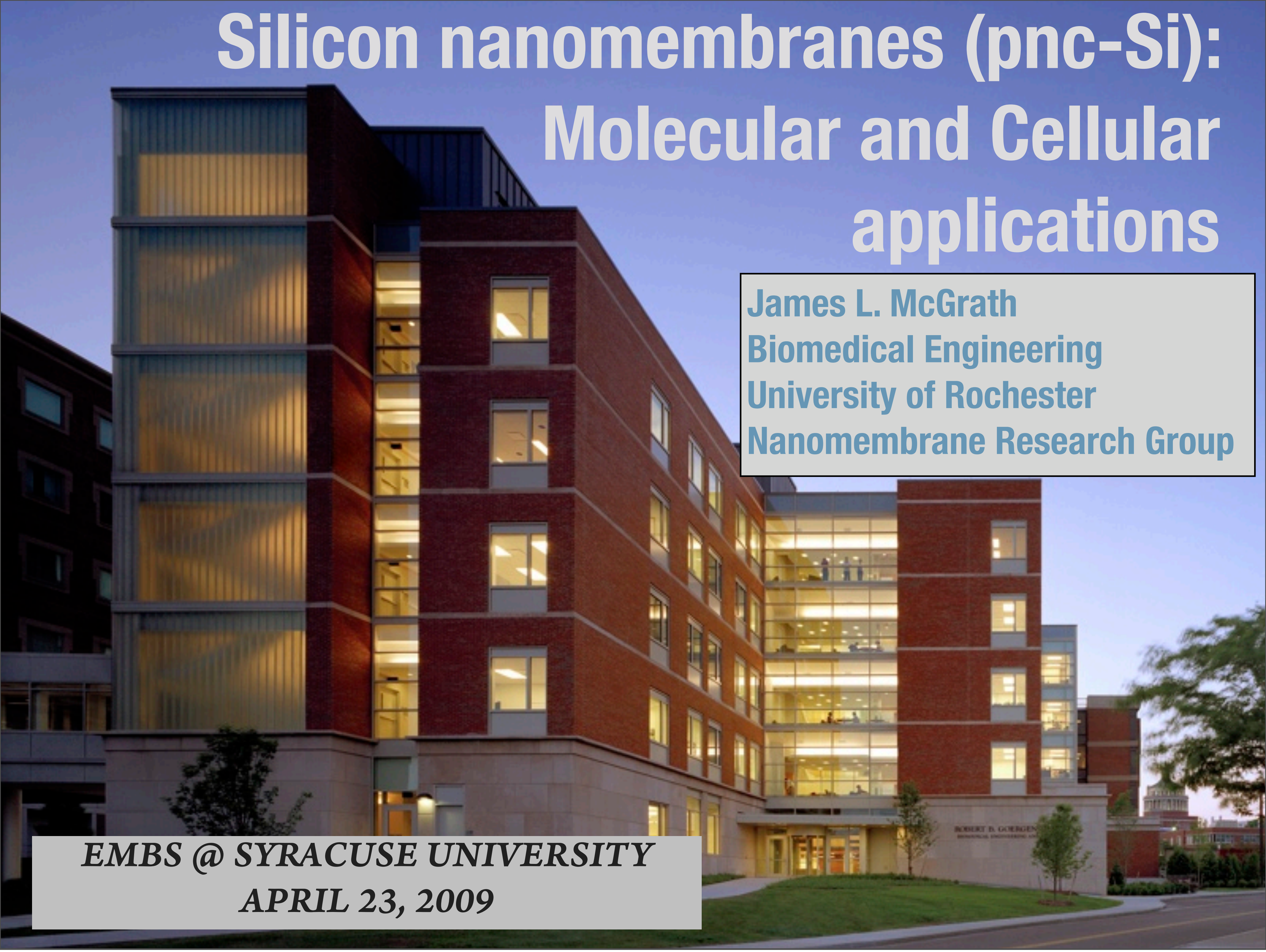
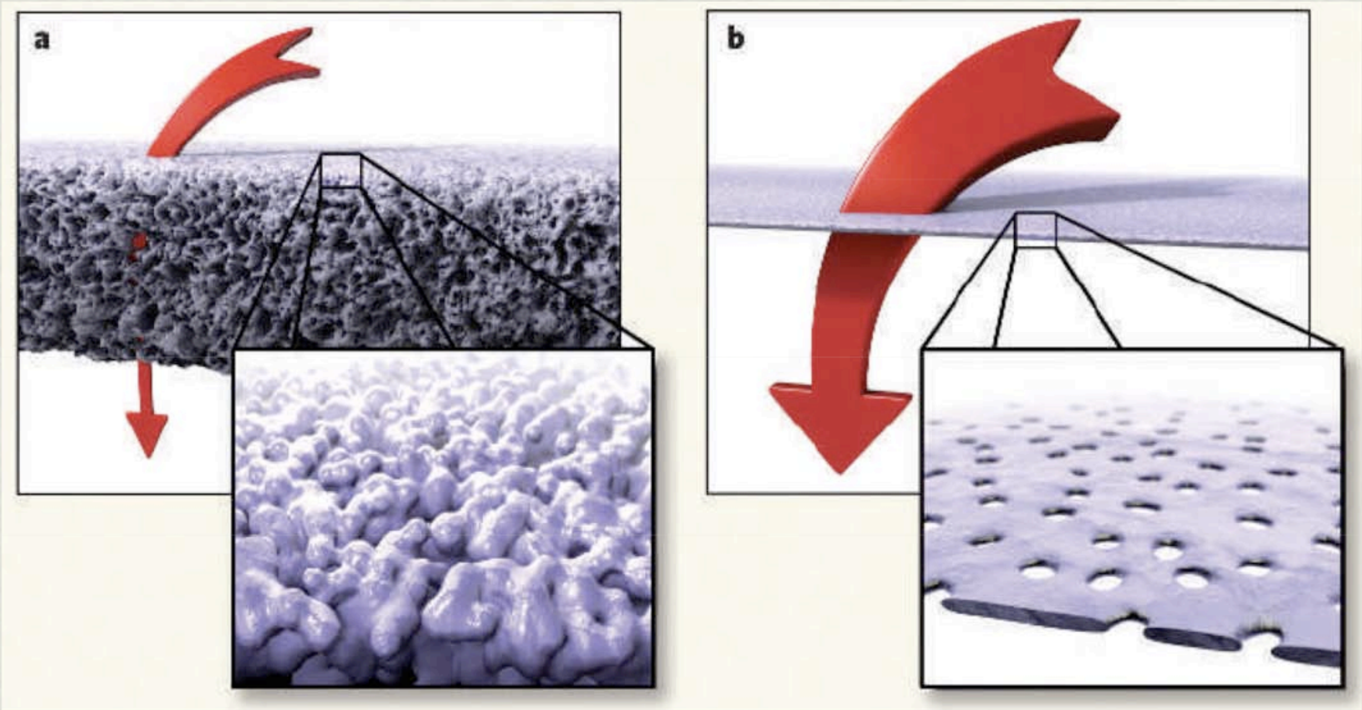


Silicon nanomembranes (pnc-Si): Molecular and Cellular applications

James L. McGrath
Biomedical Engineering
University of Rochester
Nanomembrane Research Group

EMBS @ SYRACUSE UNIVERSITY
APRIL 23, 2009

Silicon Nanomembranes
(pnc-Si - porous nanocrystalline silicon)



15nm thick
5-80 nm pores

Thinner = faster transport and less sample loss

A. van den Berg and M. Wessling, Nature 445, 726, 2007

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Nanomembrane Research Group

Bioengineeing Group

Jim McGrath

Tom Gaborski*

Jess Snyder *(Protein separations)*

Anant Agrawal *(Cellular studies)*

Barrett Nehilla *(Cell applications)*

Henry Chung (Microfluidics)

Crowe, Hoffman, Summers (undergraduates)

Materials Group

Philippe Fauchet

Chris Striemer*

Dave Fang *(Material development)*

Maryna Kavalenka *(Air permeability)*

SiMPore Inc.*

Rick Richmond

Jamie Roussie

JP Desormeaux

Karl Reisig

Nakul Nataraj

Collaborations

Shigeru Amemiya, PITT

Bill Bernhard, URMC

RIT: SMFL

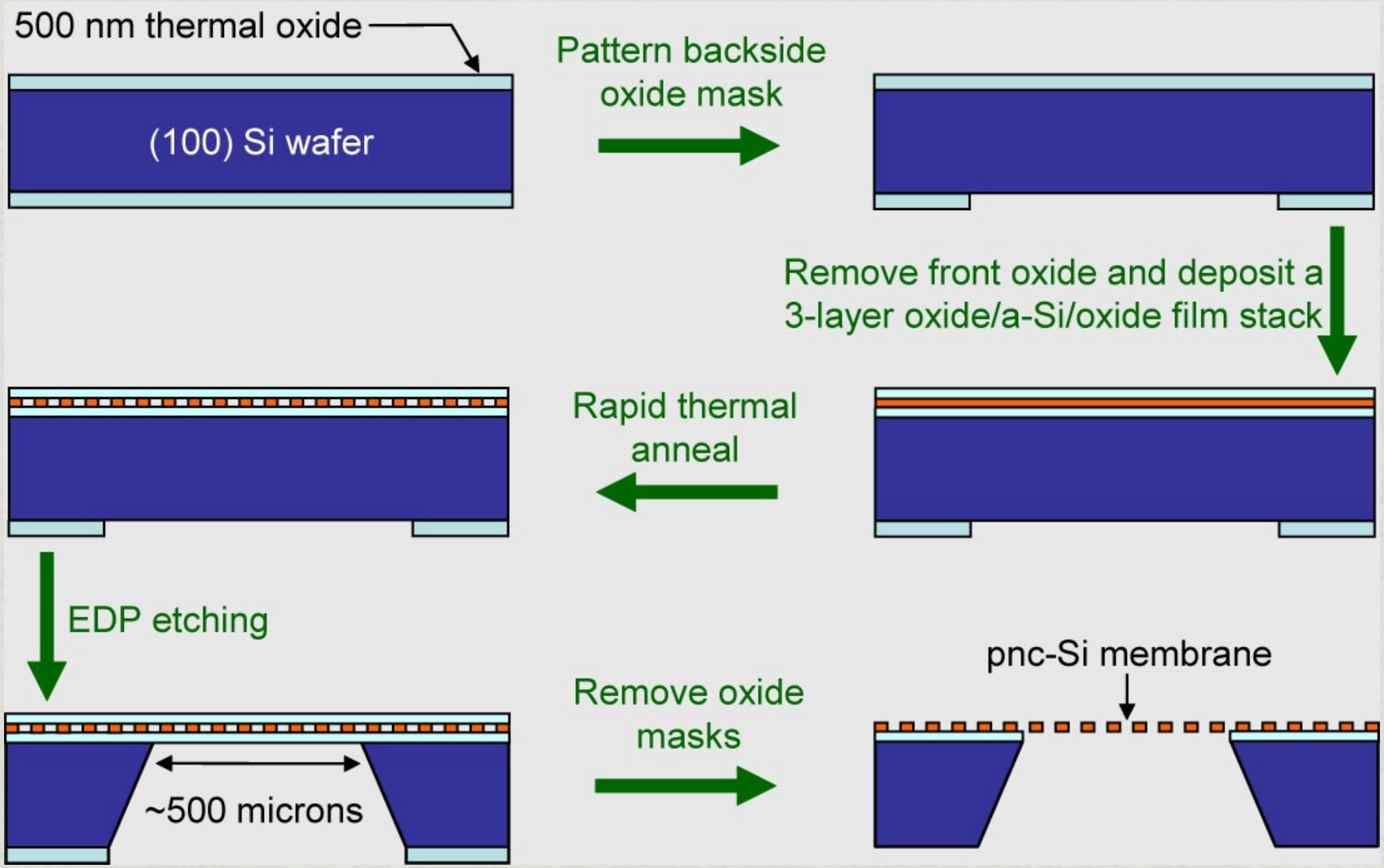
Funding

NSF, NIH, CSTI, J&J, NYSTAR, CEIS

Outline

- **Overview of pnc-Si**
- Transport
- Separations
- Cell Culture
- Other Applications

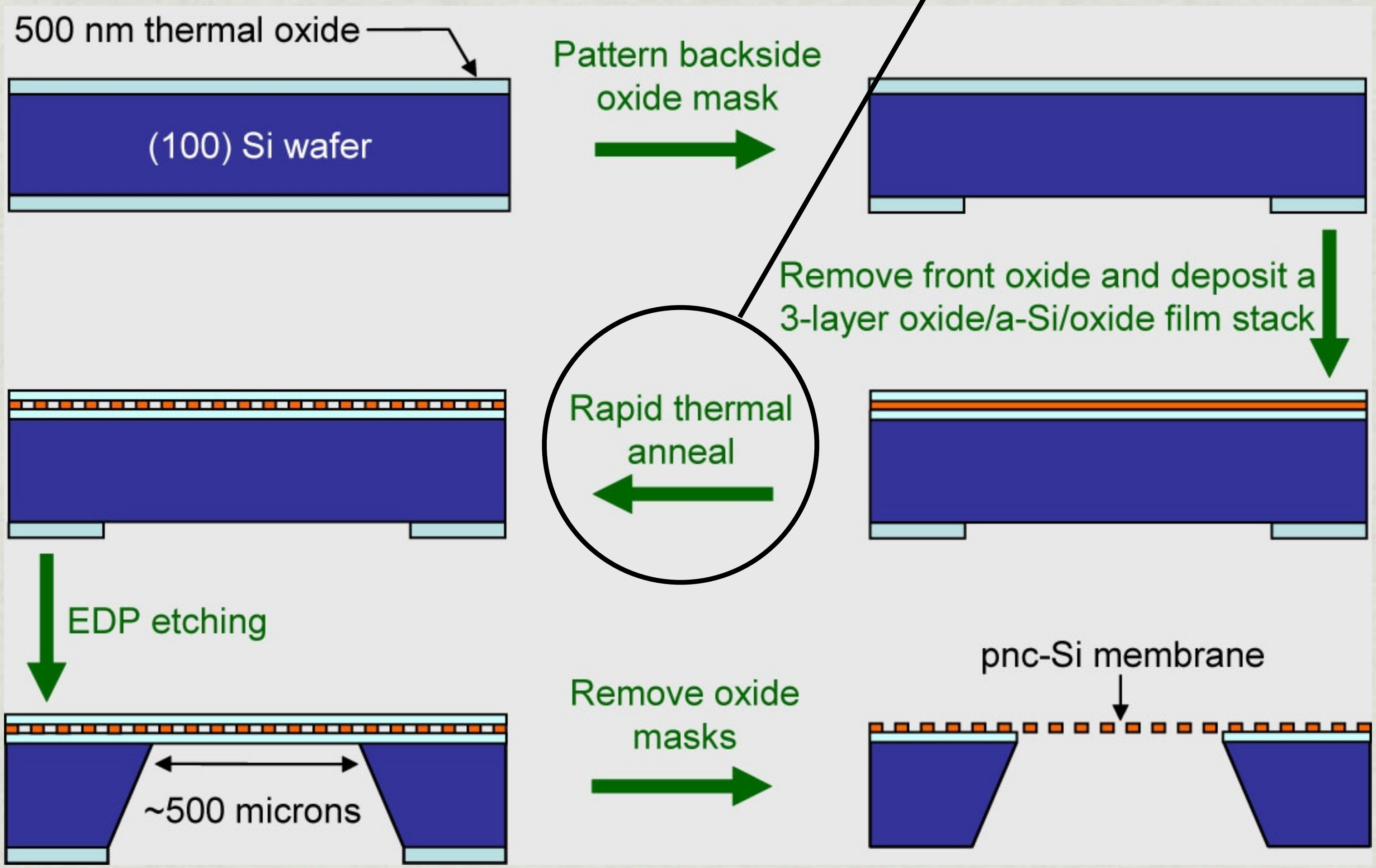
Fabrication



Striemer, C.S, et al. 2007, Nature, 445:749-53

Fabrication

RAPID = SECONDS



Striemer, C.S, et al. 2007, Nature, 445:749-53

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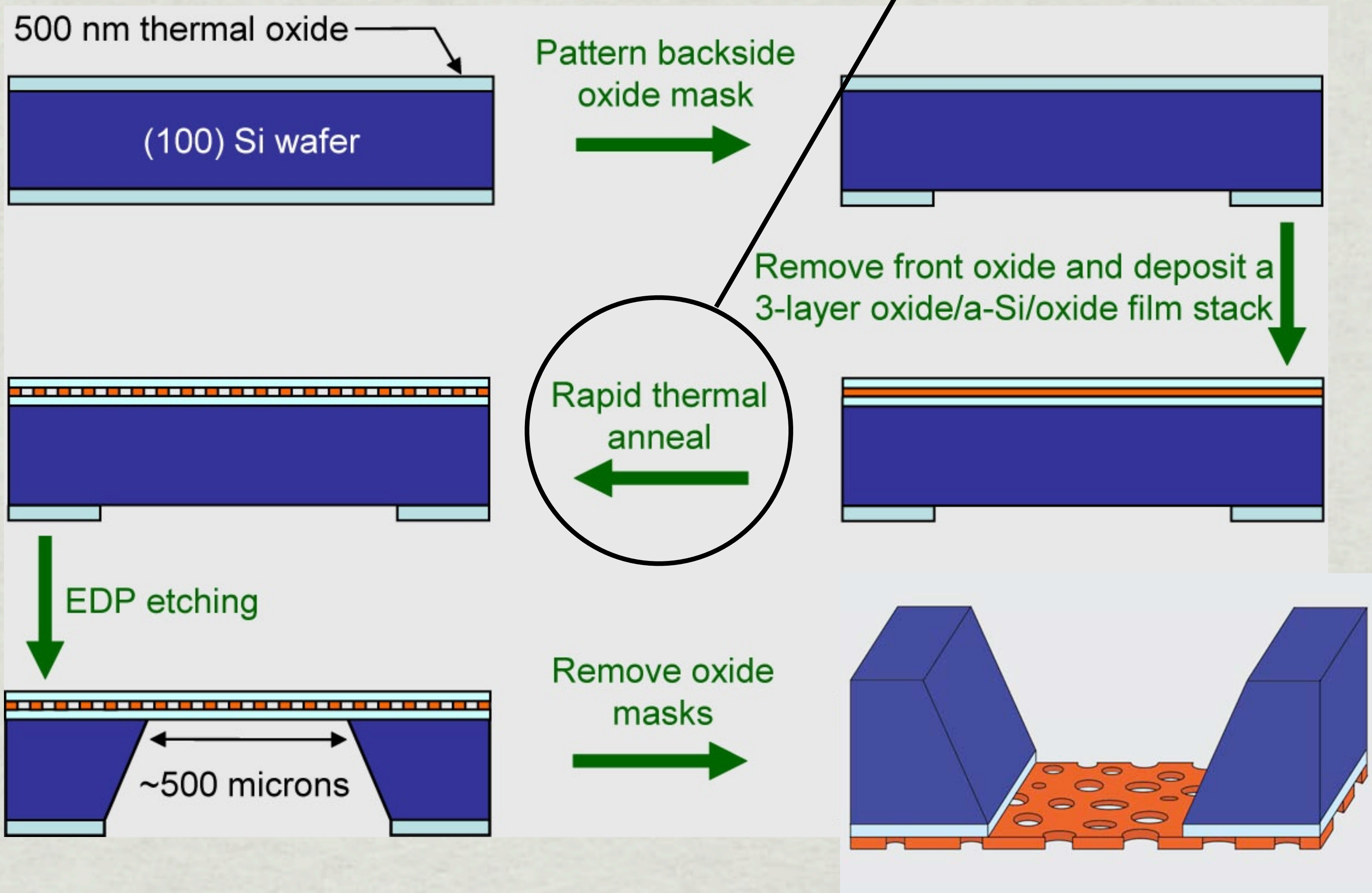
Fabrication

RAPID = SECONDS



Striemer, C.S, et al. 2007, Nature, 445:749-53

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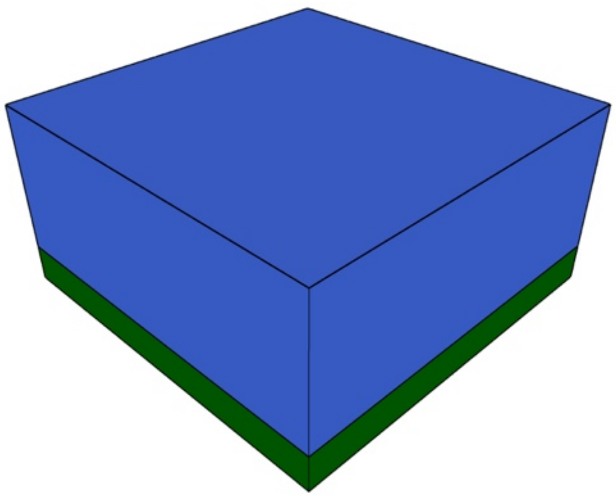
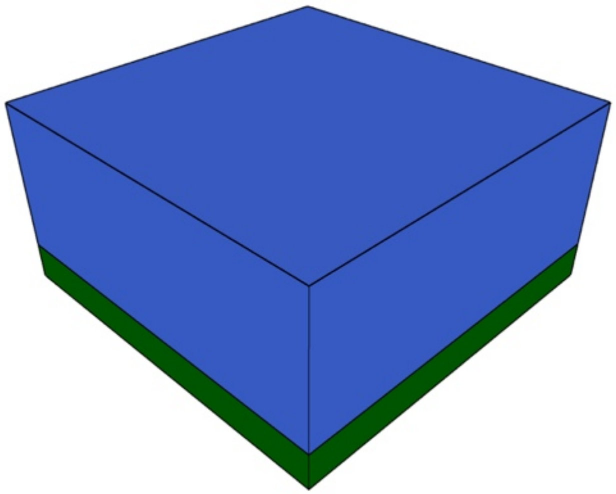
physical vapor deposition

frontside

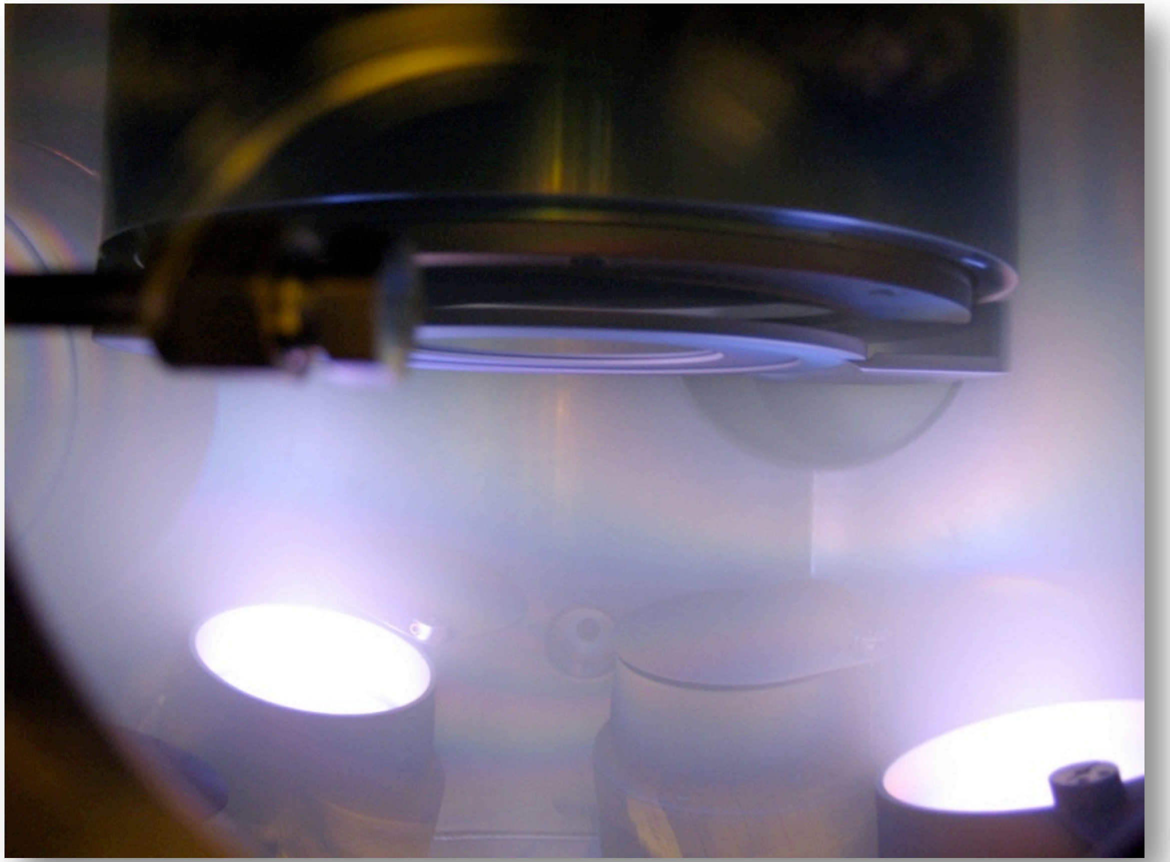


physical vapor deposition

frontside

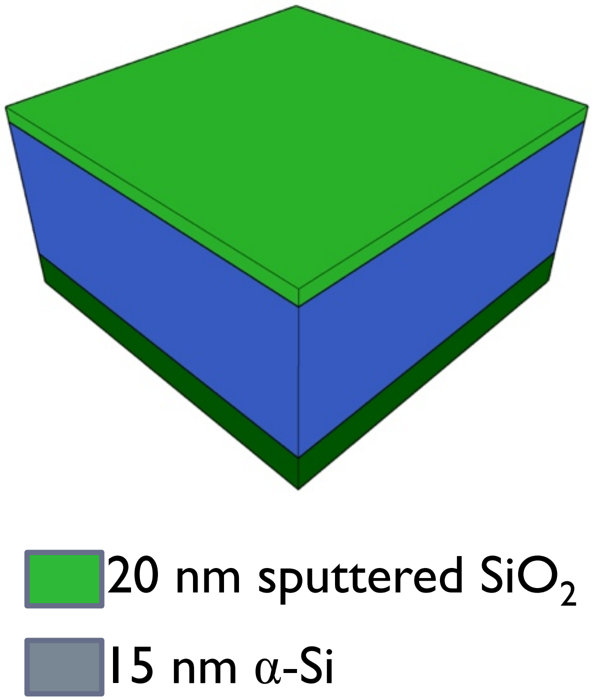


rf magnetron sputtering



physical vapor deposition

frontside



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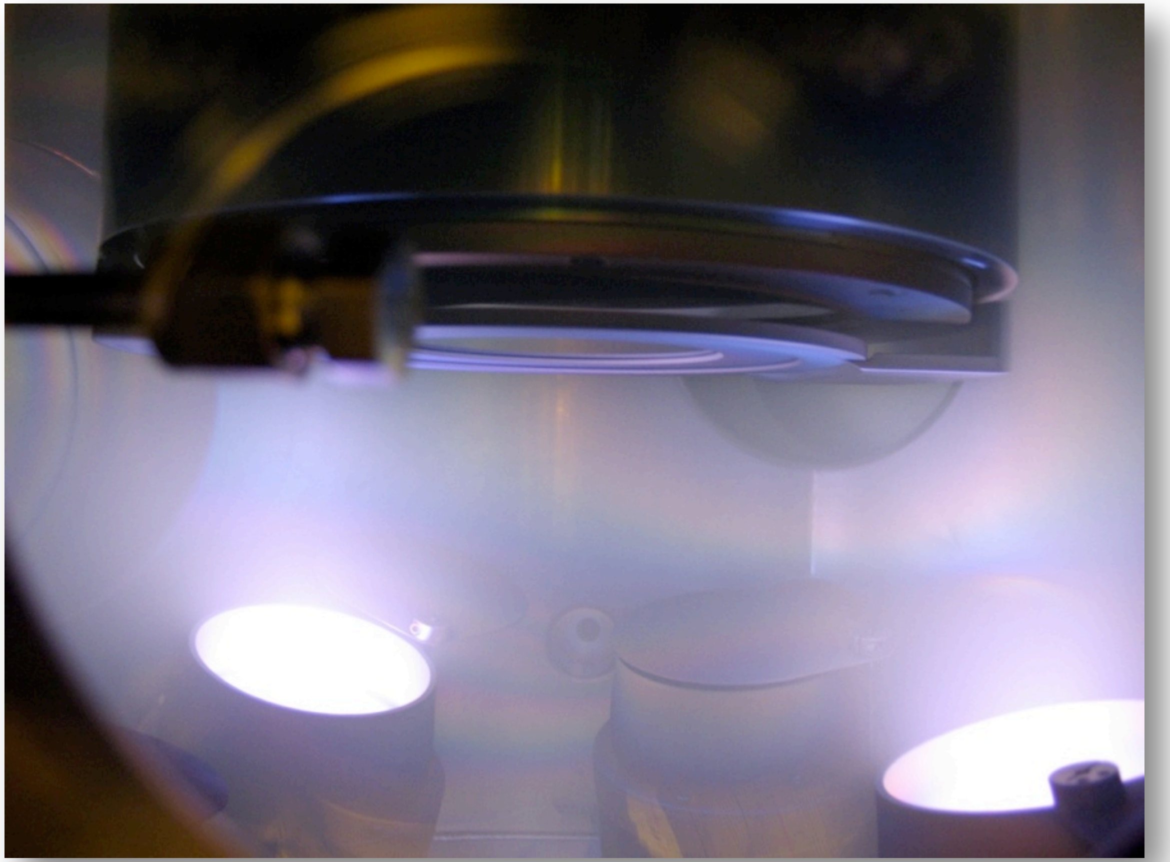
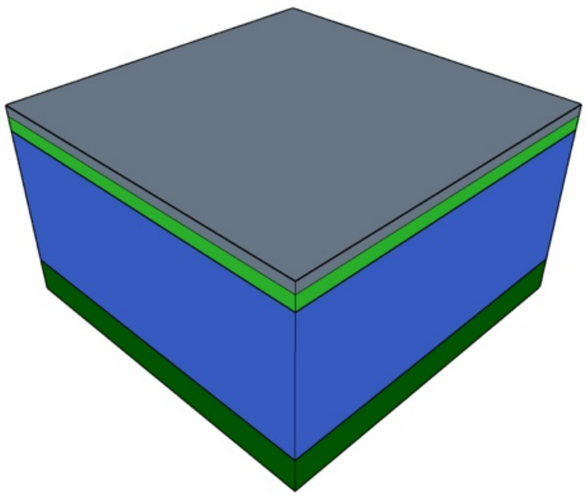


physical vapor deposition

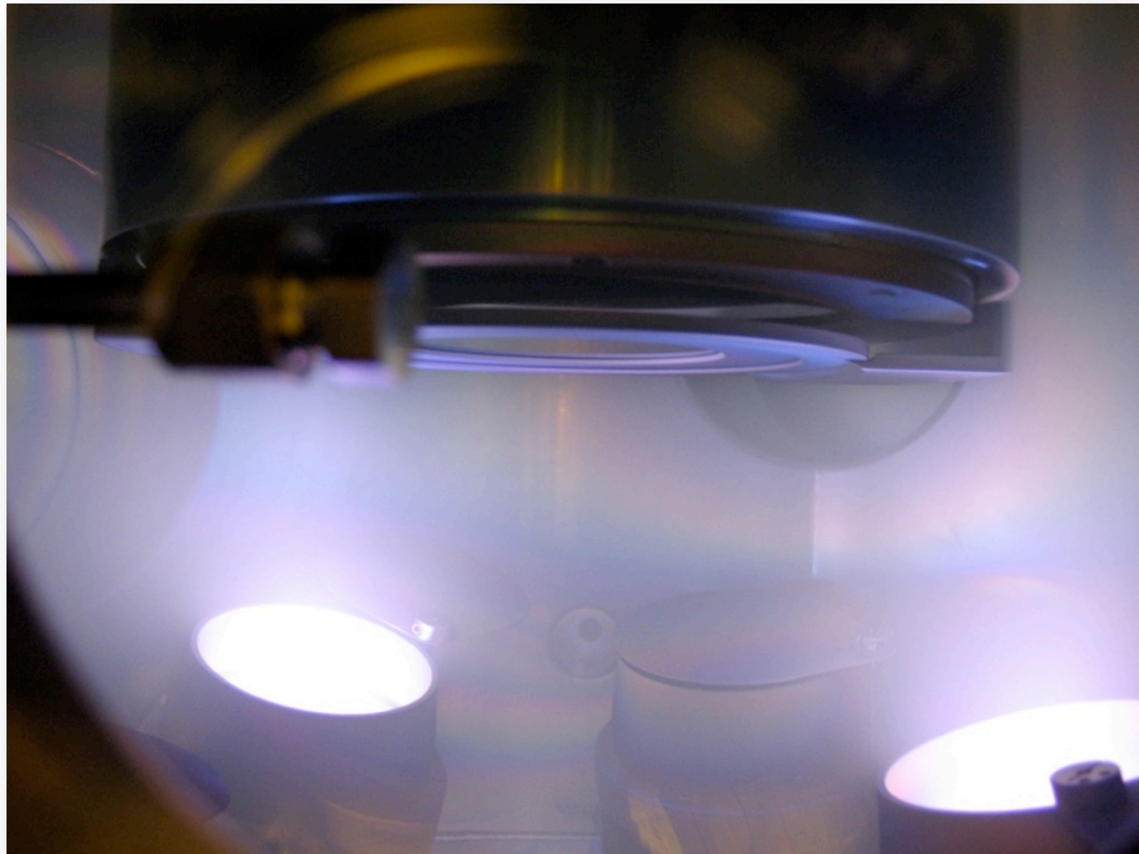
frontside



20 nm sputtered SiO_2

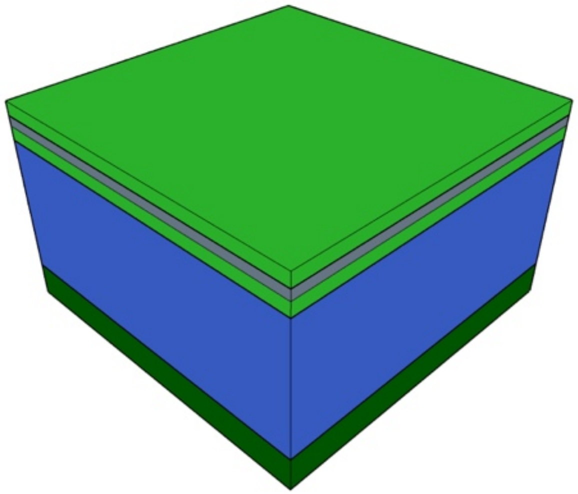
15 nm α-Si

rf magnetron sputtering



physical vapor deposition

frontside



20 nm sputtered SiO_2

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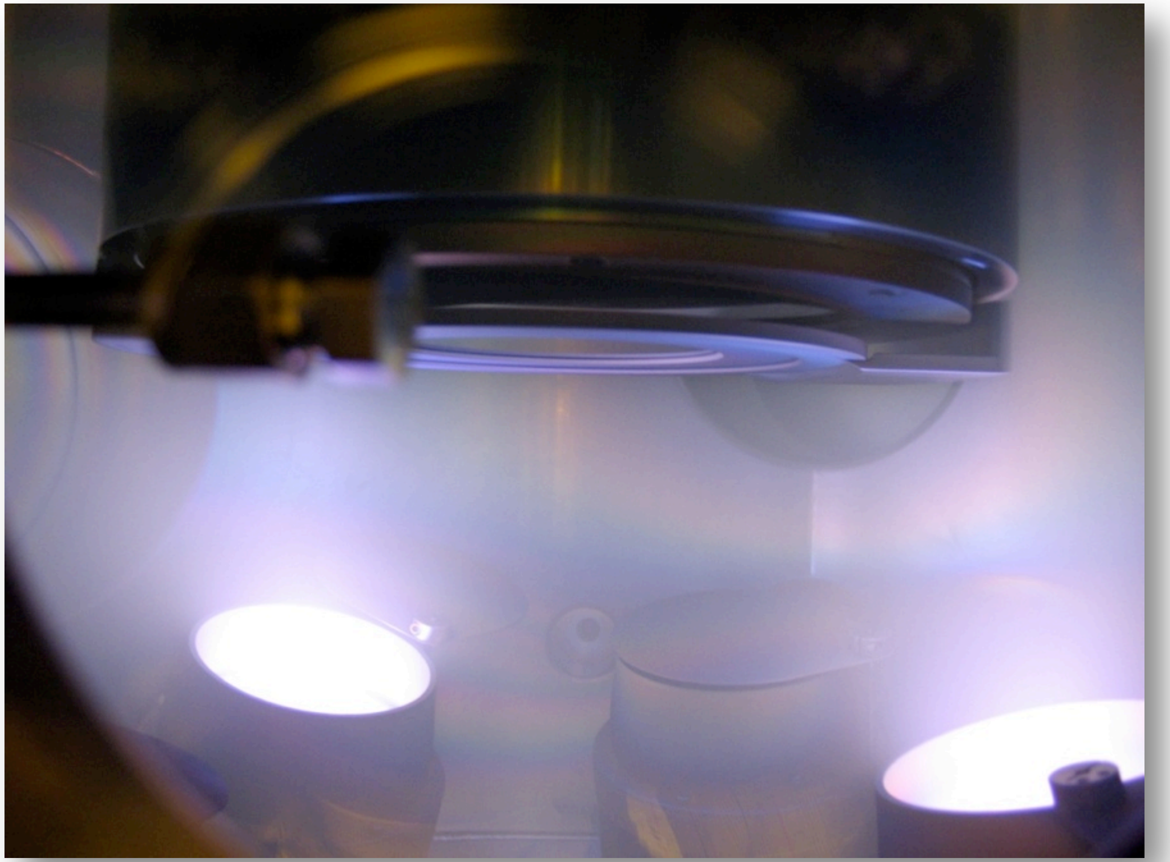
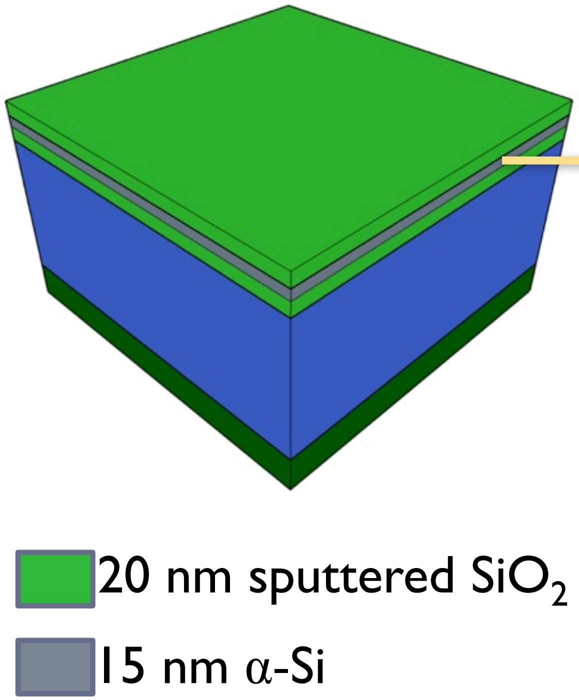
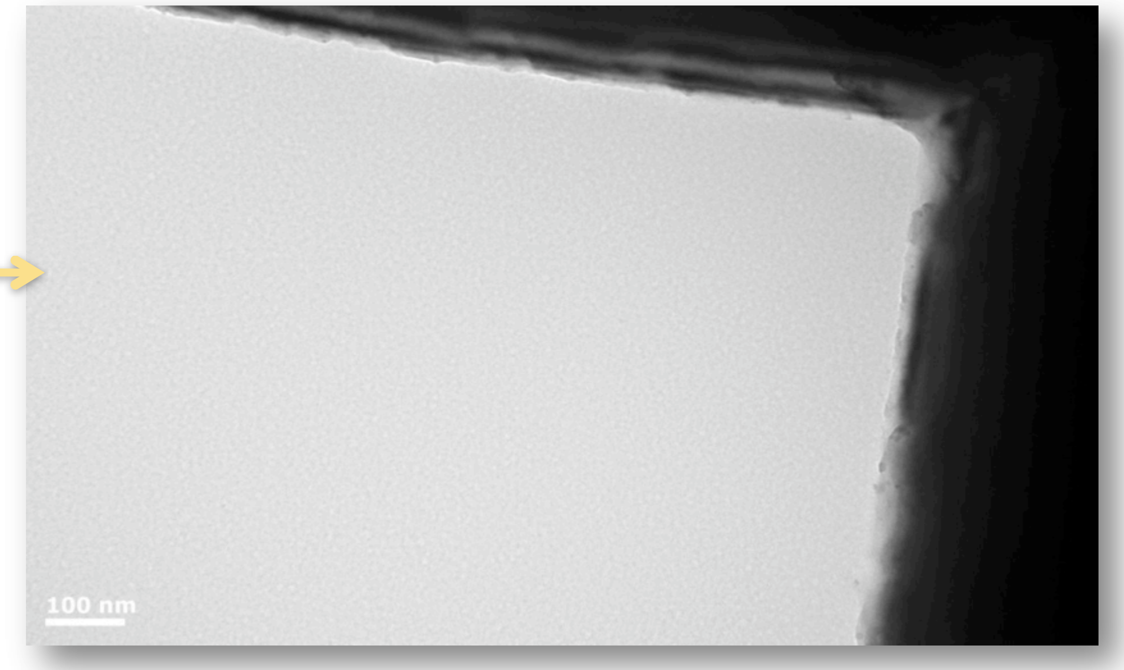


physical vapor deposition

frontside

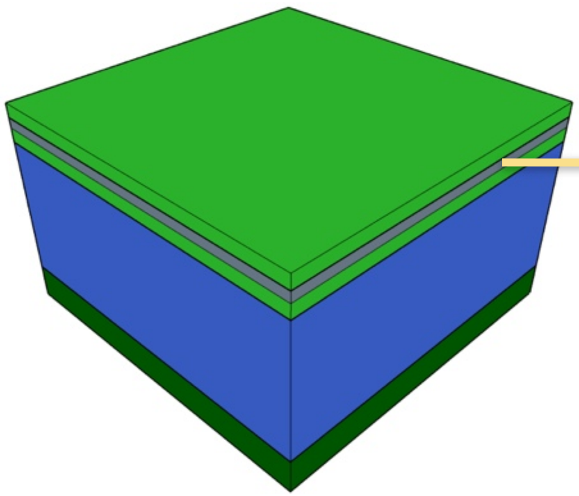


amorphous Si

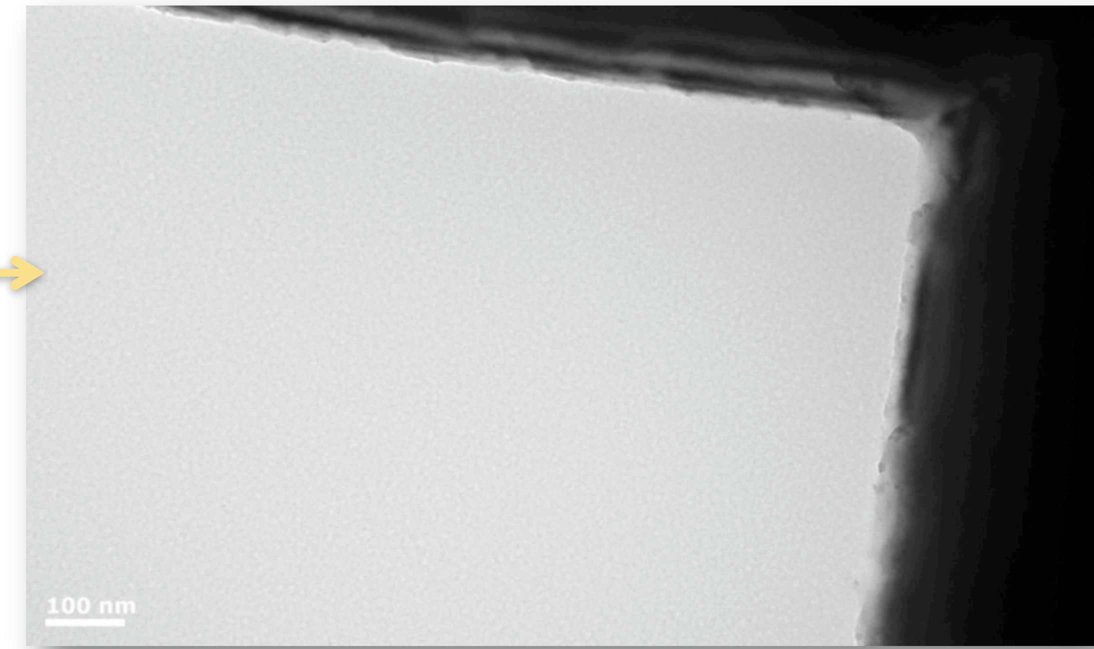


rapid thermal anneal

frontside



amorphous Si



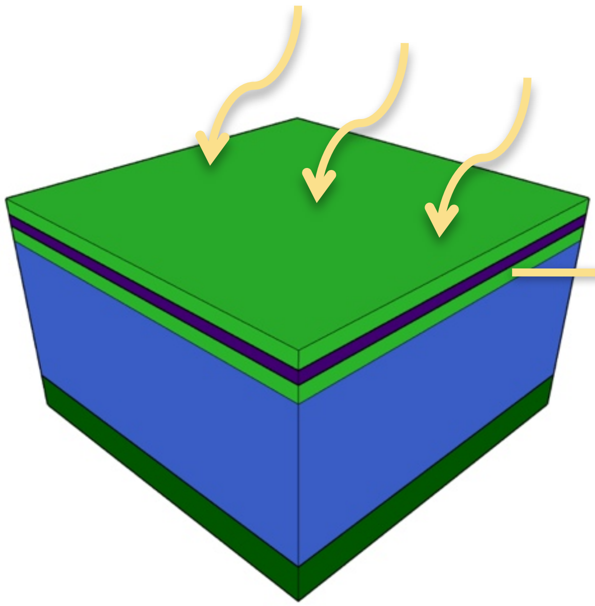
20 nm sputtered SiO_2

15 nm α-Si

rapid thermal anneal

frontside

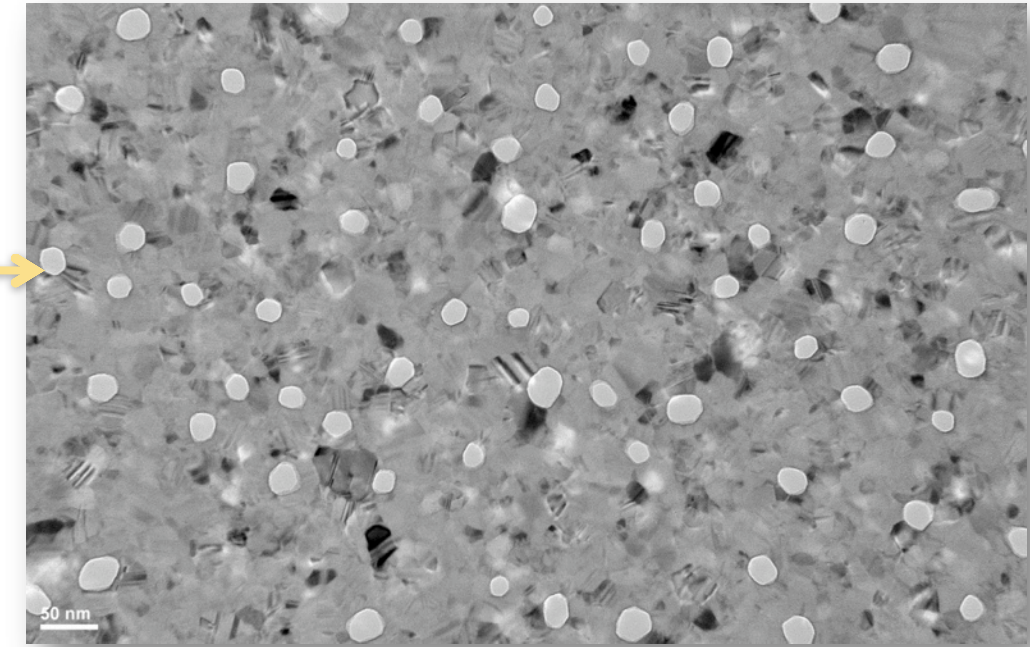
700 °C – 1000 °C < 5 min



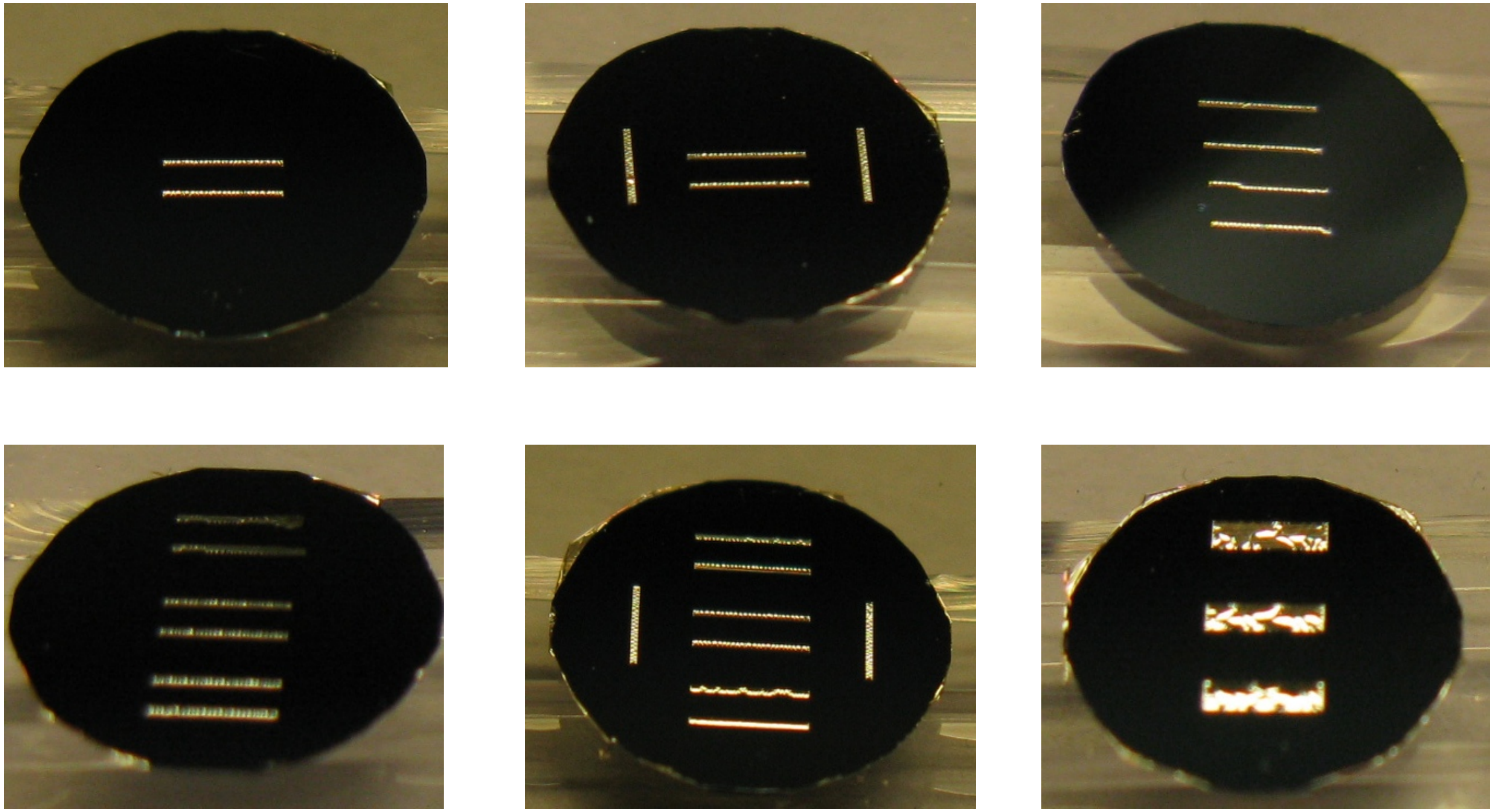
■ 20 nm sputtered SiO_2

■ 15 nm pnc-Si

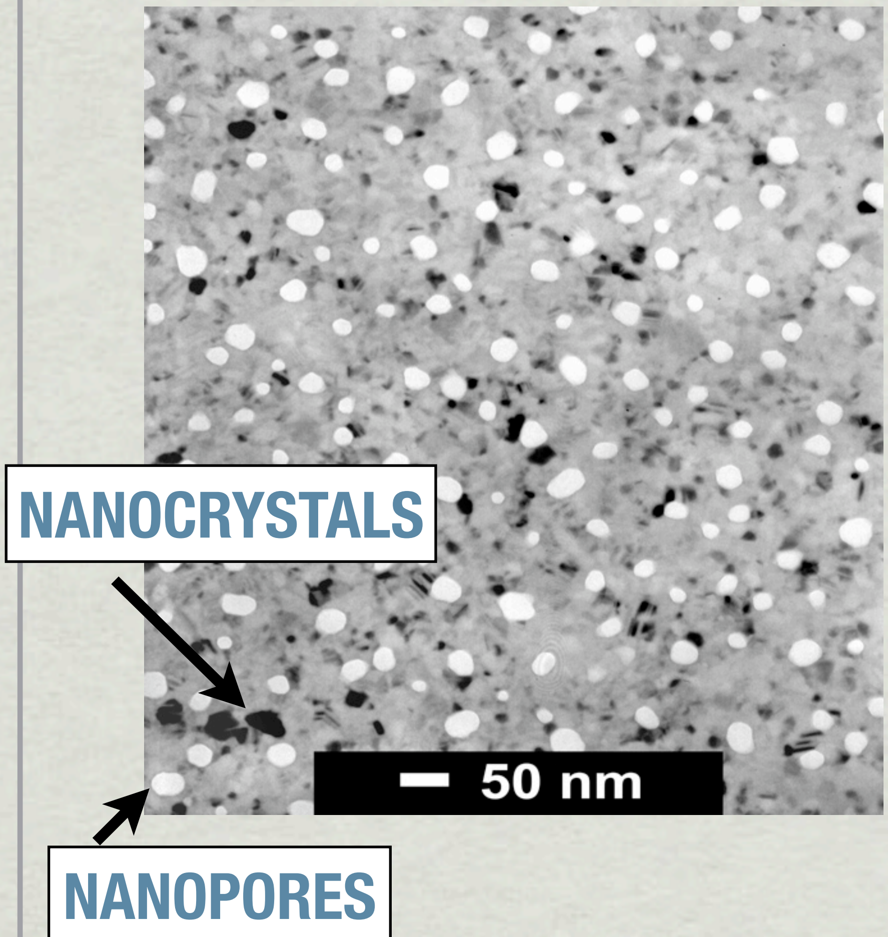
pnc-Si



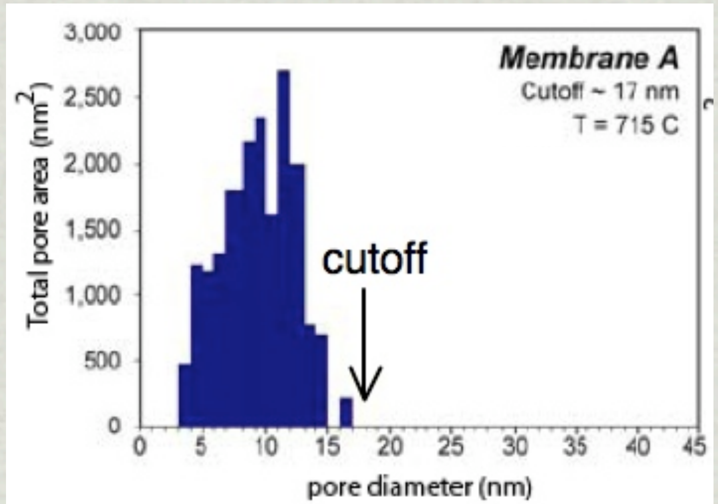
variety of formats



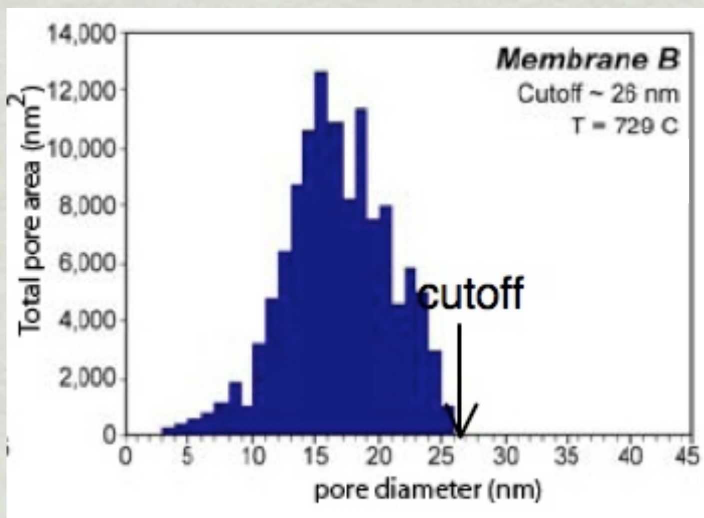
Sharp Cut-offs and Tunable Pore Sizes



Striemer, C.S, et al. 2007, Nature, 445:749-53



T = 715C



T = 729C

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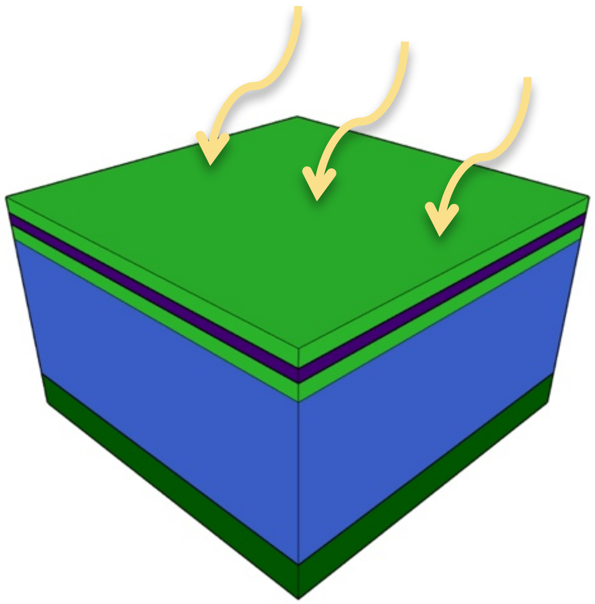
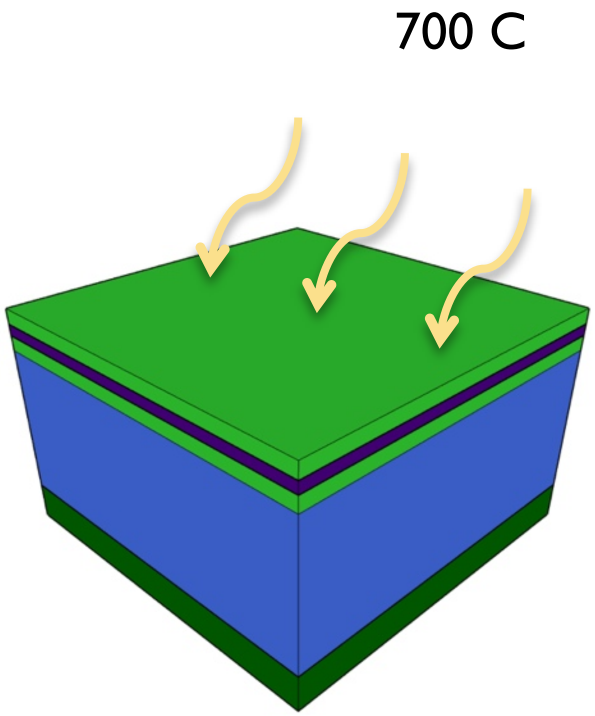
pore size & density – rtp temperature



20 nm sputtered SiO_2

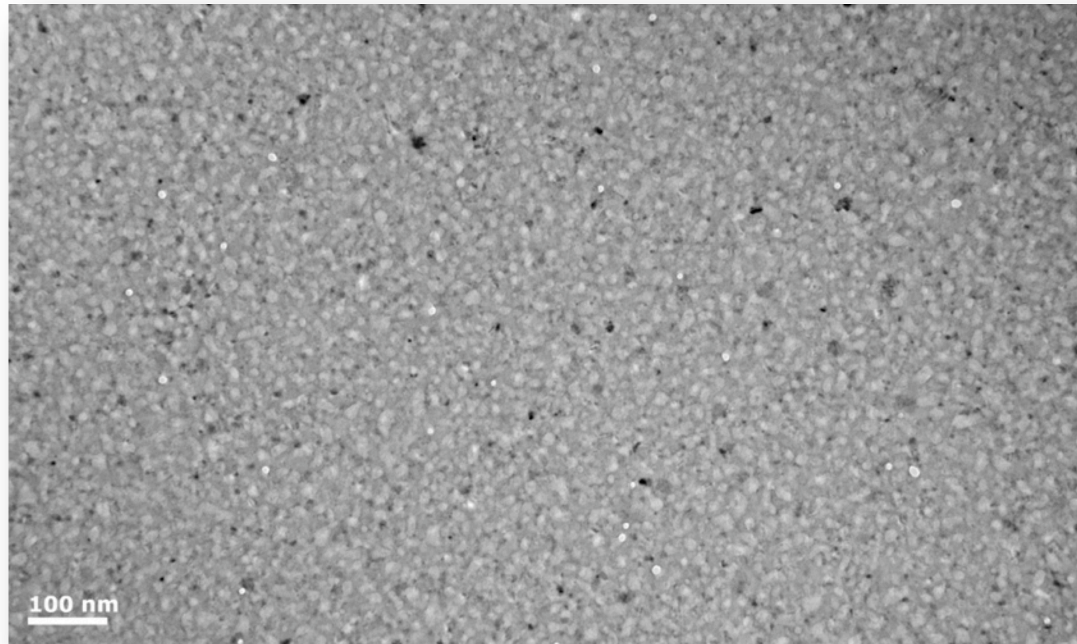
15 nm pnc-Si

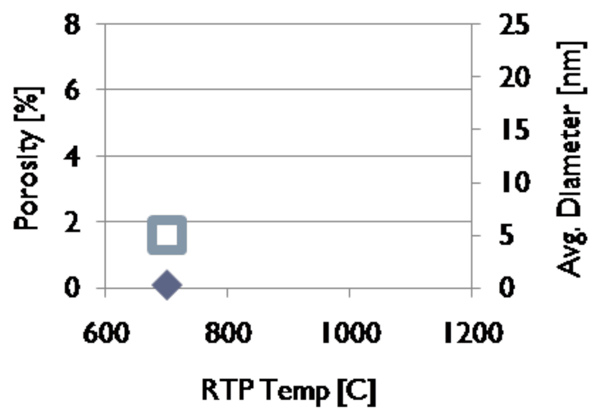
pore size & density – rtp temperature



20 nm sputtered SiO_2

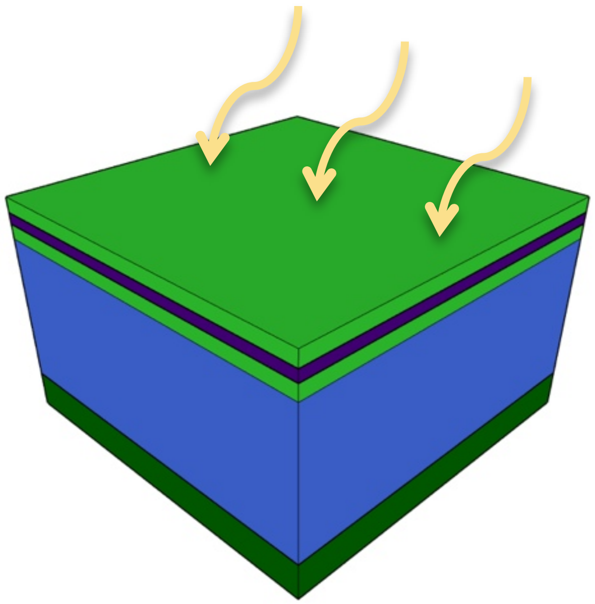
15 nm pnc-Si





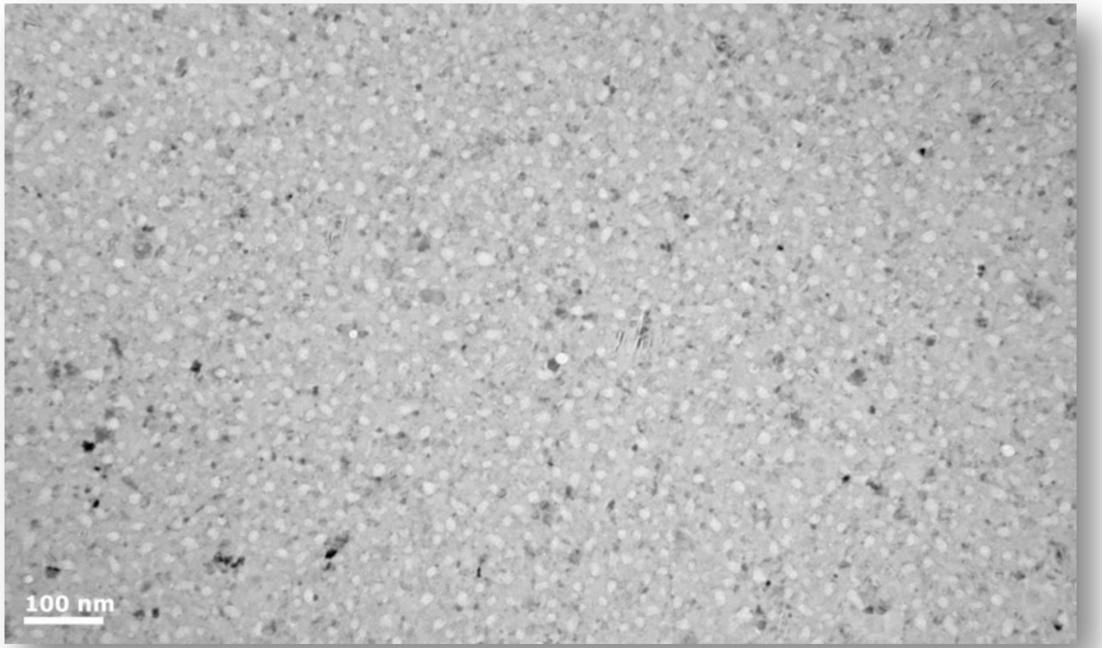
pore size & density – rtp temperature

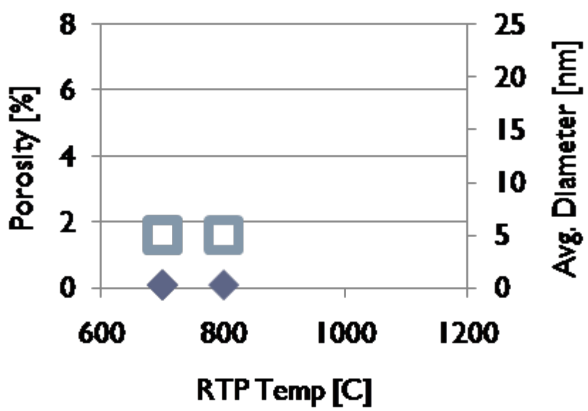
800 C



20 nm sputtered SiO_2

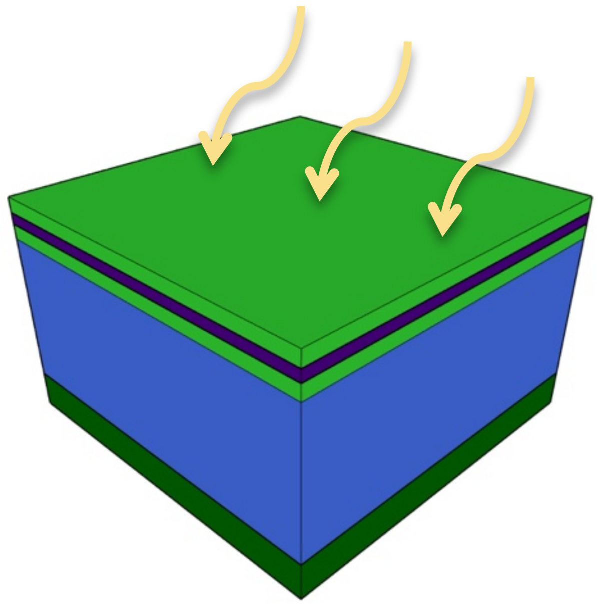
15 nm pnc-Si





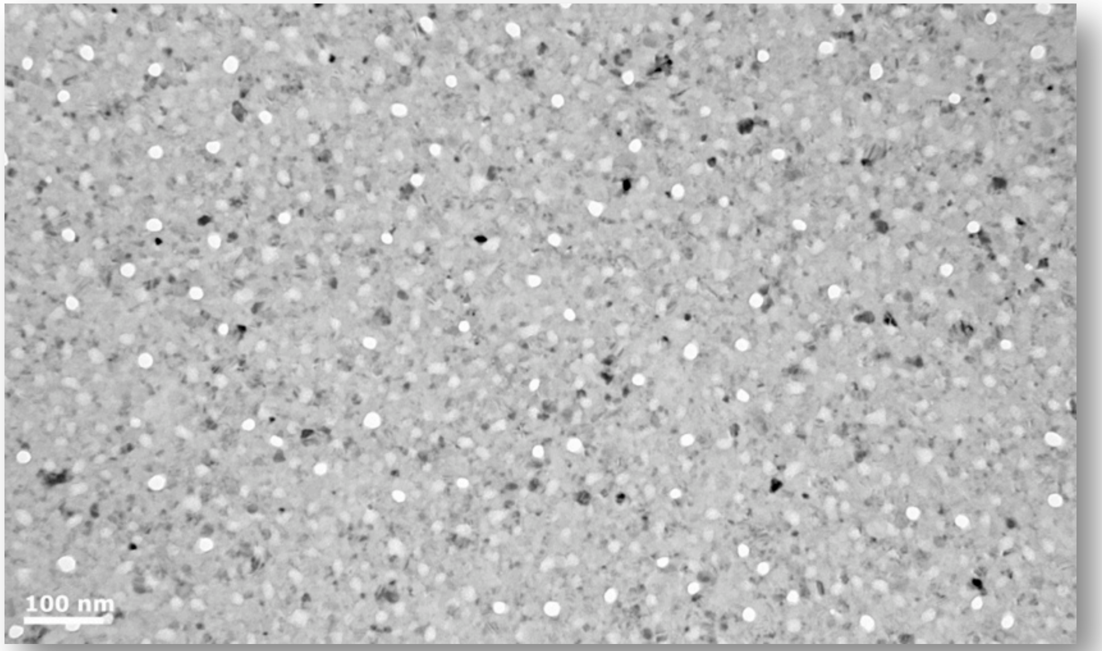
pore size & density – rtp temperature

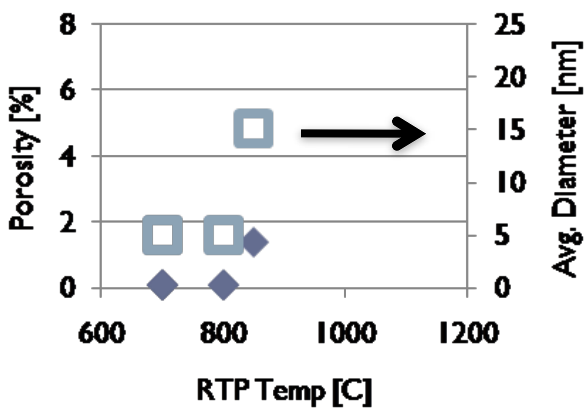
850 C



20 nm sputtered SiO_2

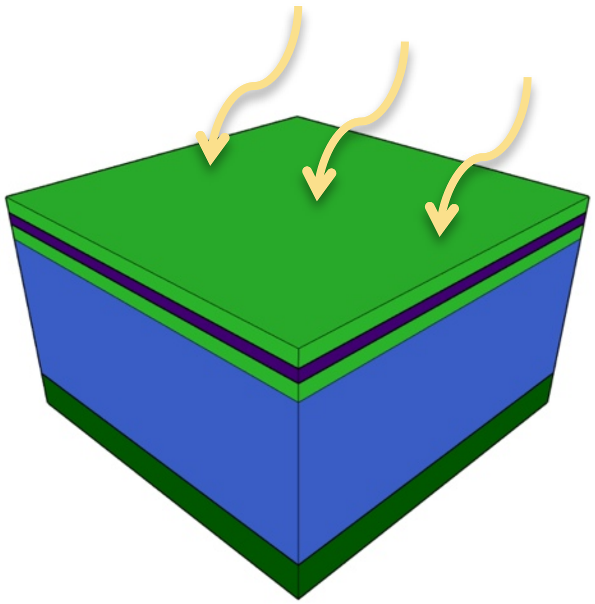
15 nm pnc-Si





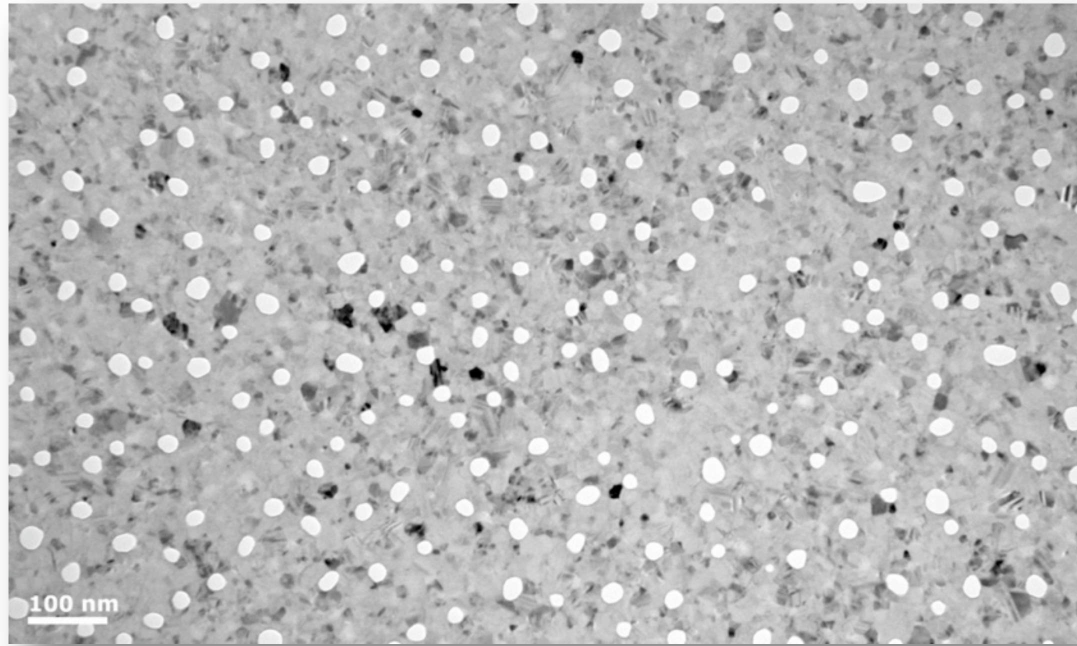
pore size & density – rtp temperature

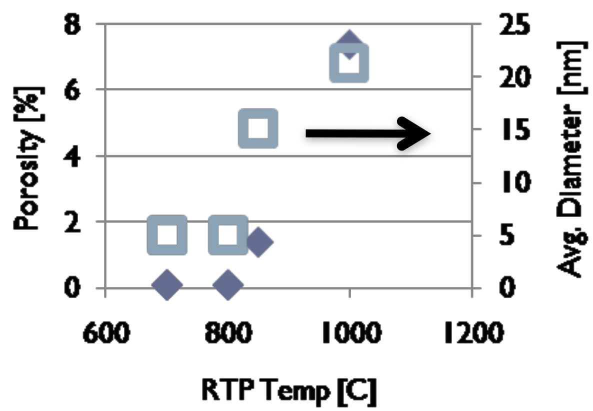
1000 C



20 nm sputtered SiO_2

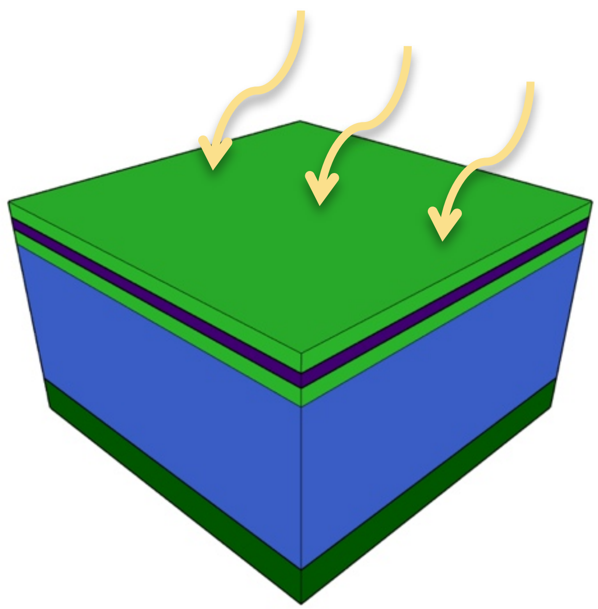
15 nm pnc-Si

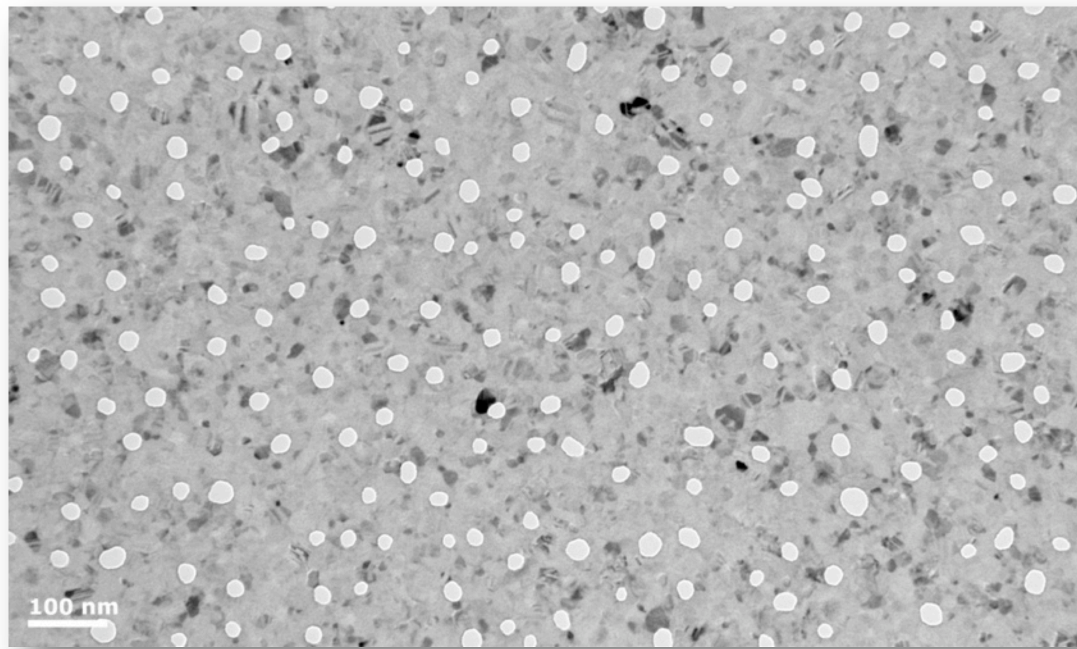




pore size & density – rtp temperature

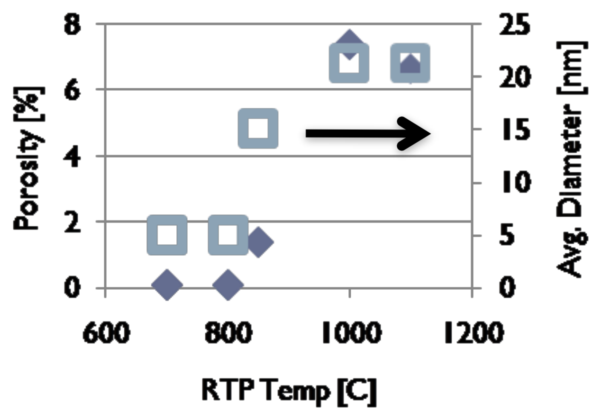
1100 C





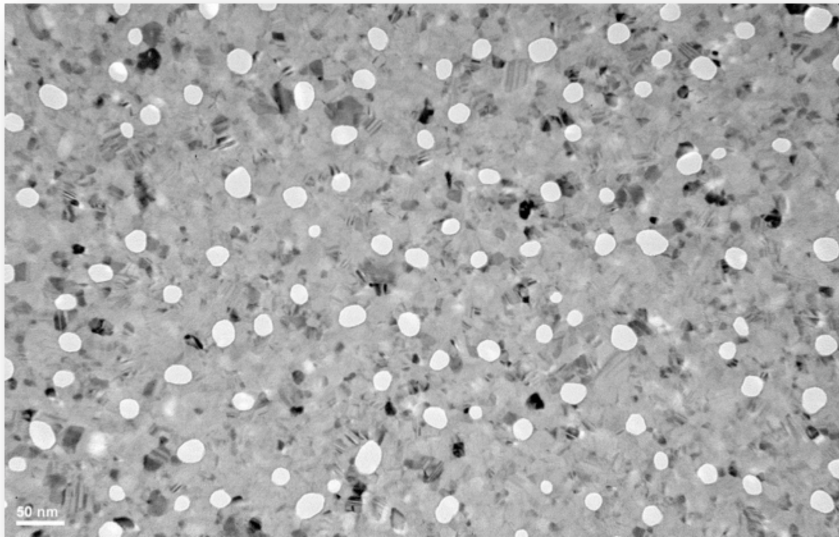
20 nm sputtered SiO_2

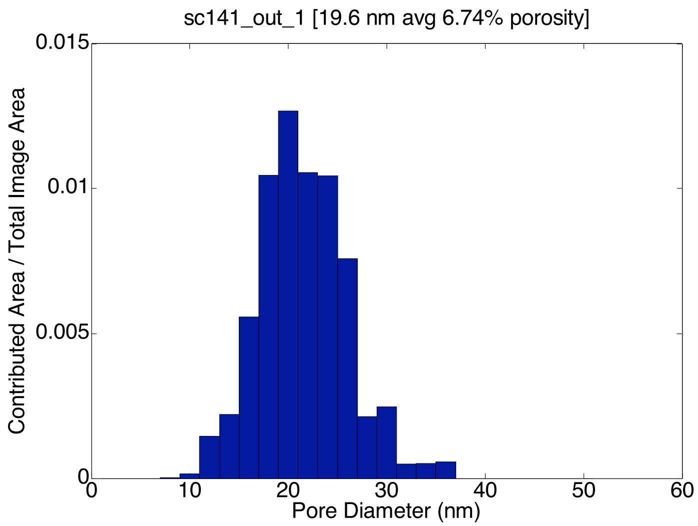
15 nm pnc-Si



controlling morphology – thickness

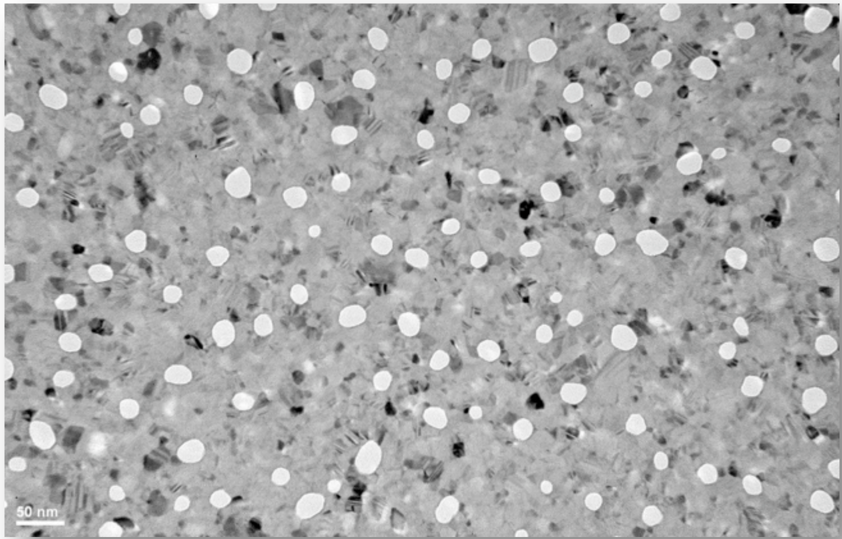
15 nm pnc-Si

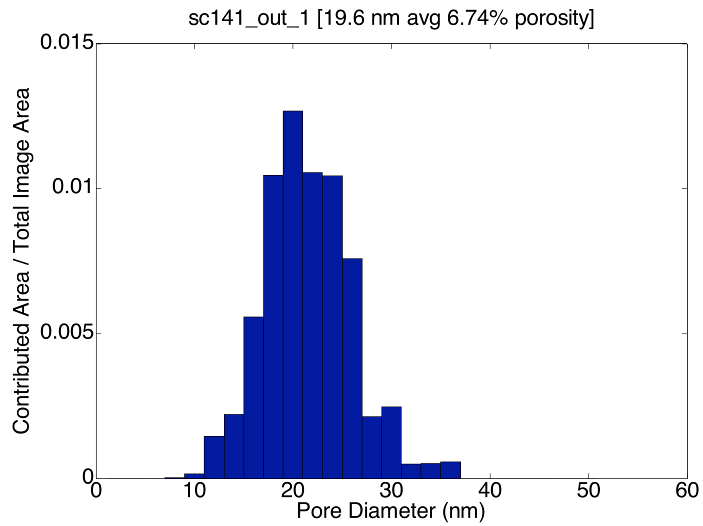




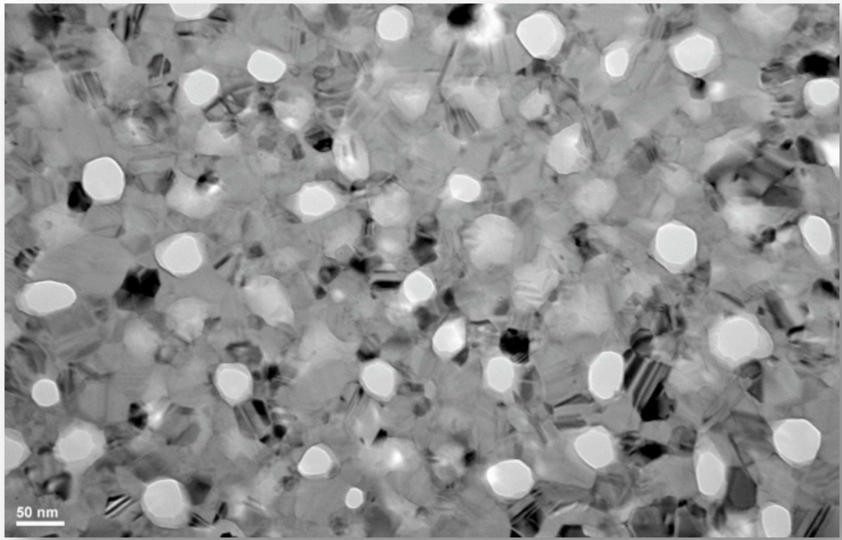
controlling morphology – thickness

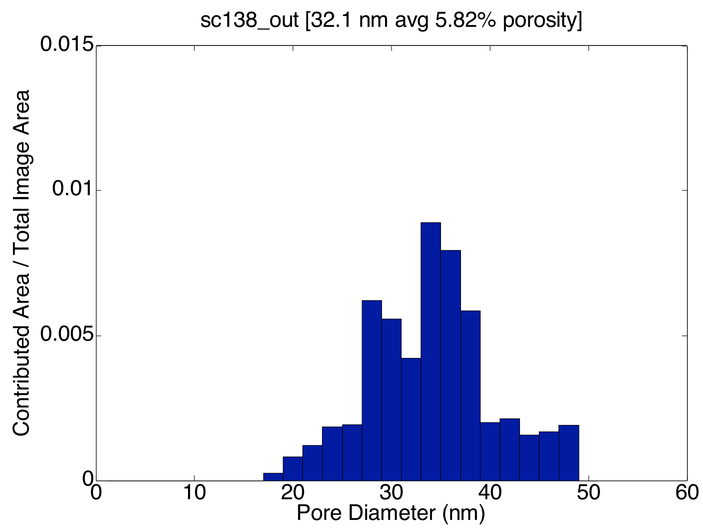
15 nm pnc-Si



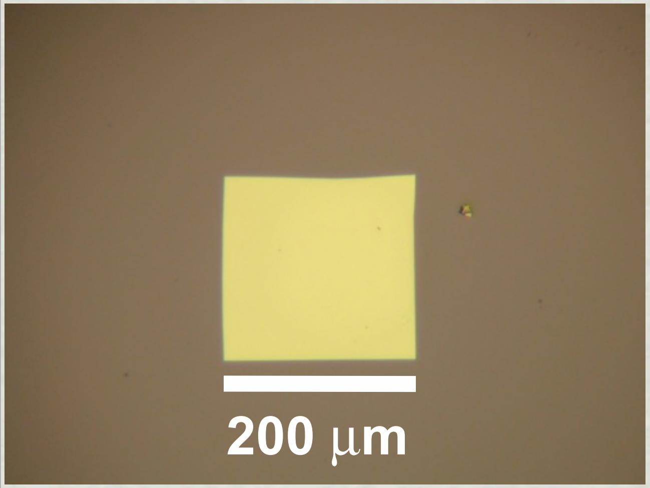


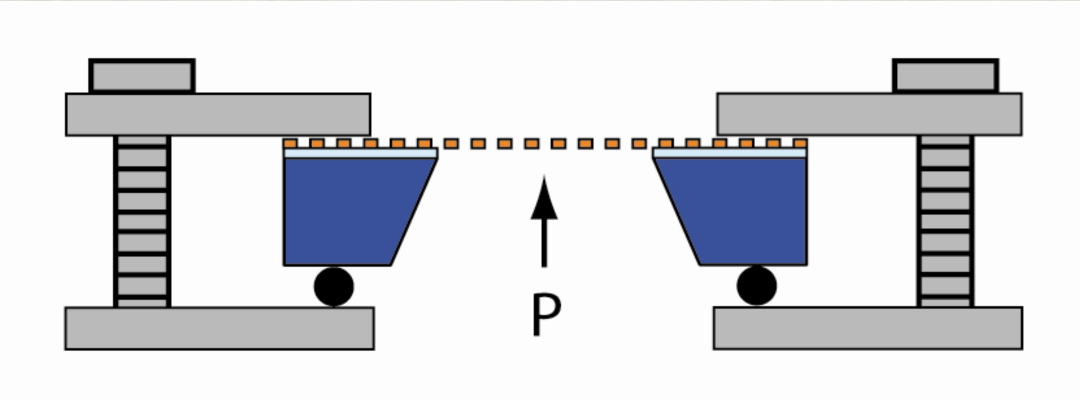
30 nm pnc-Si





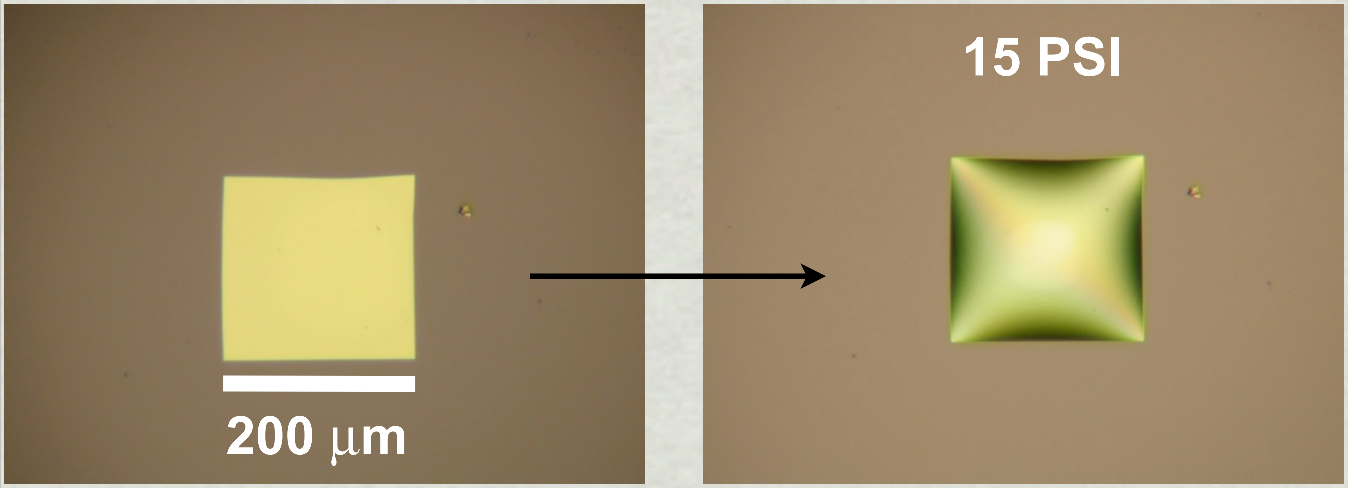
Mechanically Robust

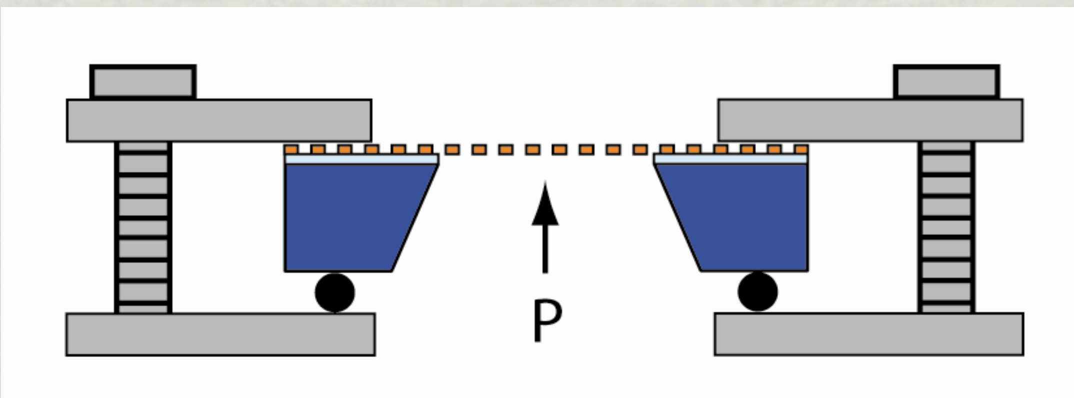




Striemer, C.S, et al. 2007, Nature, 445:749-53

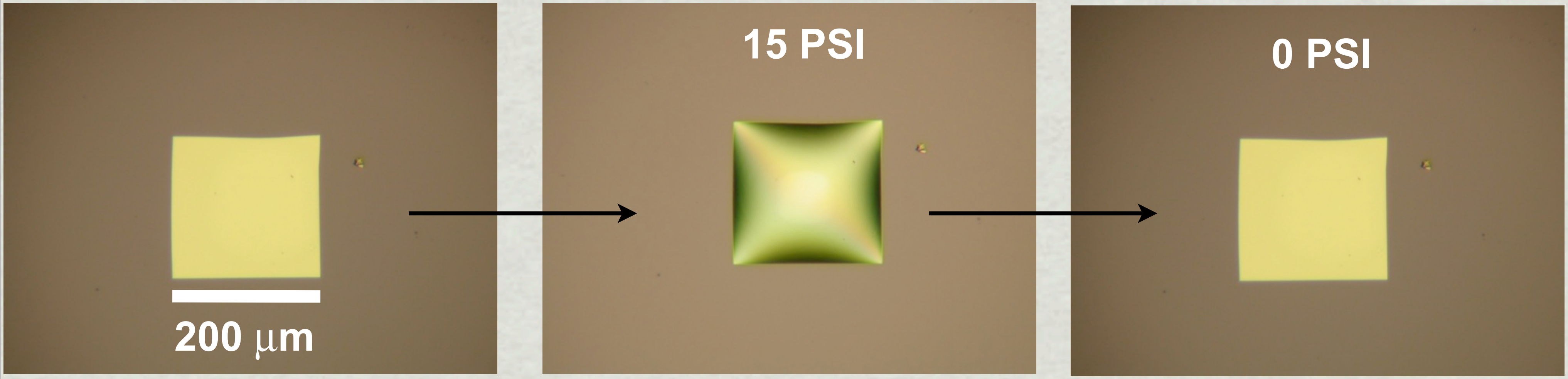
Mechanically Robust

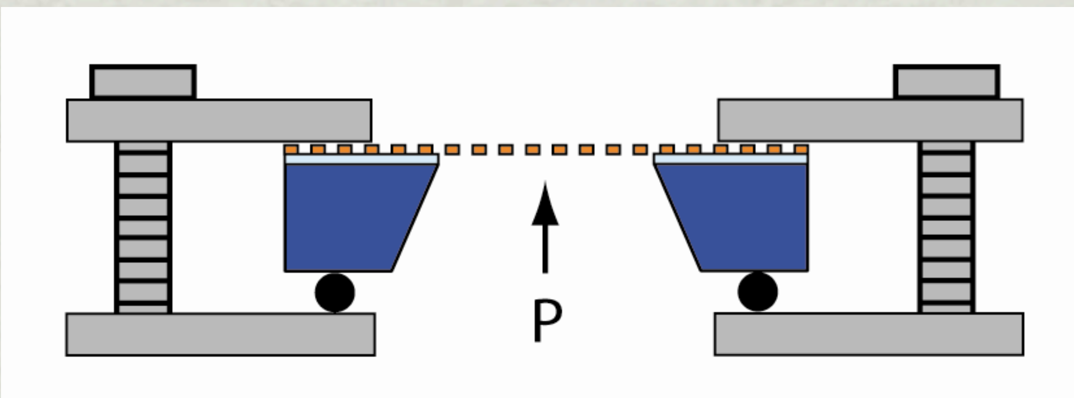




Striemer, C.S, et al. 2007, Nature, 445:749-53

Mechanically Robust





Striemer, C.S, et al. 2007, Nature, 445:749-53

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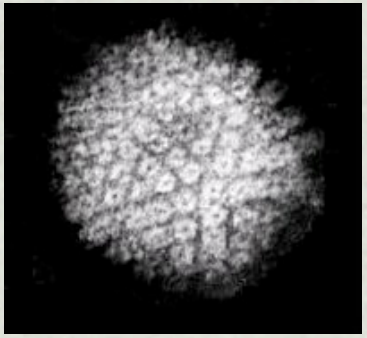
Key Biological Sizes

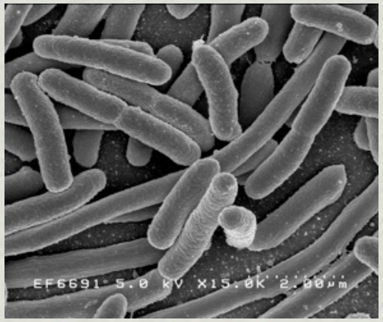
small solutes

proteins

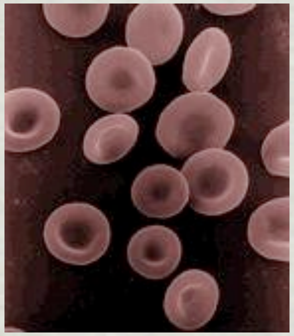
virus



bacteria



eukaryotic cells



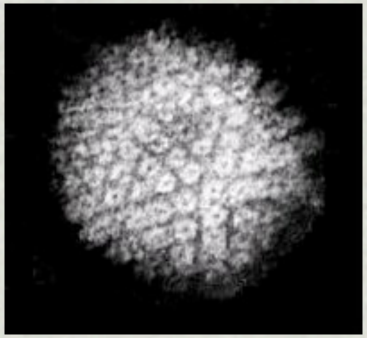
1 nm — 10 nm — 1 um — 10 um

Key Biological Sizes

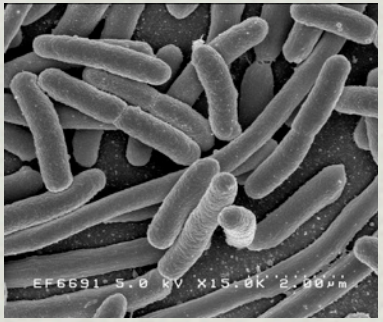
small solutes

proteins

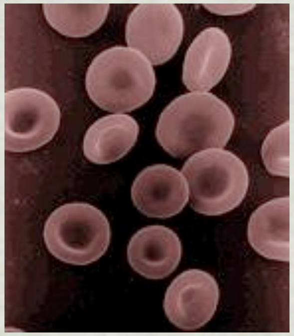
virus



bacteria



eukaryotic cells



1 nm — 10 nm — 1 um — 10 um

PNC-SI (5-80 NM)

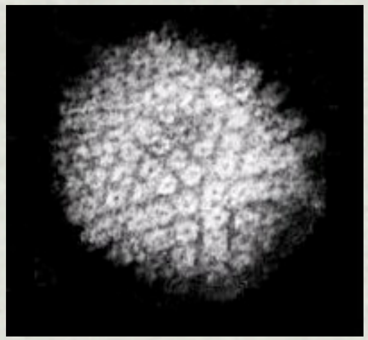
NRG 2009

Key Biological Sizes

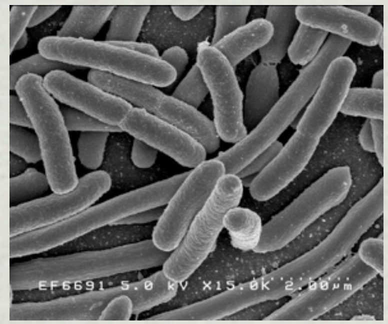
small solutes

proteins

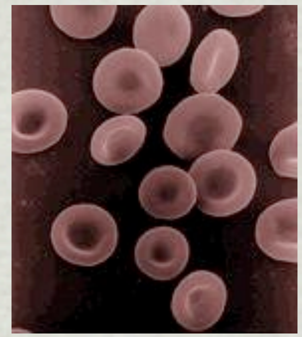
virus



bacteria



eukaryotic cells



1 nm — 10 nm — 1 um — 10 um

PNC-SI (5-80 NM)
@ 0.1%-15%

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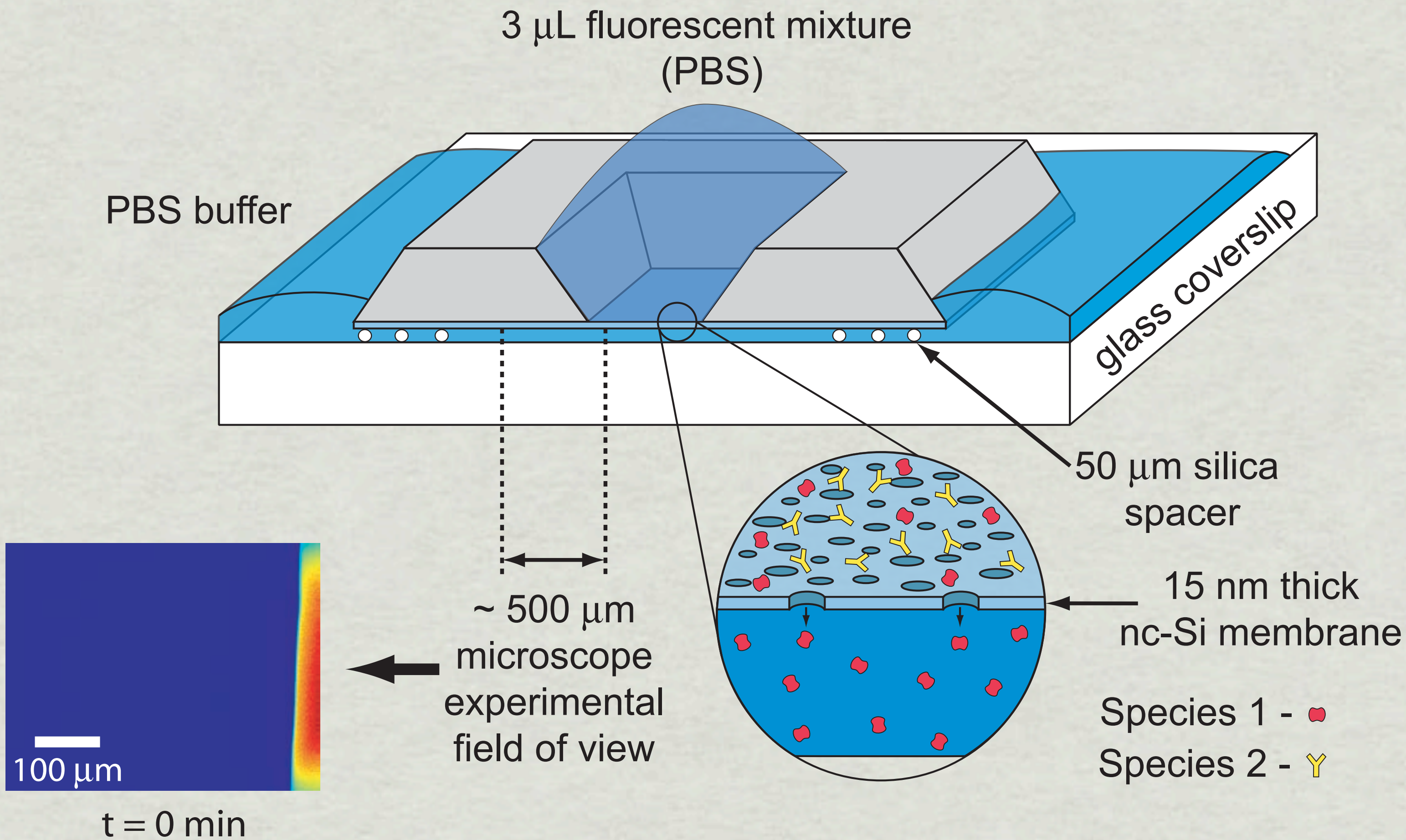
Size Based Separation



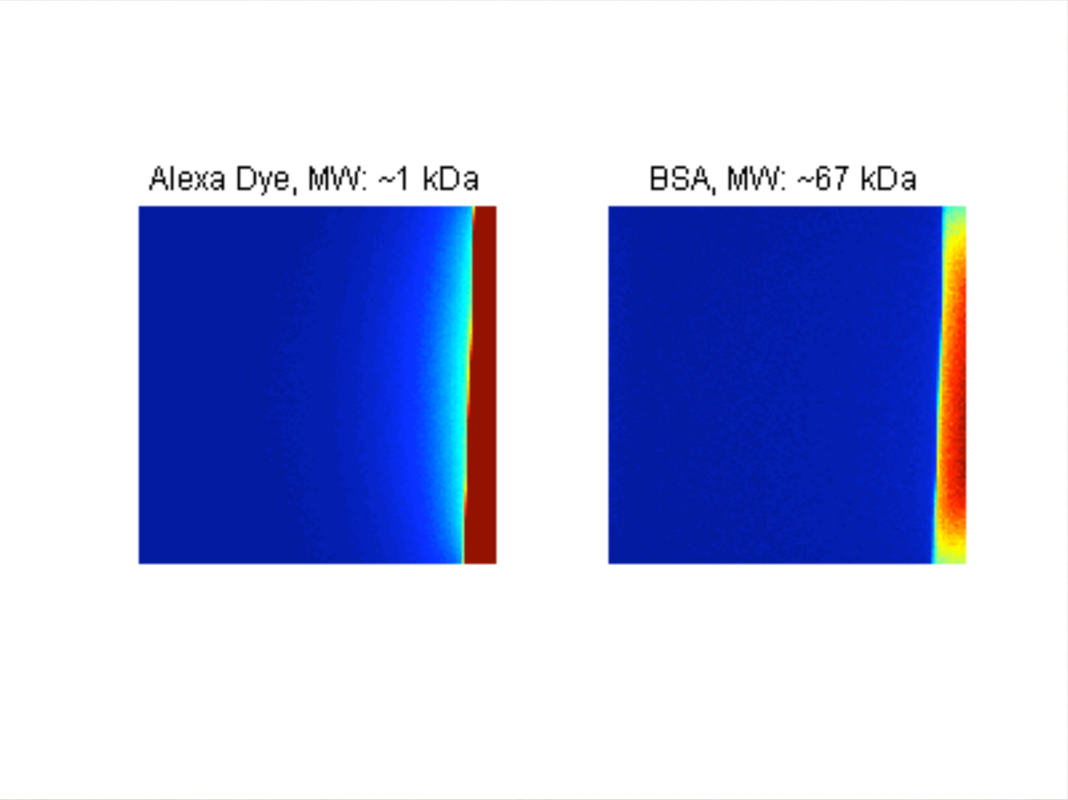
Striemer, C.S, et al. 2007, Nature, 445:749-53

NRG 2009

Size Based Separation

Striemer, C.S, et al. 2007, Nature, 445:749-53

Size Based Separation



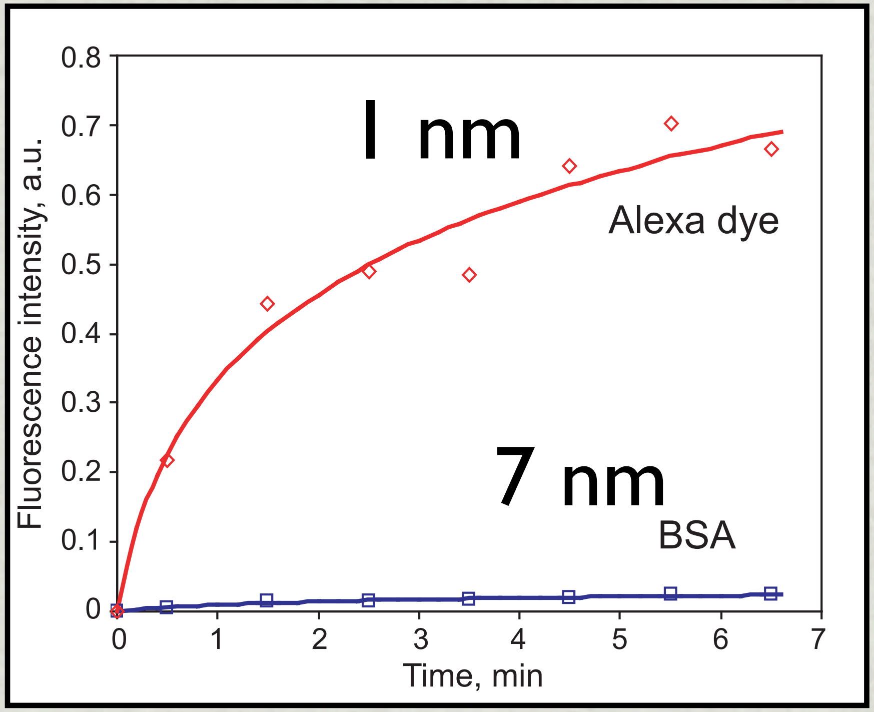
Striemer, C.S, et al. 2007, Nature, 445:749-53

NRG 2009

Size Based Separation

Striemer, C.S, et al. 2007, Nature, 445:749-53

Size Based Separation

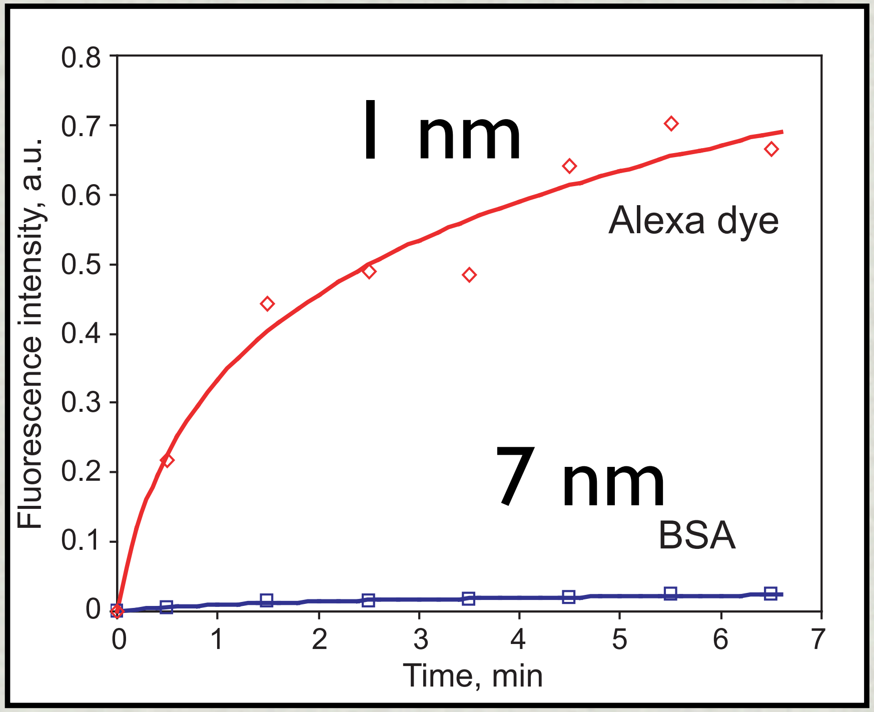


MEMBRANE A

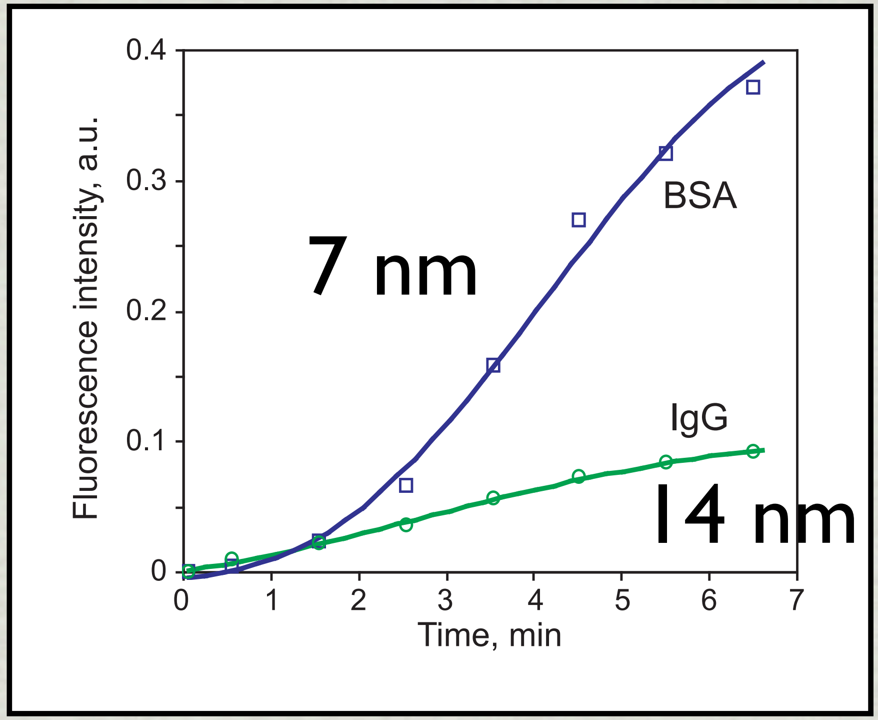
Striemer, C.S, et al. 2007, Nature, 445:749-53

NRG 2009

Size Based Separation



MEMBRANE A



MEMBRANE B

Striemer, C.S, et al. 2007, Nature, 445:749-53

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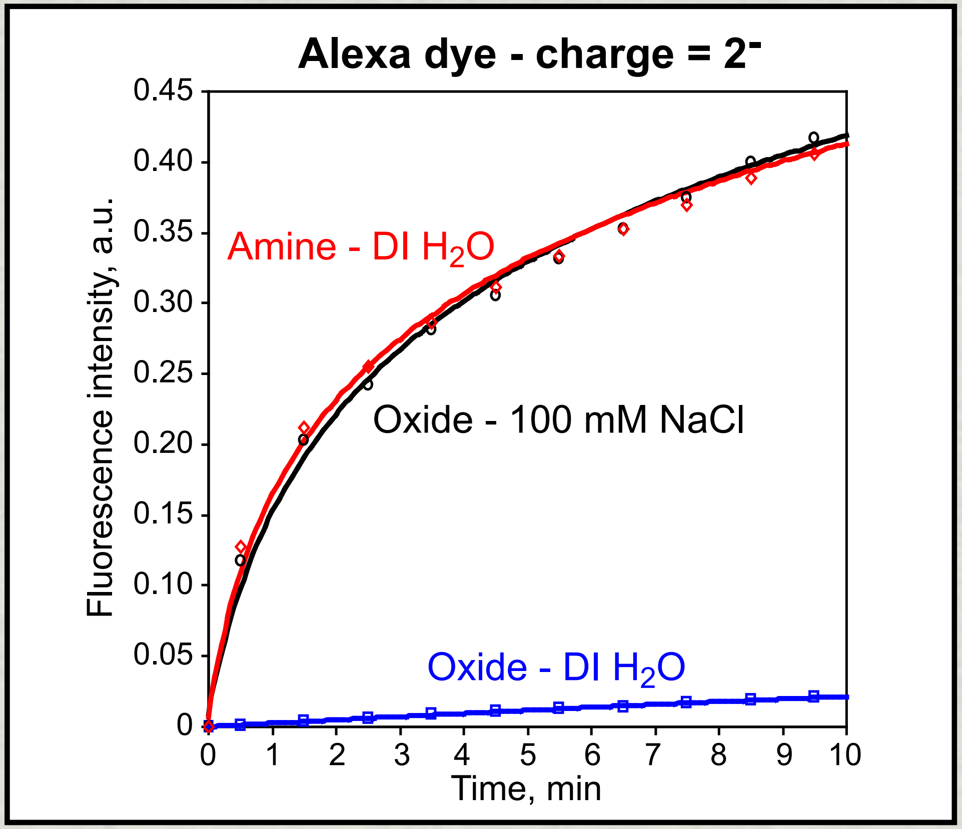
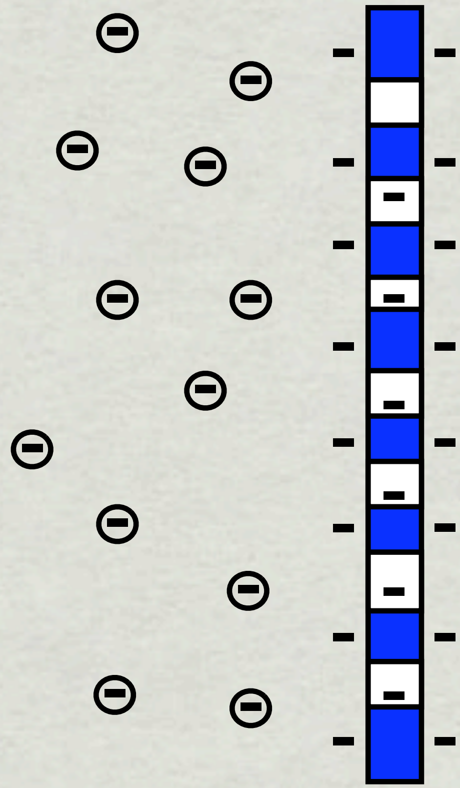
Charge Based Separation





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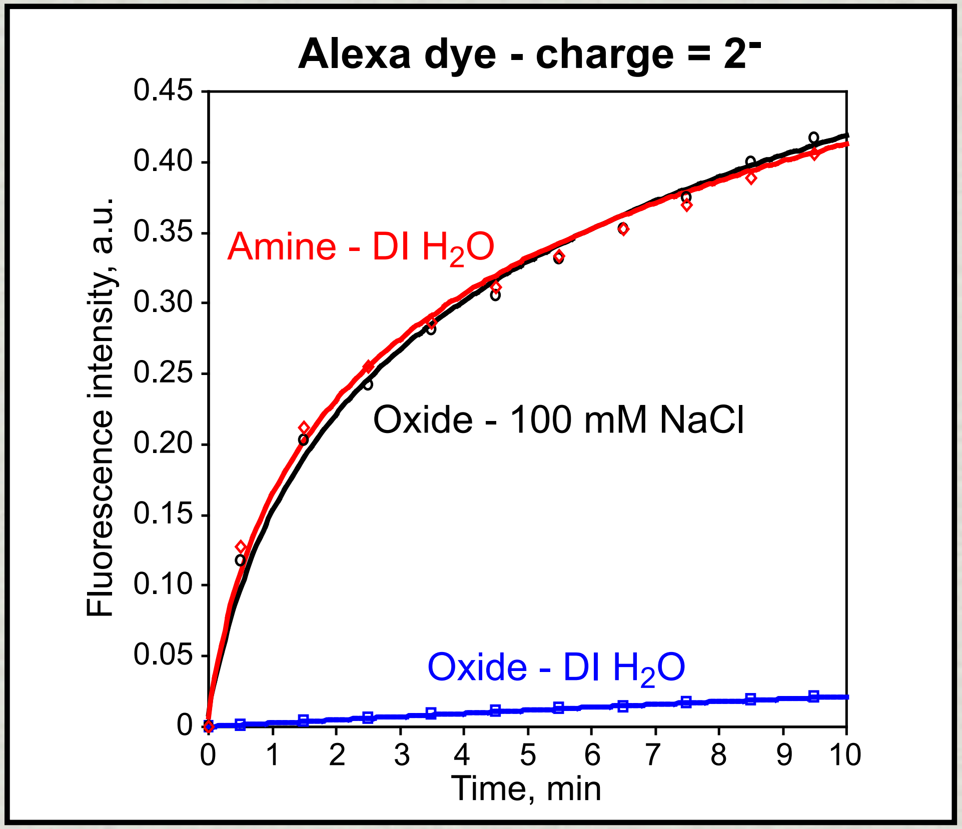

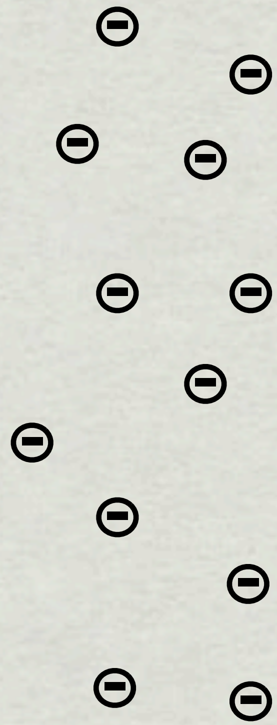

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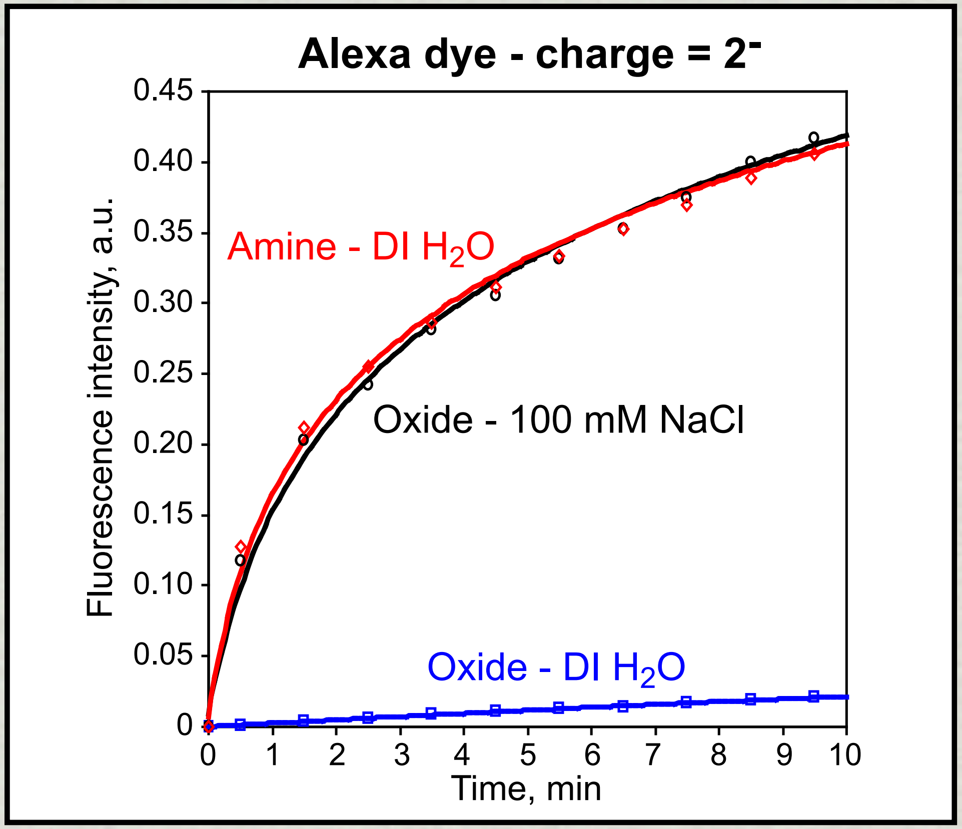

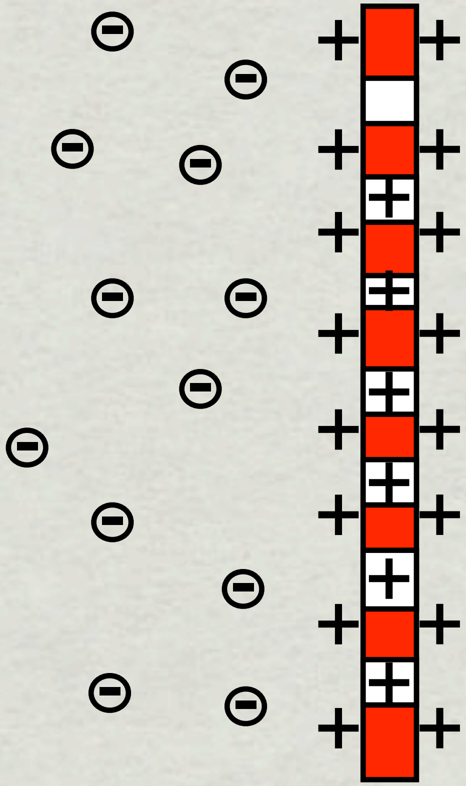

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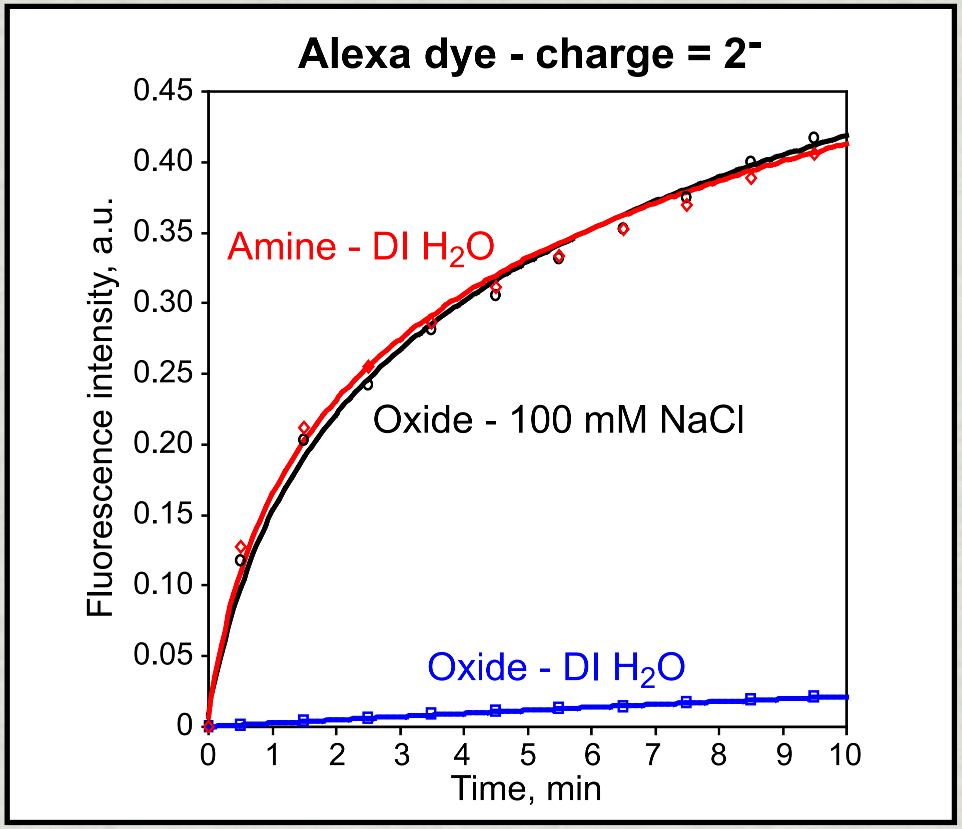

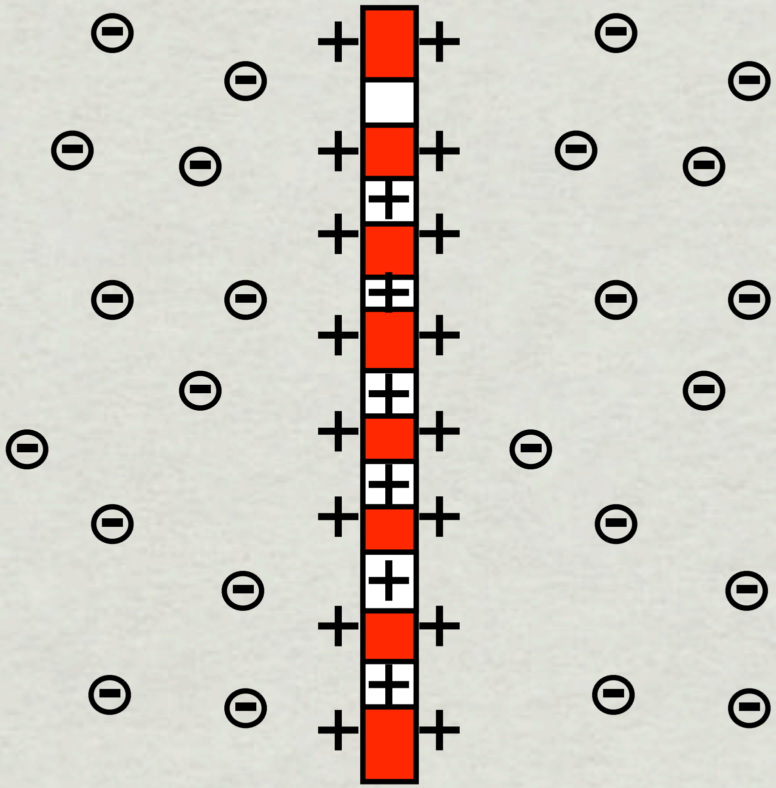

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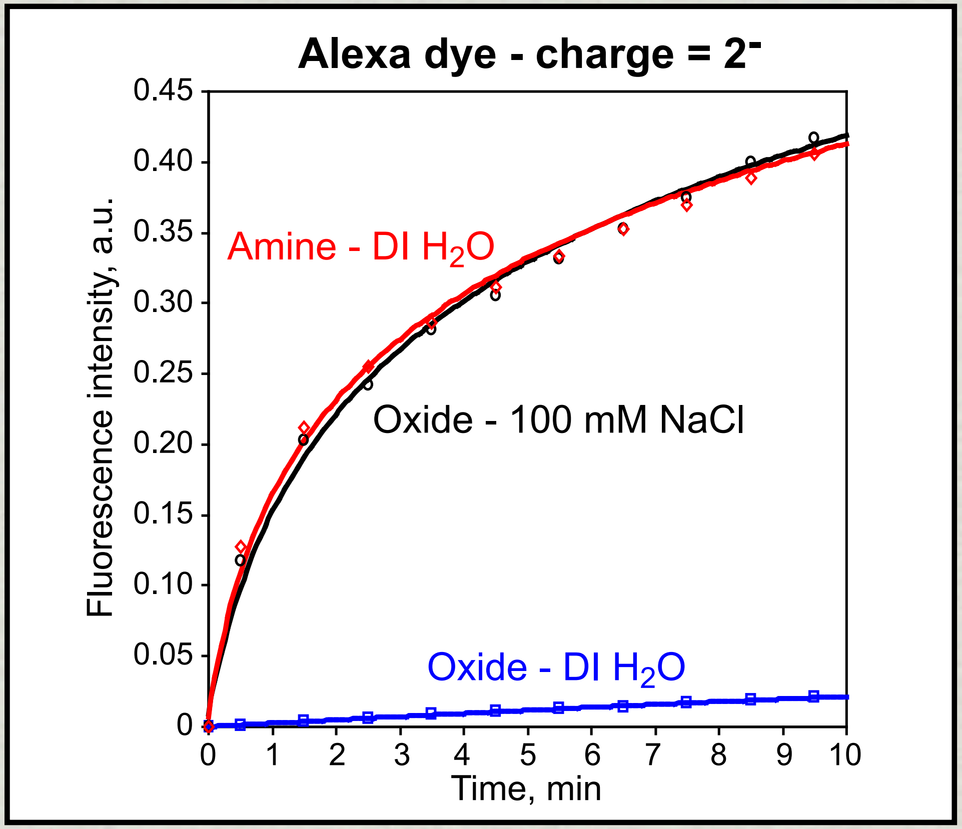

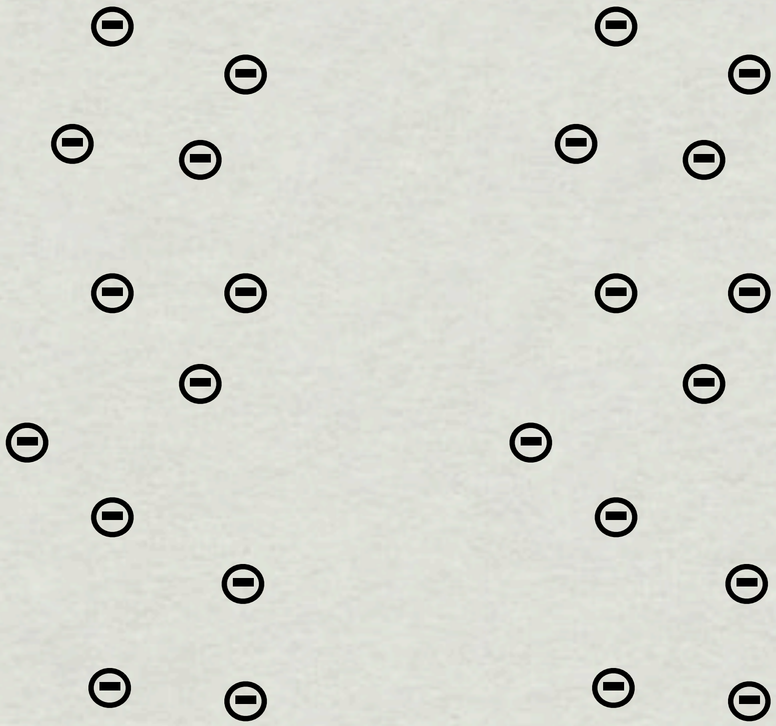

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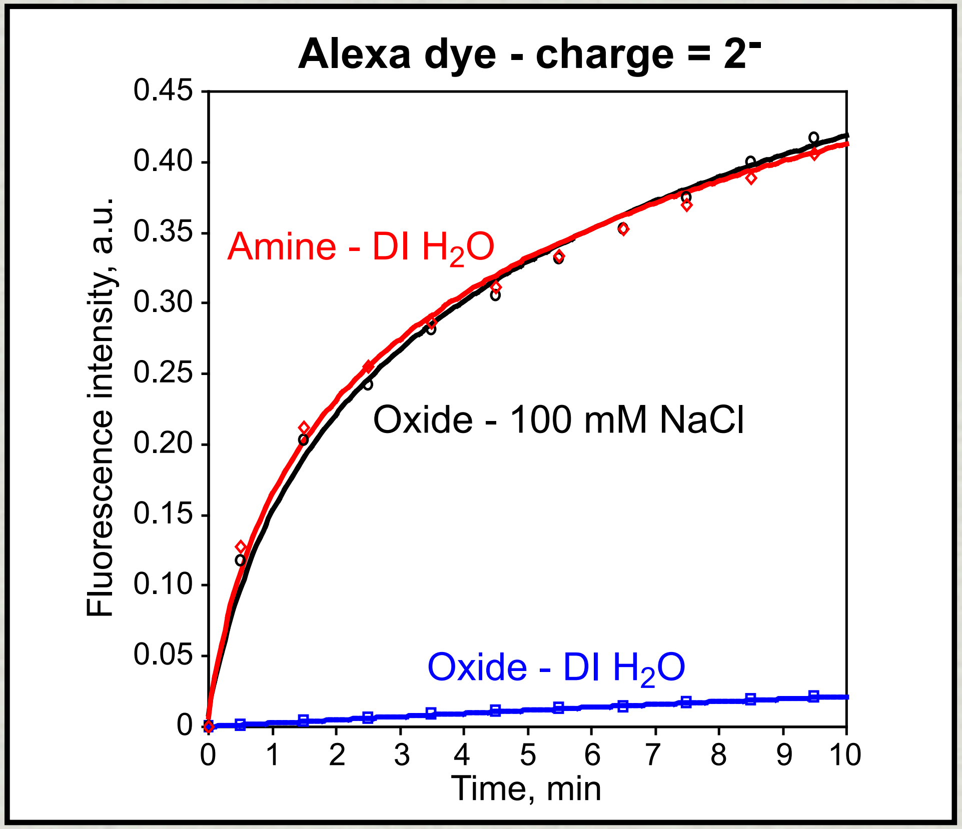

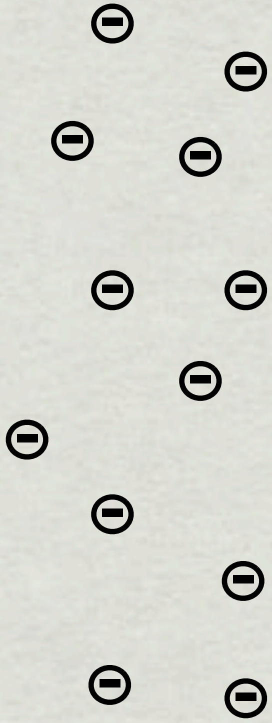

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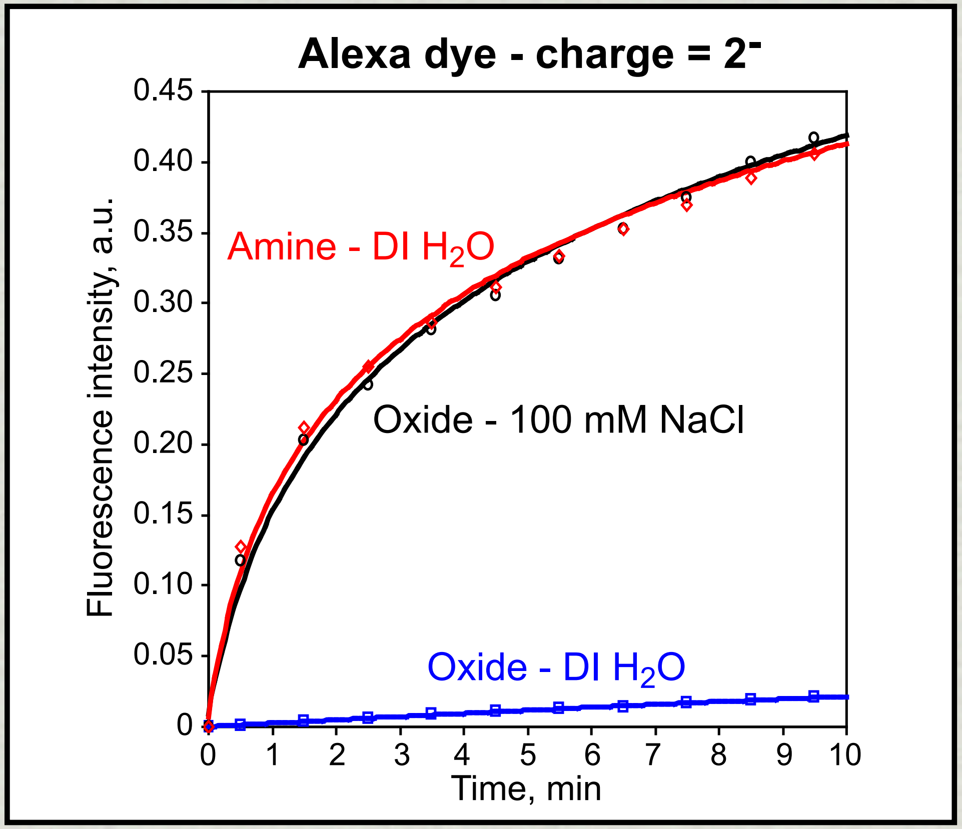

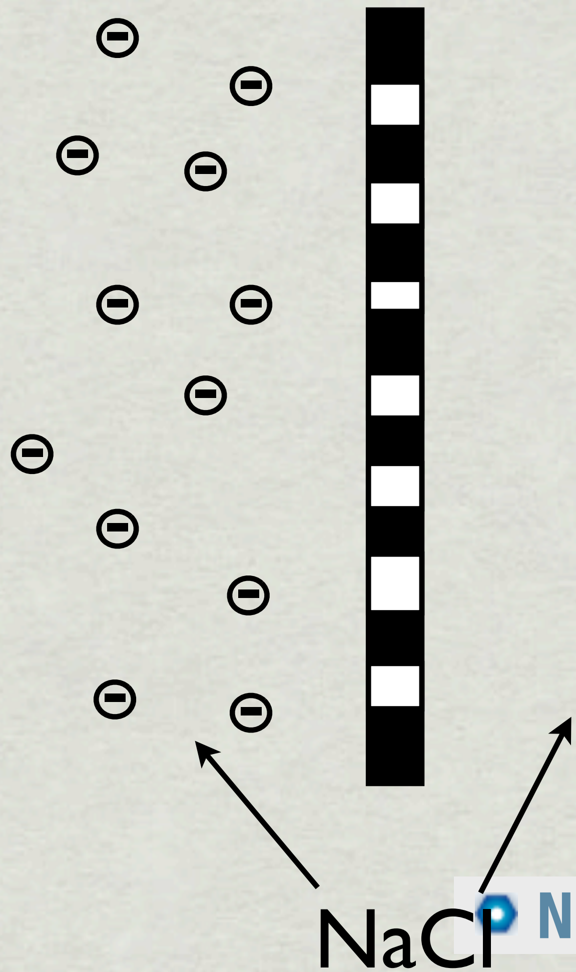

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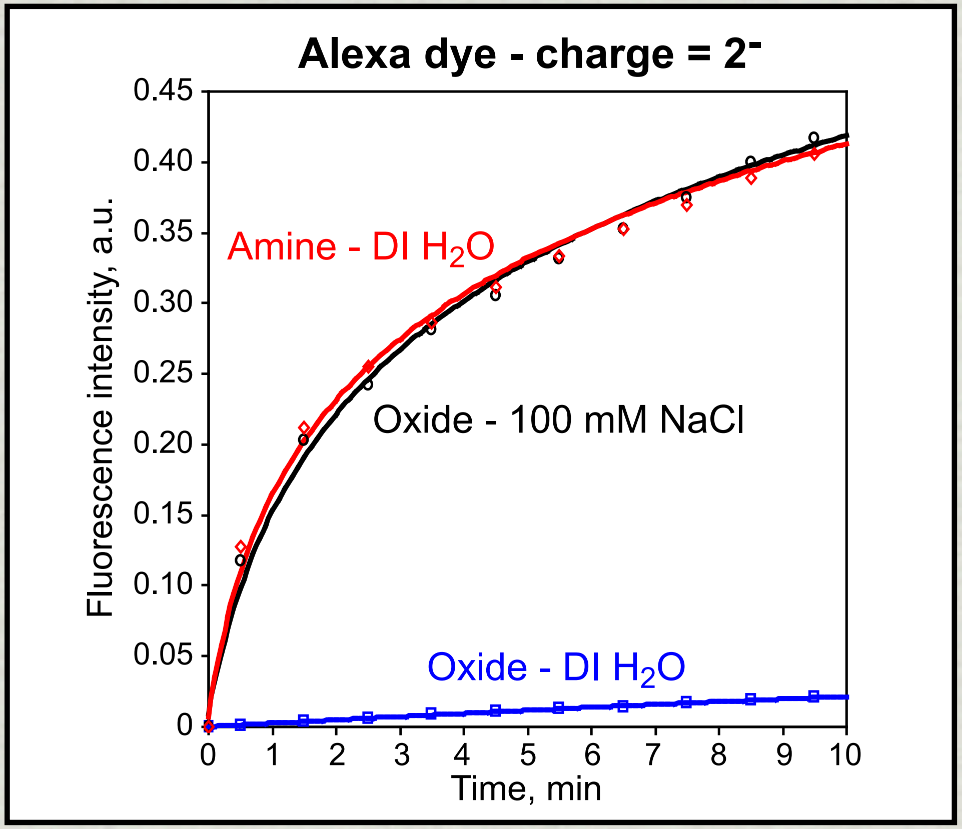

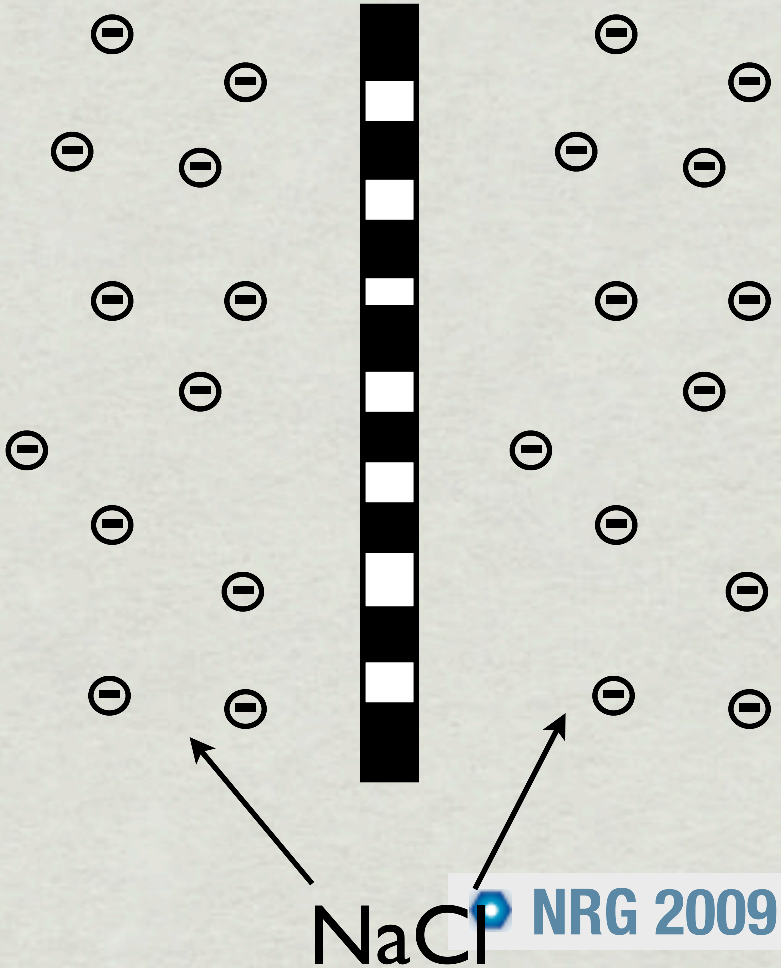

Striemer, C.S, et al. 2007, Nature, 445:749-53

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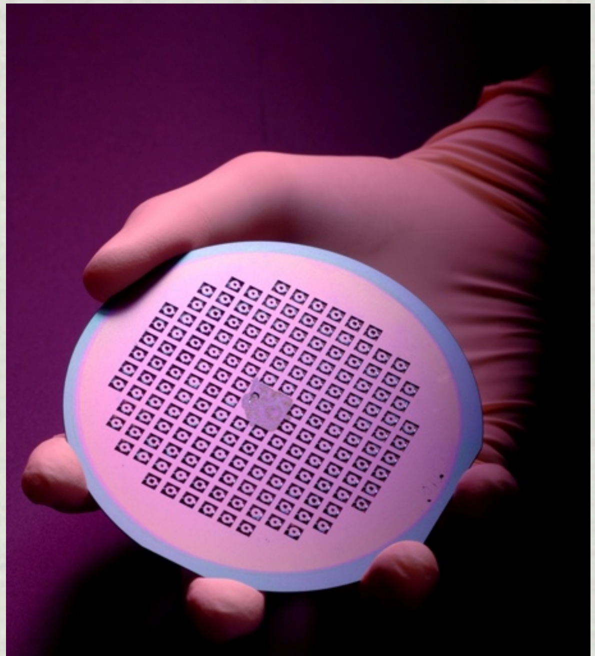
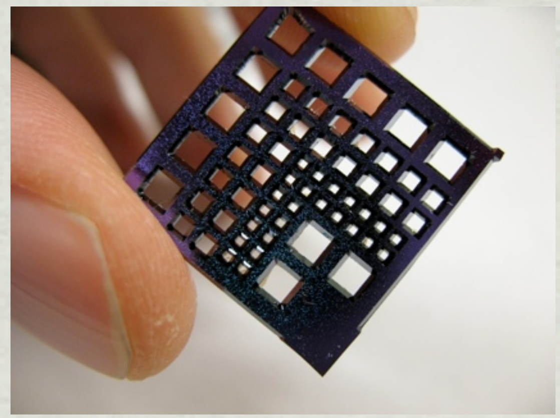
Scalable, flexible, economical fabrication





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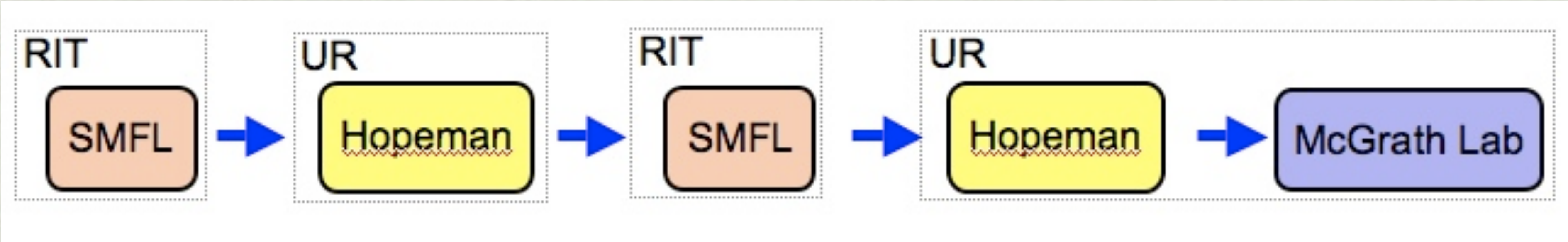
Production Flow

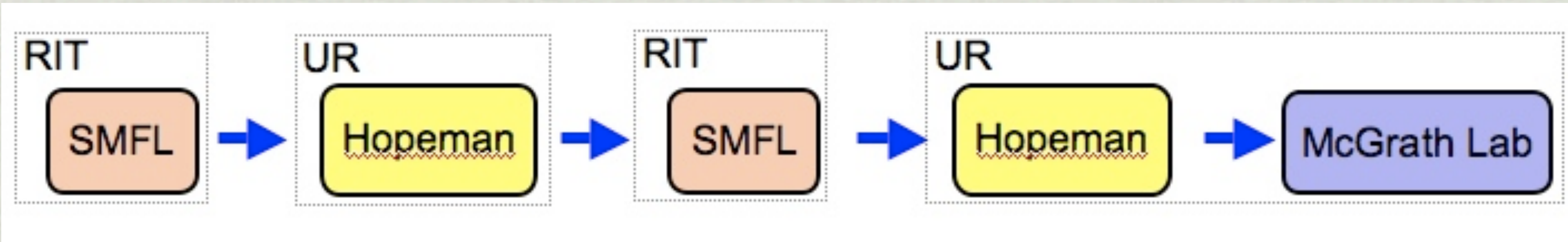
PAST



PATTERNING **DEPOSITION** **THERMAL ANNEALING** **ETCHING** **TESTING & APPLICATIONS**

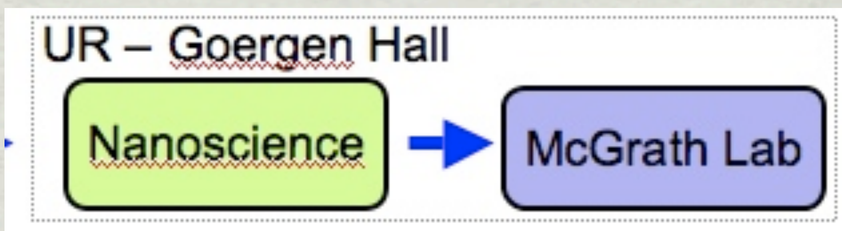
Production Flow

PAST



PATTERNING **DEPOSITION** **THERMAL ANNEALING** **ETCHING** **TESTING & APPLICATIONS**

NEAR FUTURE

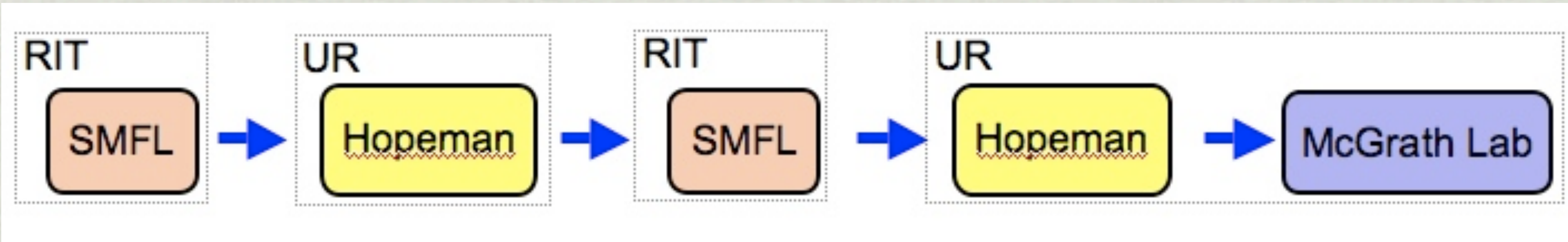


ALL FABRICATION **TESTING & APPLICATIONS**

NRG 2009

Production Flow

PAST



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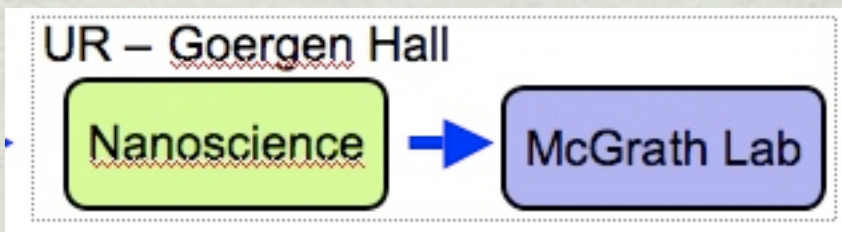


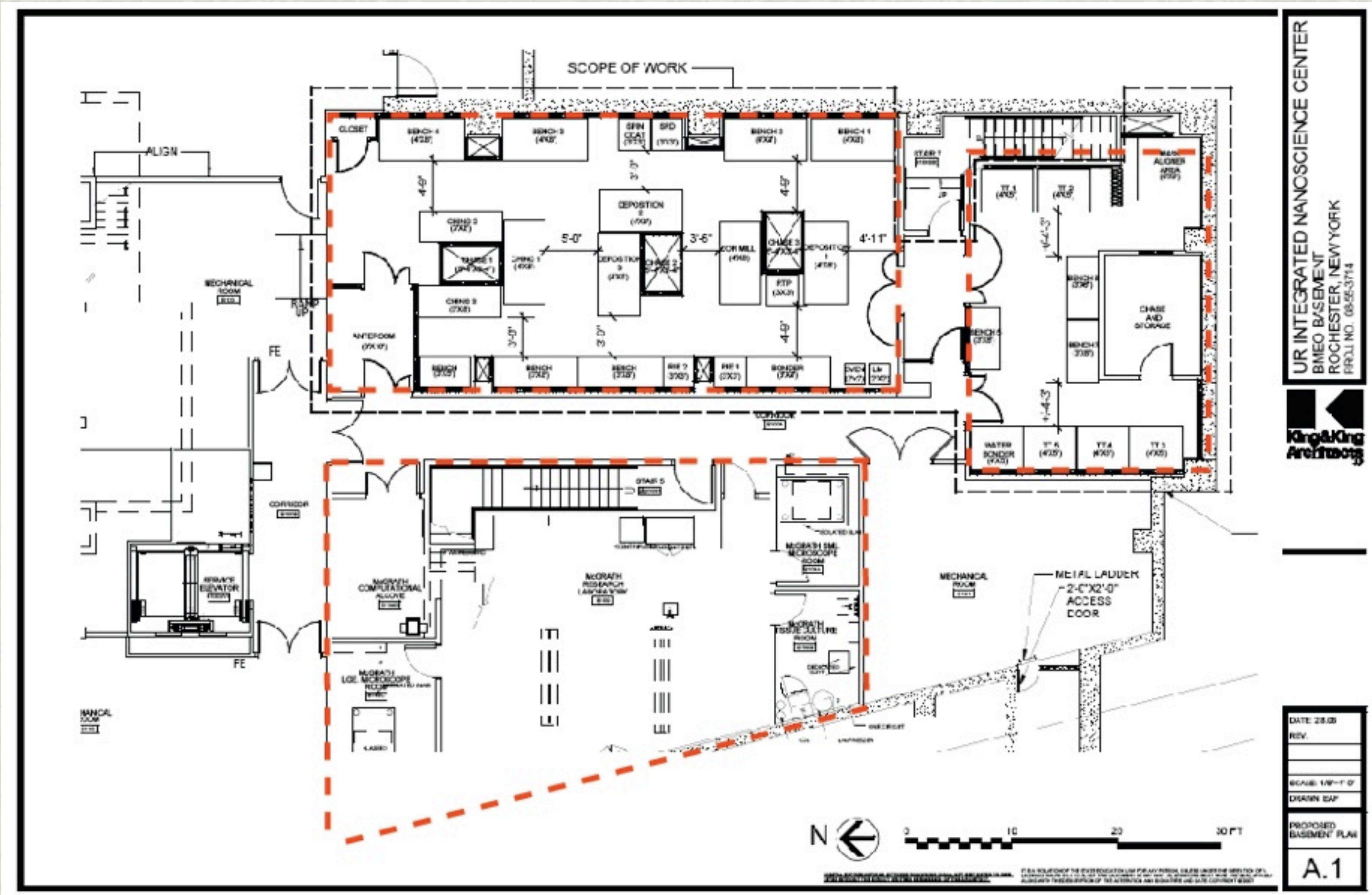
ALL FABRICATION **TESTING & APPLICATIONS**

MADE POSSIBLE BY PURCHASE OF NEW SYSTEMS

- **SURFACE PREP**
- **ANNEALING**
- **DEPOSITION**

NRG 2009

UR's Nanoscience Center



NRG 2009

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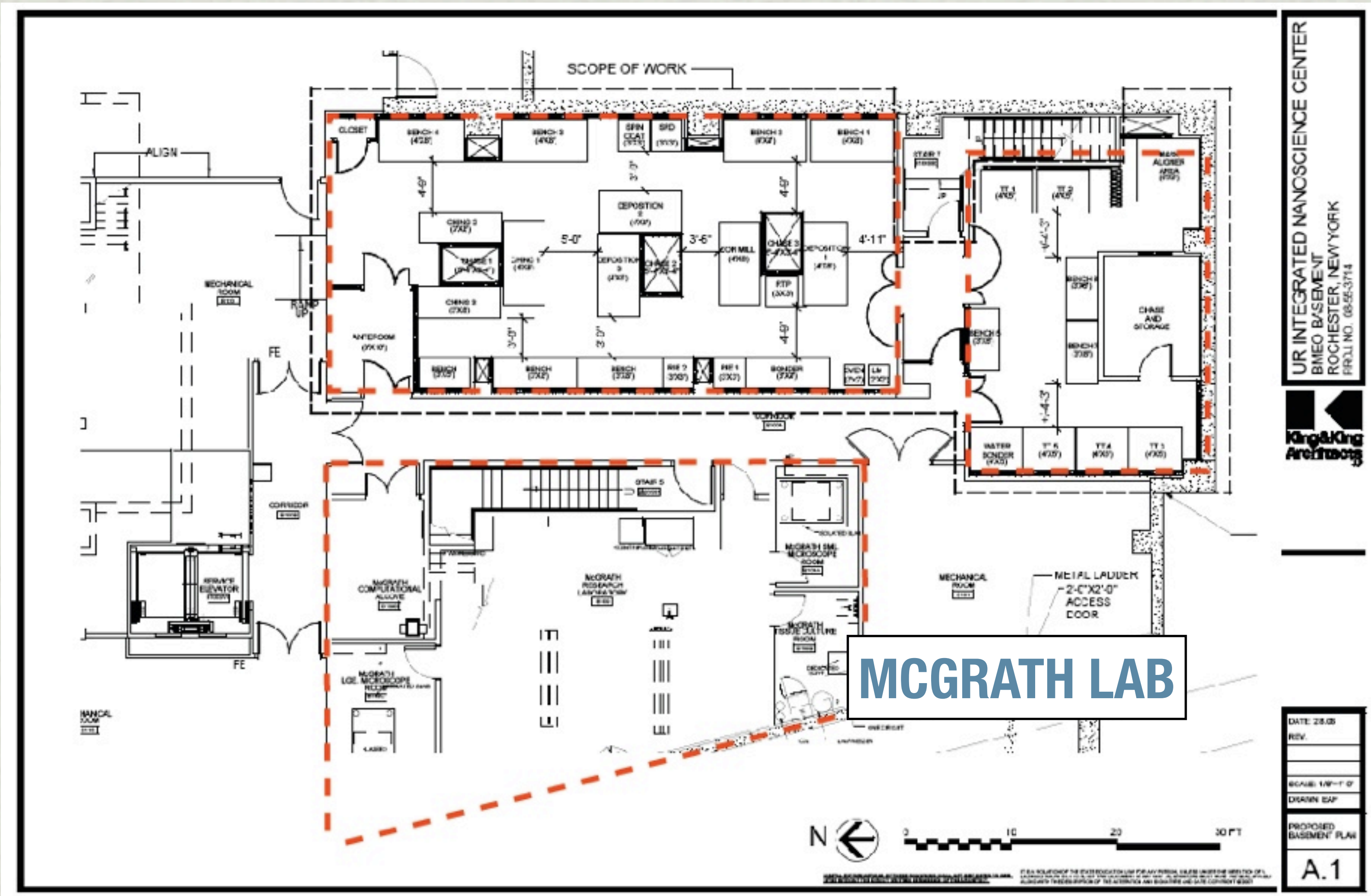
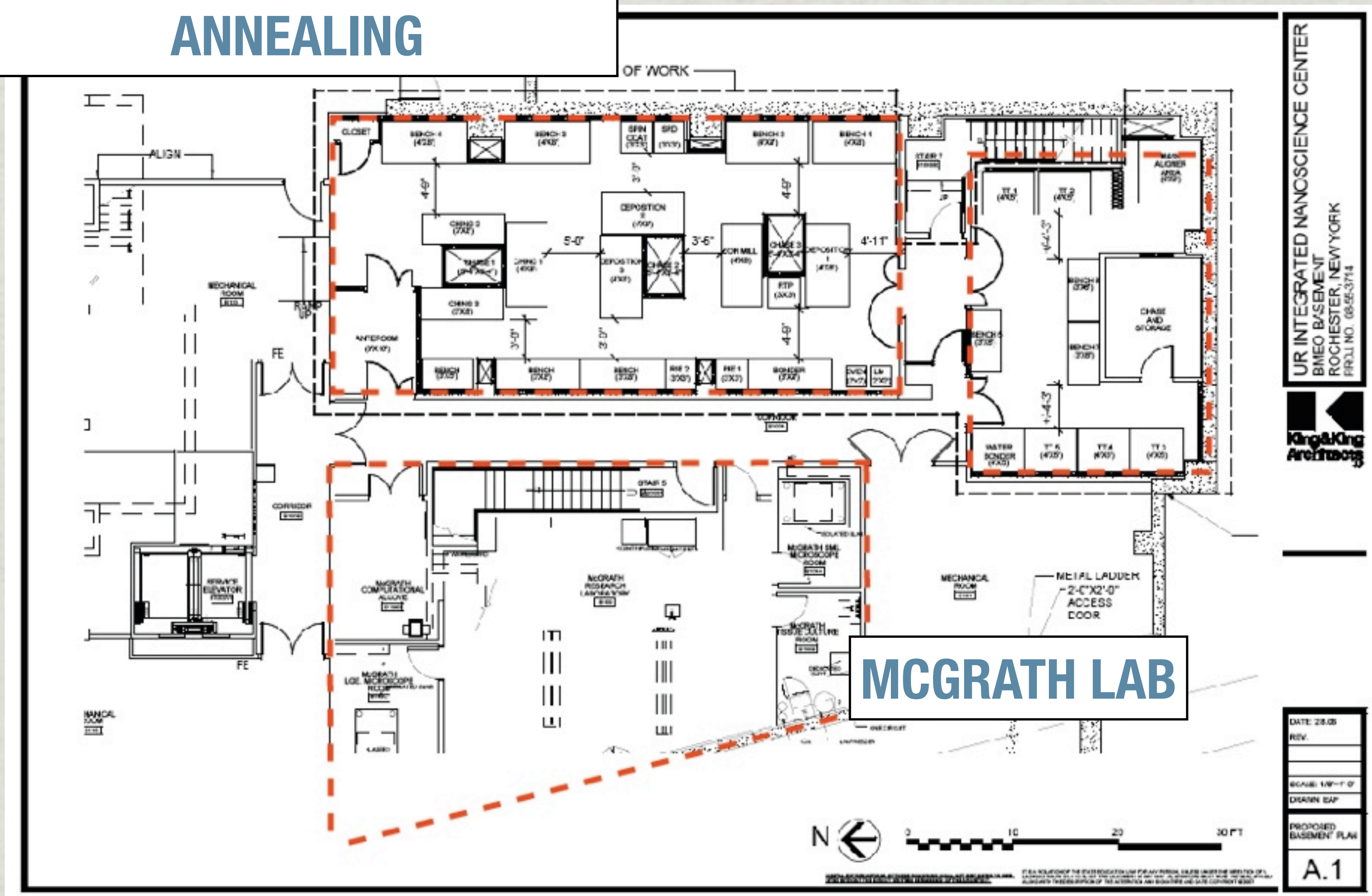


NRG 2009

UR's Nanoscience Center

SURFACE PREP, DEPOSITION AND ANNEALING



MCGRATH LAB

NRG 2009

UR's Nanoscience Center

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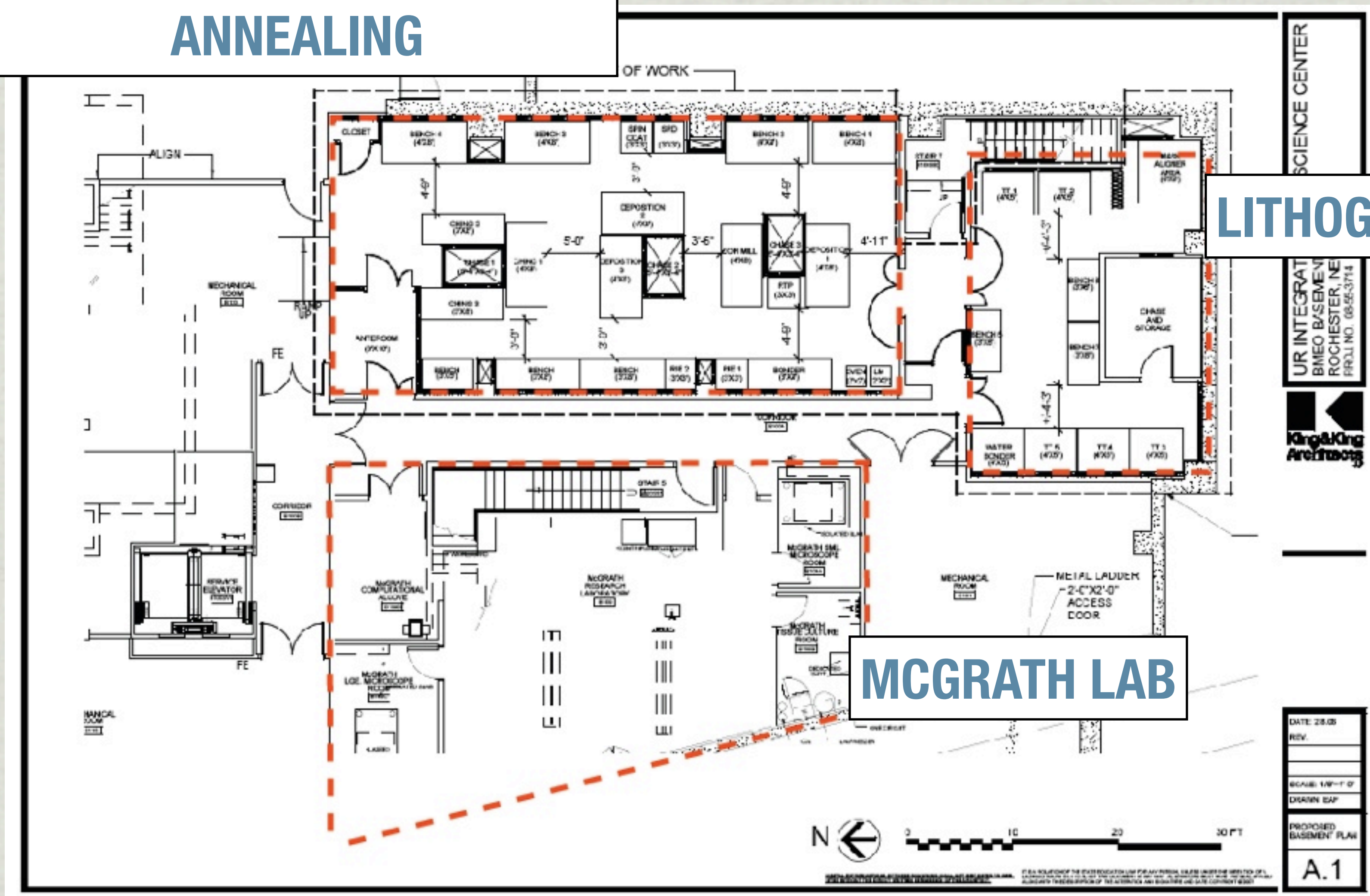
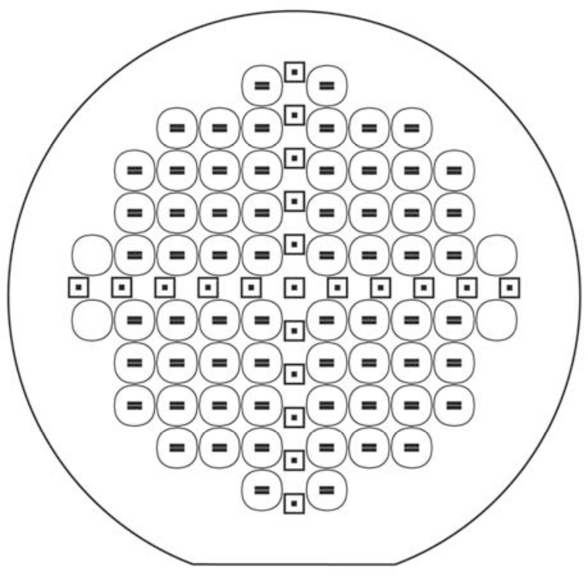


LITHOGRAPHY

MCGRATH LAB

NRG 2009

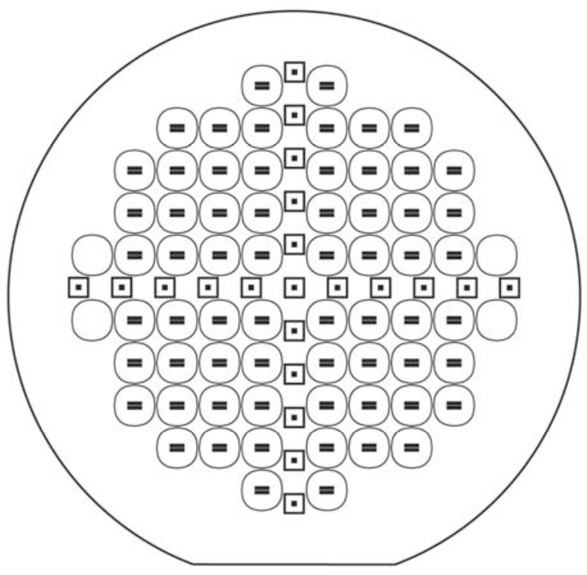
Manufacturing Possibilities and Challenges



4” wafer

CURRENTLY: 68 INSERTS PER WAFER

Manufacturing Possibilities and Challenges



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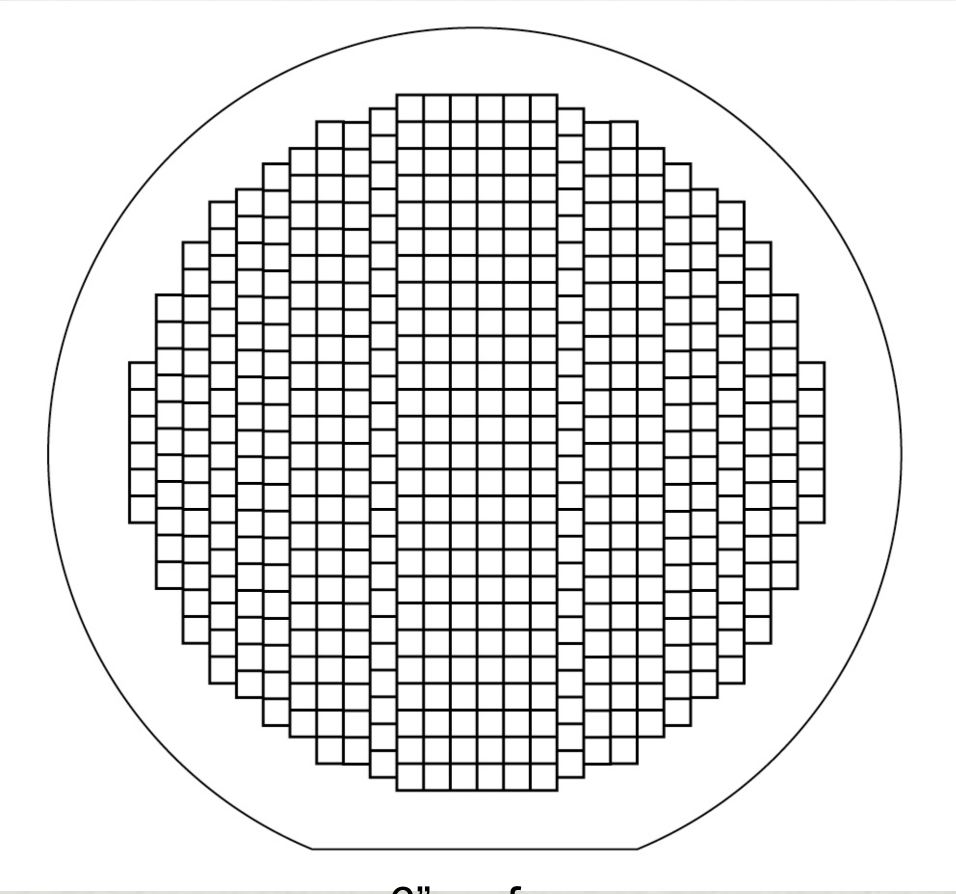

6" wafer

> 500 INSERTS PER WAFER

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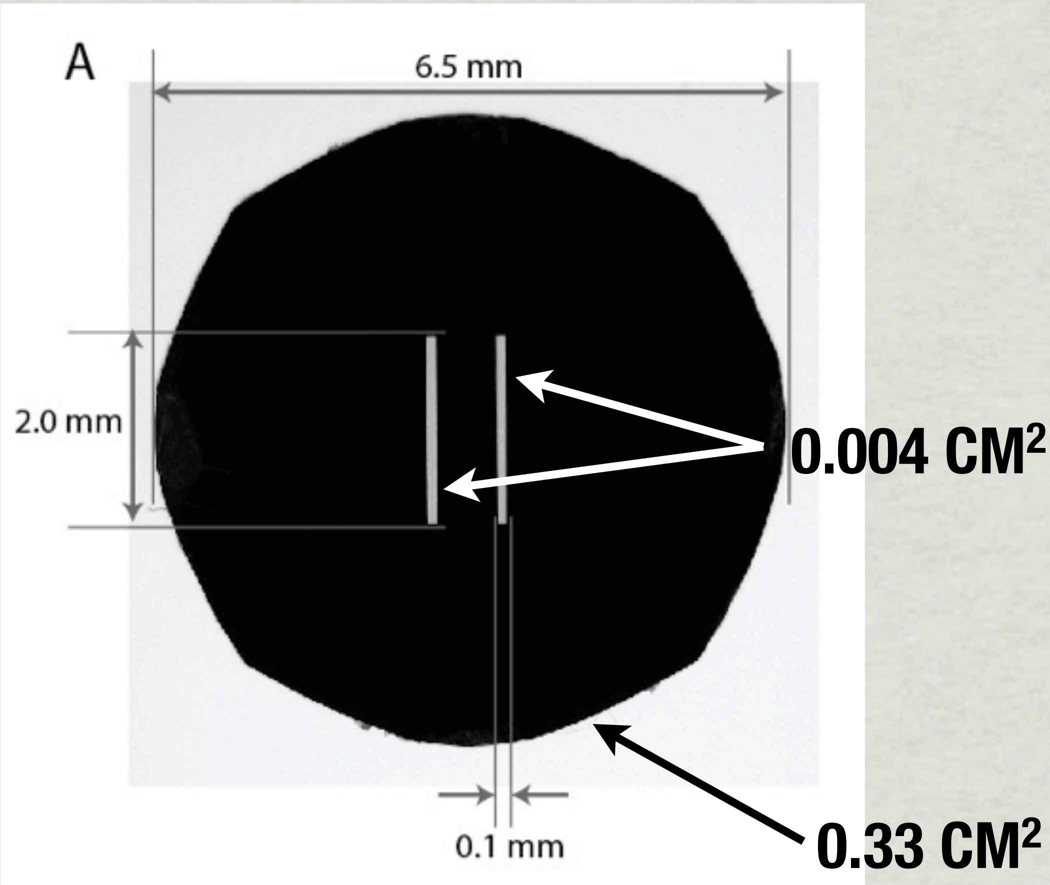
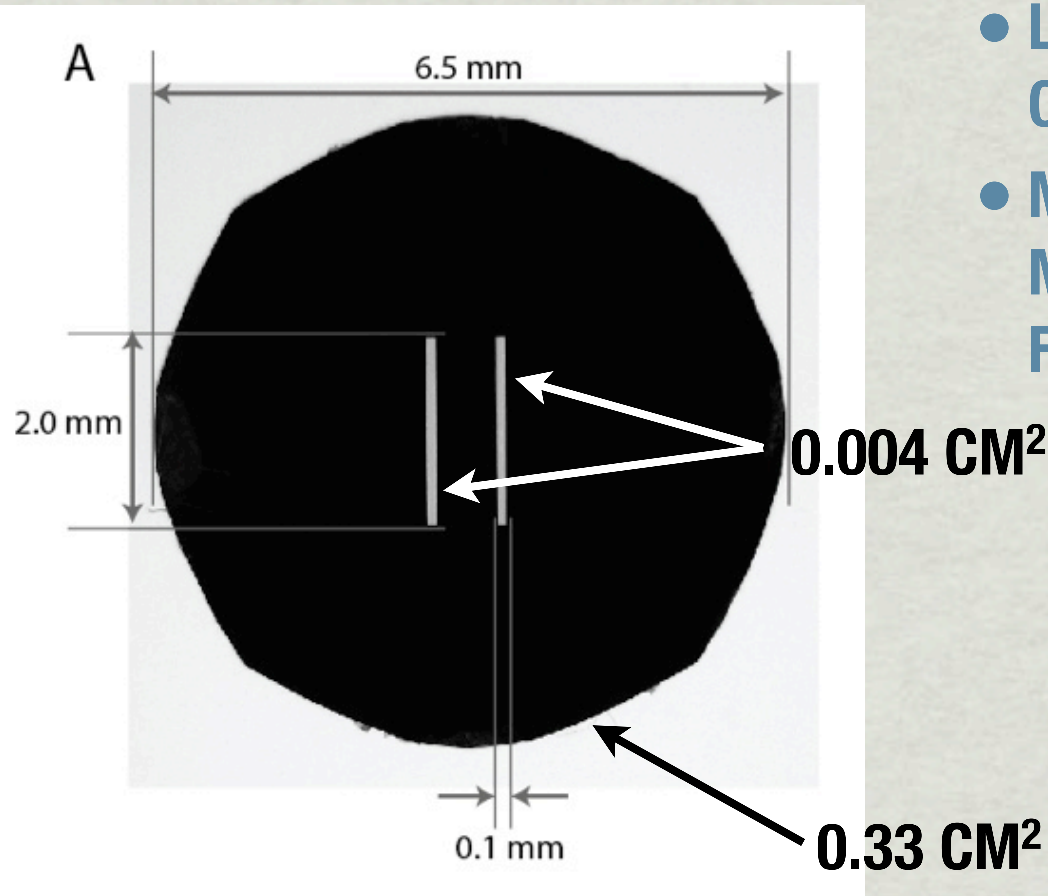
Manufacturing Possibilities and Challenges

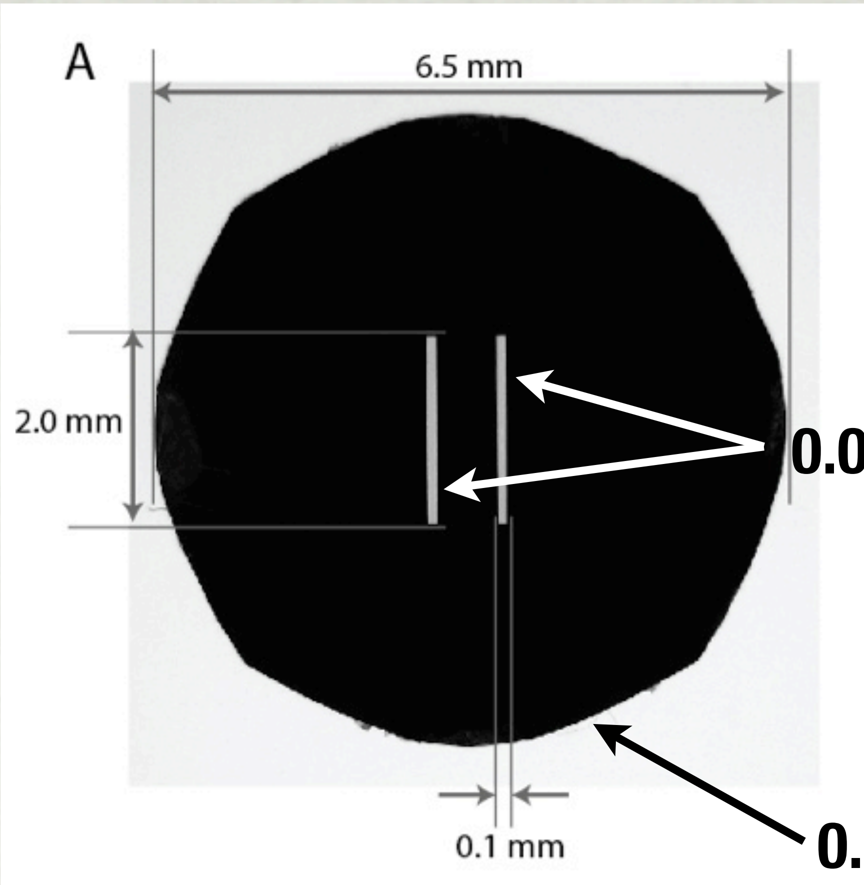


Manufacturing Possibilities and Challenges



- LESS THAN 1% OF AREA IS CURRENTLY ACTIVE
- MADE NECESSARY BY ETCHING, MECHANICS, AND DEFECT FREQUENCY

Manufacturing Possibilities and Challenges



0.004 CM^2

0.33 CM^2

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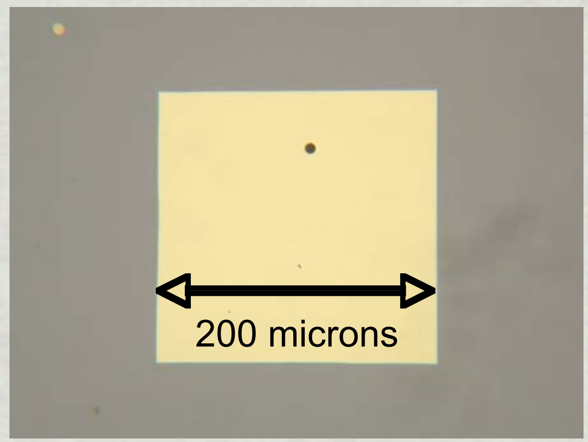
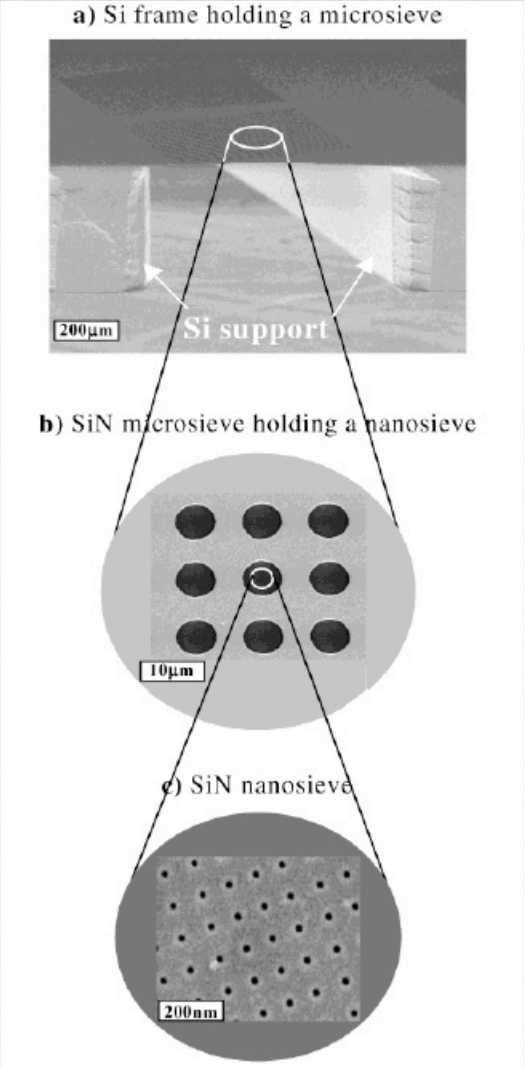


Ultrathin SiN membranes



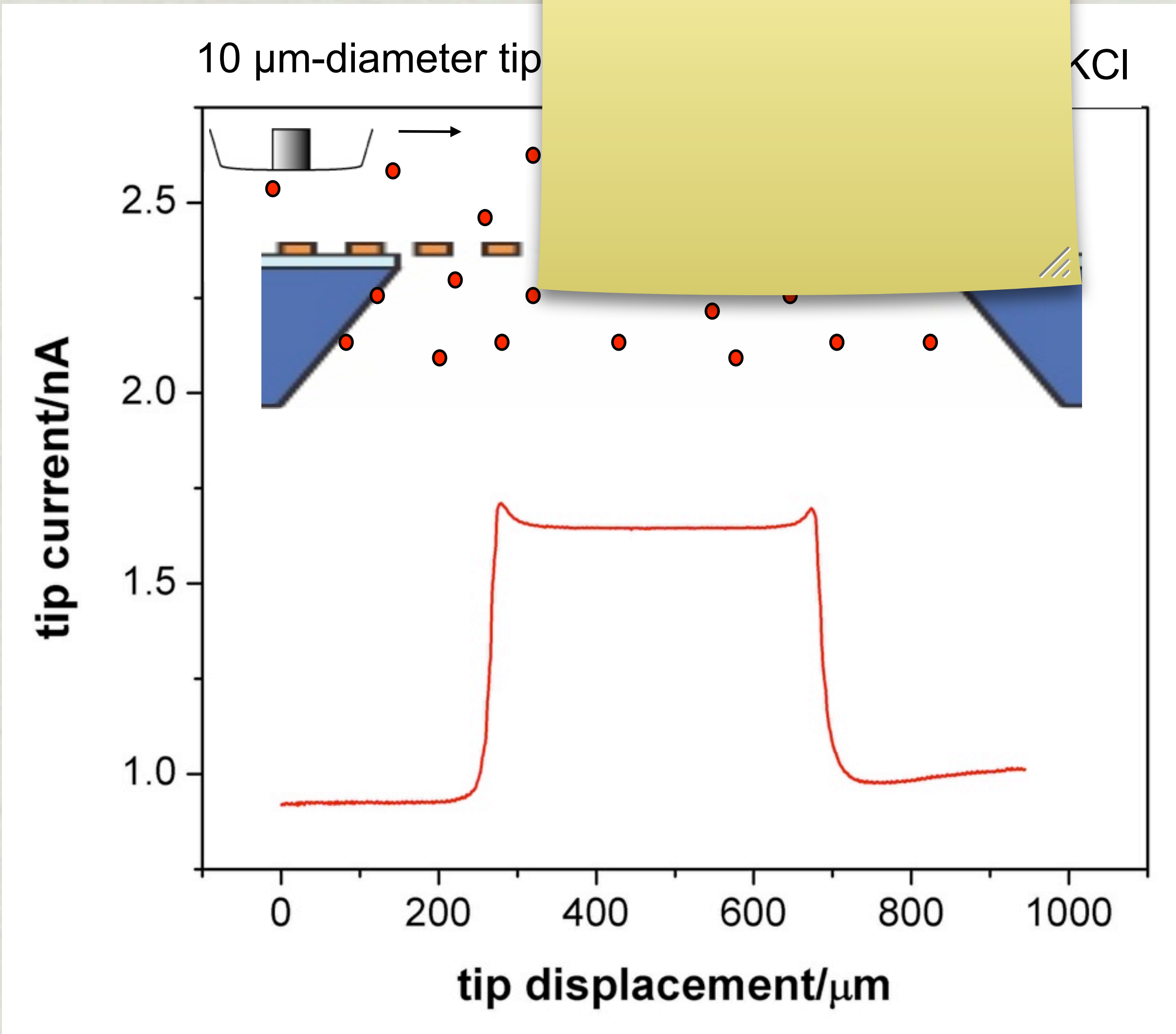
Tong, et al. (2004). Silicon Nitride Nanosieve Membrane. Nano Letters 4, 283-287

- SiN - 10 nm thick but elaborate and impractical
- No demonstrated separations
- Appreciated all the potential and issues (air flow, water permeability, and mechanics)

High Diffusive Perm

Shigeru Amemiya

- Instrinsic permeability of 5.2 x 10^{-2} cm/s measured using Scanning Electrochemical Microscopy.
- Experimental results & pore histograms are consistent with theory that neglects pore resistance
- Between 2-3 orders higher than small molecule diffusion permeability of reconstituted cellulose or PES.



Kim et al. 2008, JACS 130:4230-4231

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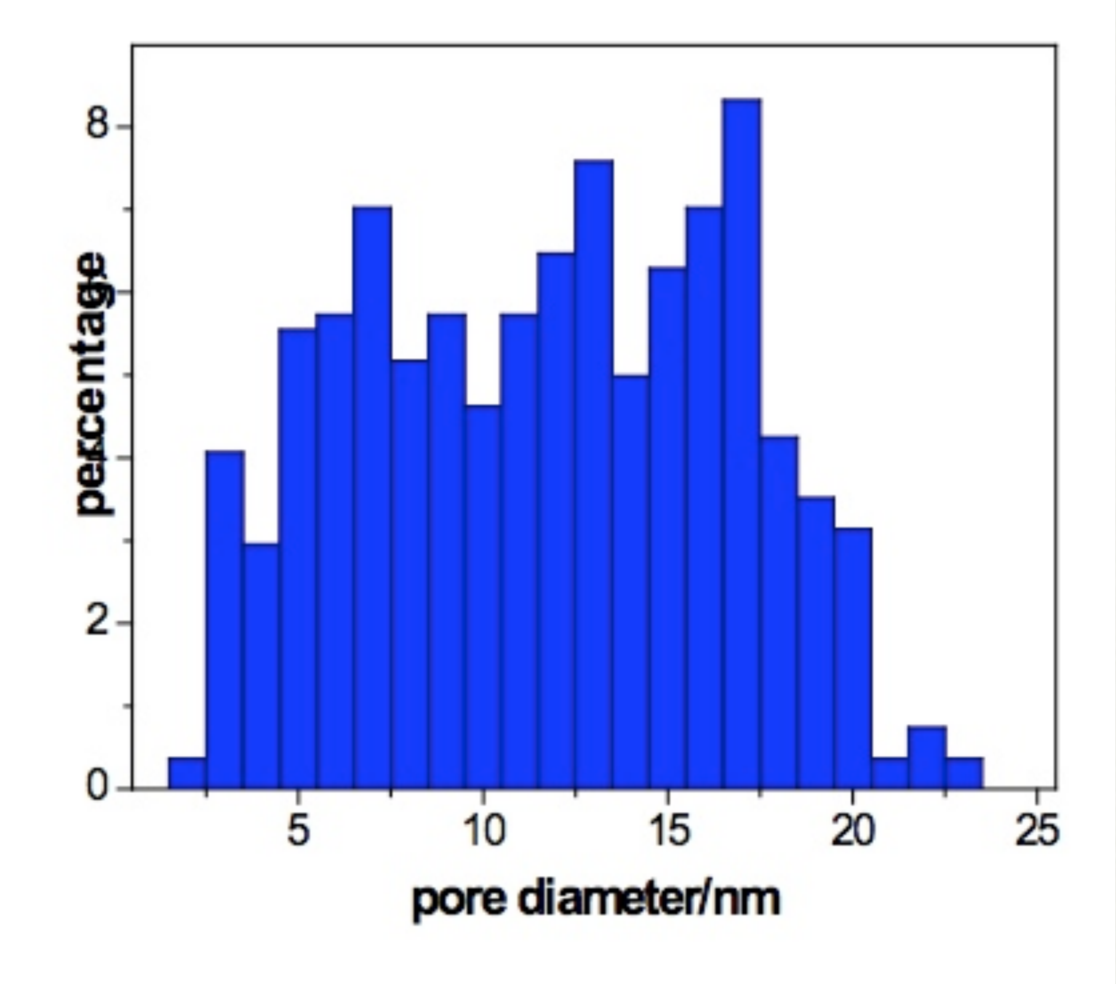

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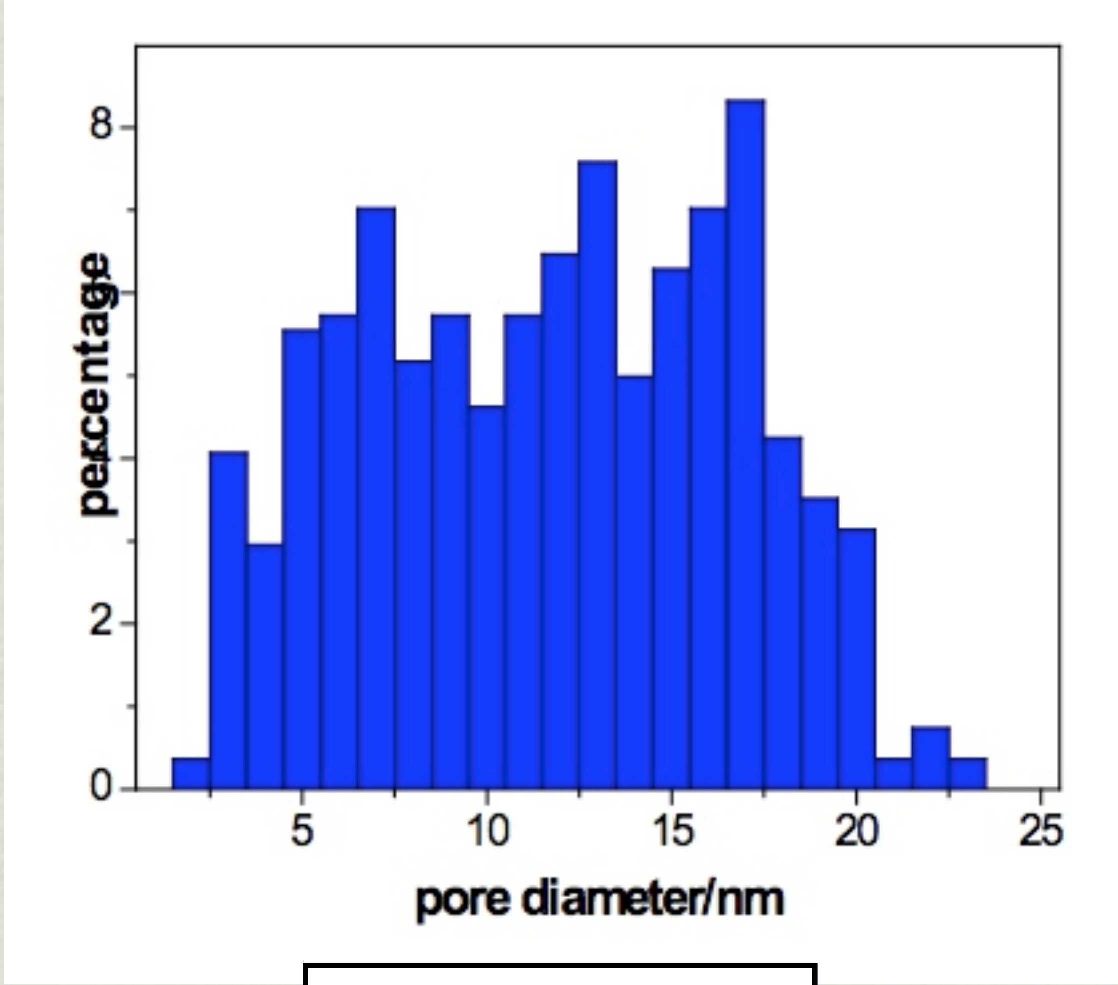
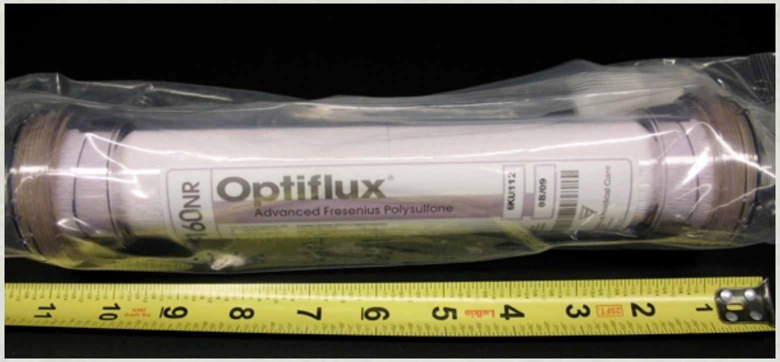


$$k = 2DNr$$

Kim et al. 2008, JACS 130:4230-4231

NRG 2009

Higher Permeability = Smaller ...



- *For current devices: active area is 1.8 m^2 and transmembrane water flow is ~10 ml/min @ 3 psi.*
- *1000x improved permeability would require only 18 cm^2. So 10 dime-sized membranes with mostly (~80%) active area could support both transmembrane flow and match dialysis in the same period of time.*

NRG 2008

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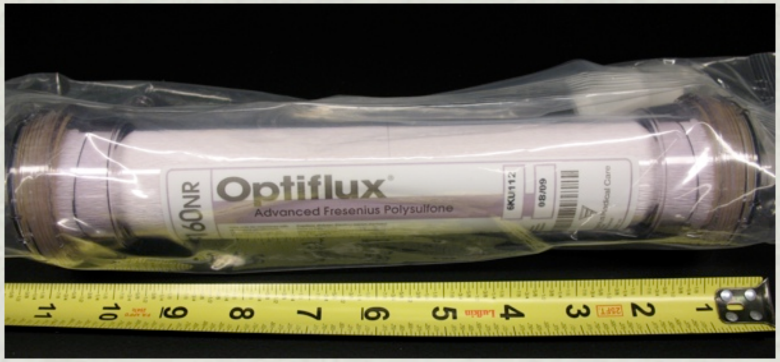

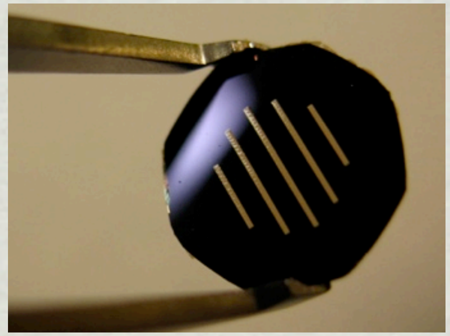

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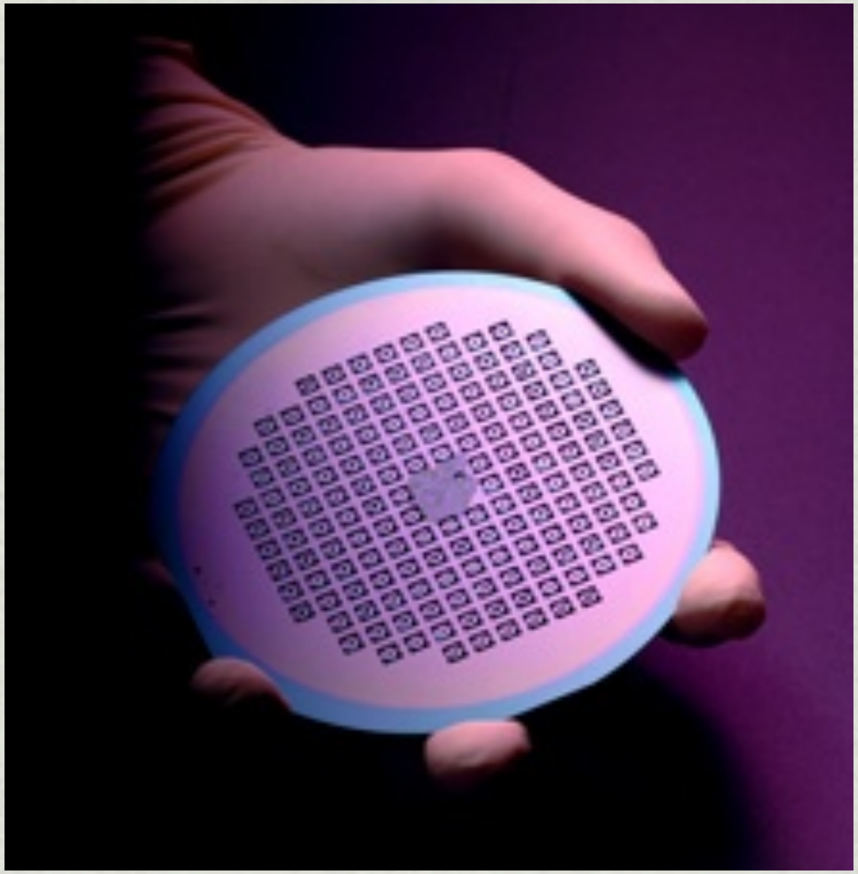
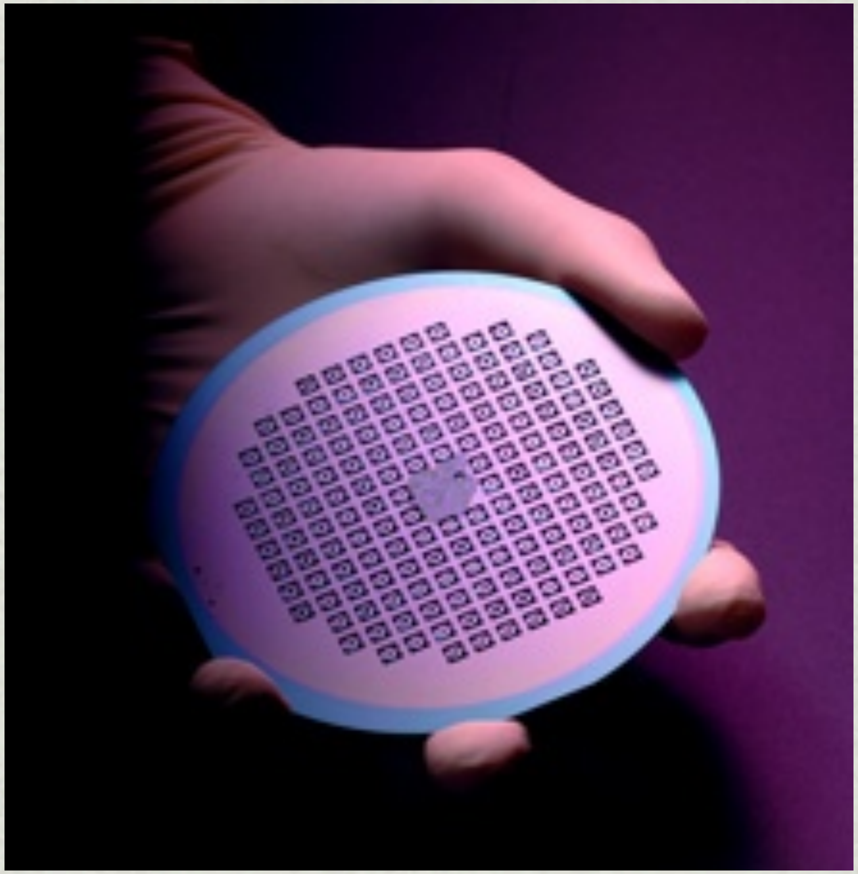
NRG 2008

... or faster?



- *Alternatively a 6" wafer of mostly active membrane could achieve the same dialysis in 1/10th of the time.*

. . . or faster?



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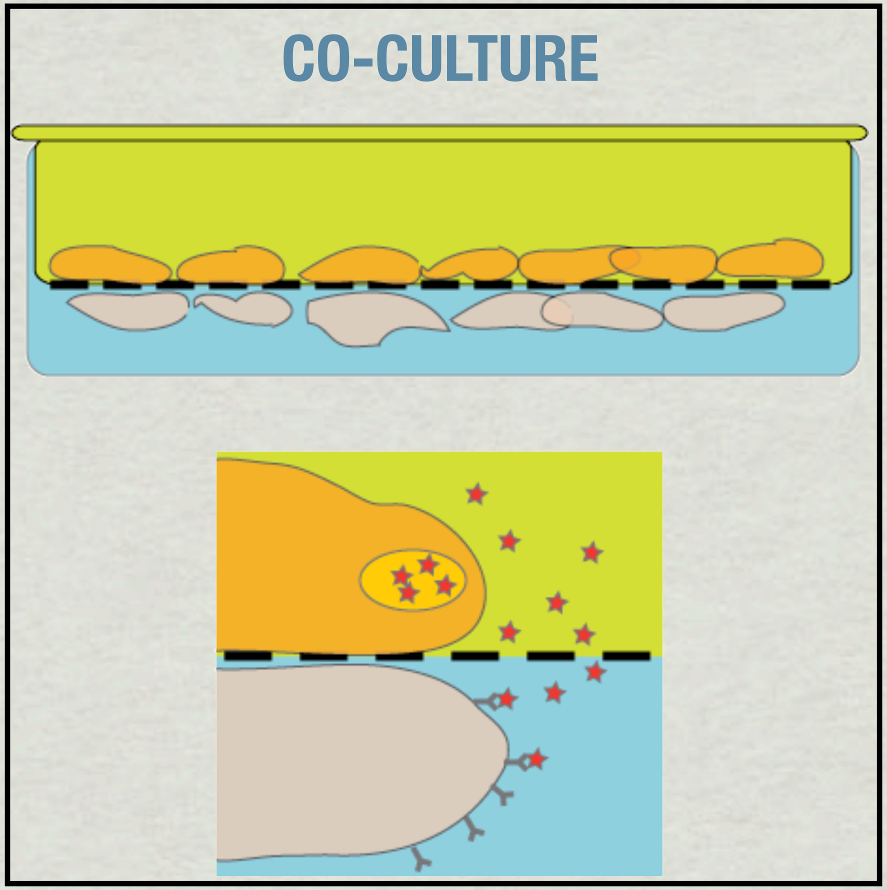
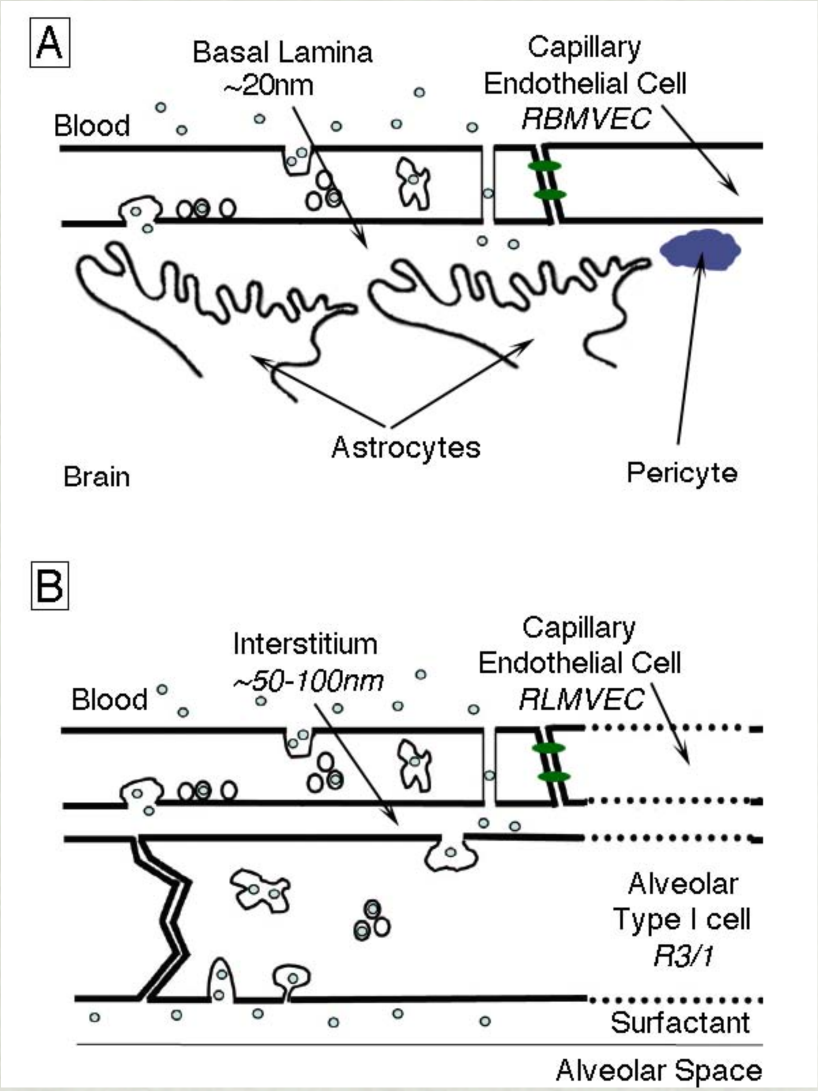
THE MATERIAL PROVIDES THE POTENTIAL

REALIZING THIS POTENTIAL IS AN ENGINEERING CHALLENGE

NRG 2008

Cellular Transwell Devices

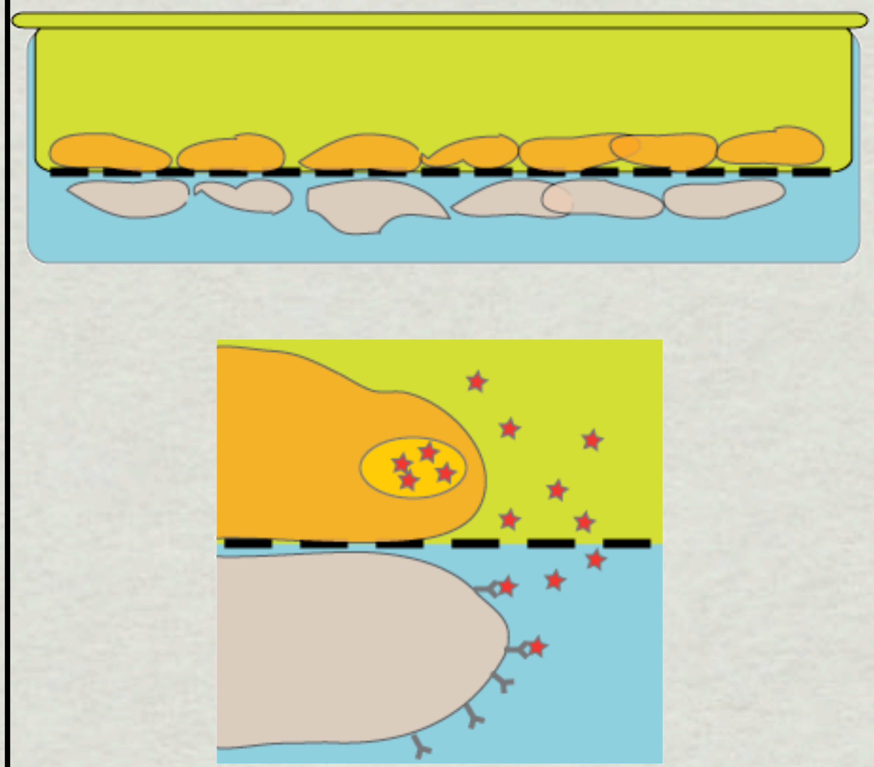




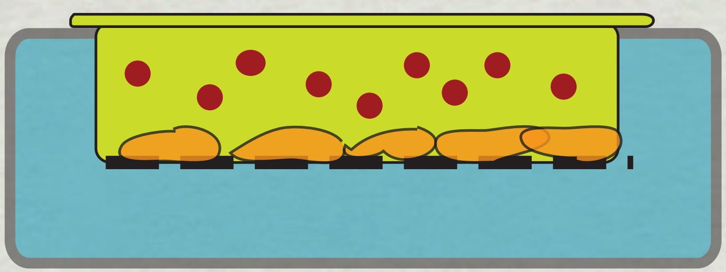
NRG 2009

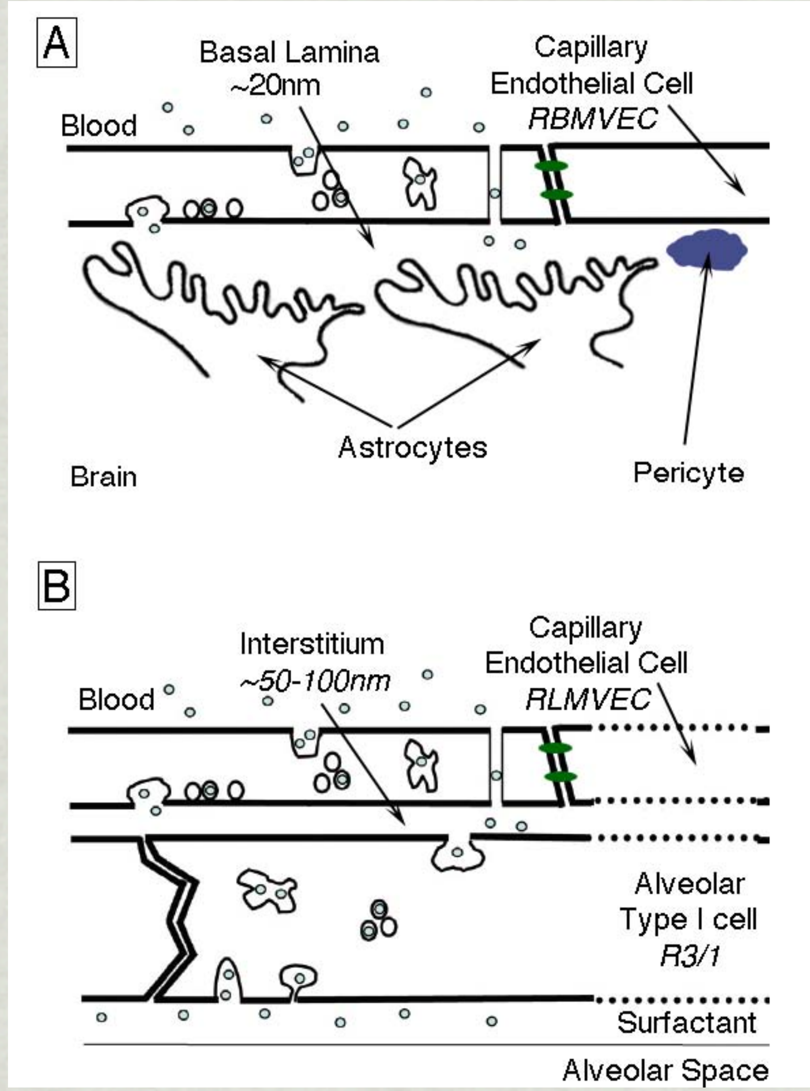
Cellular Transwell Devices

CO-CULTURE



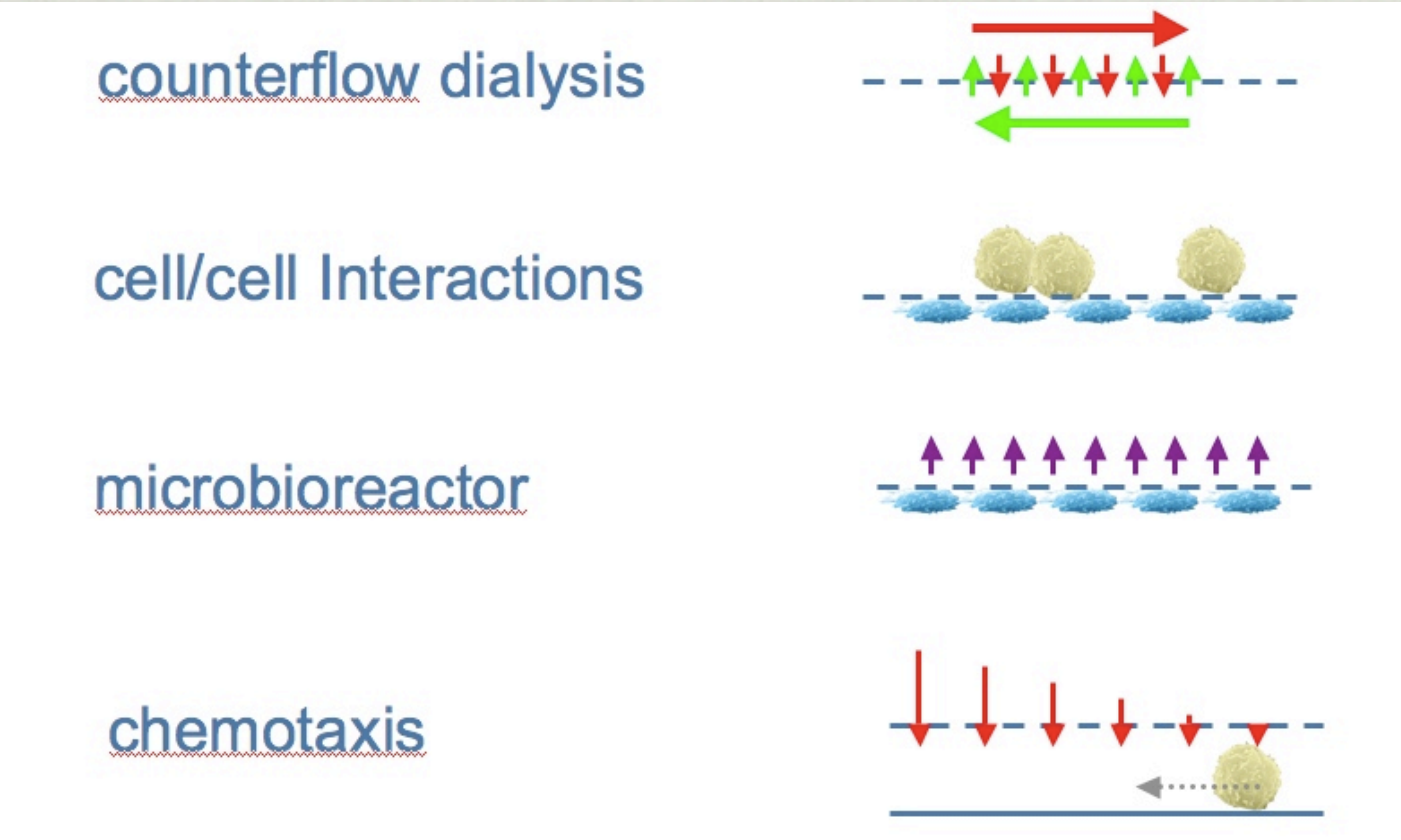
DRUG PERMEATION





NRG 2009

Microfluidics



Conclusions

- Pnc-Si is a new ultrathin nanoporous membrane material. Small membranes can be manufactured on a large scale and incorporated into practical separation devices.
- Primary application is to small scale separation of biologicals
- High air and liquid permeabilities w/ demonstrated ability to fractionate proteins, nanoparticles, etc.
- Viable as a cell-culture substrate. Cell behavior on membranes is normal.
- Microfluidics, arrayed membranes for screening applications, electrokinetics, and more …