Silicon Photonic Crystal Structures for Biosensing

Philippe M. Fauchet

Department of Electrical and Computer Engineering,

The Institute of Optics, Department of Biomedical Engineering and Materials Science Program

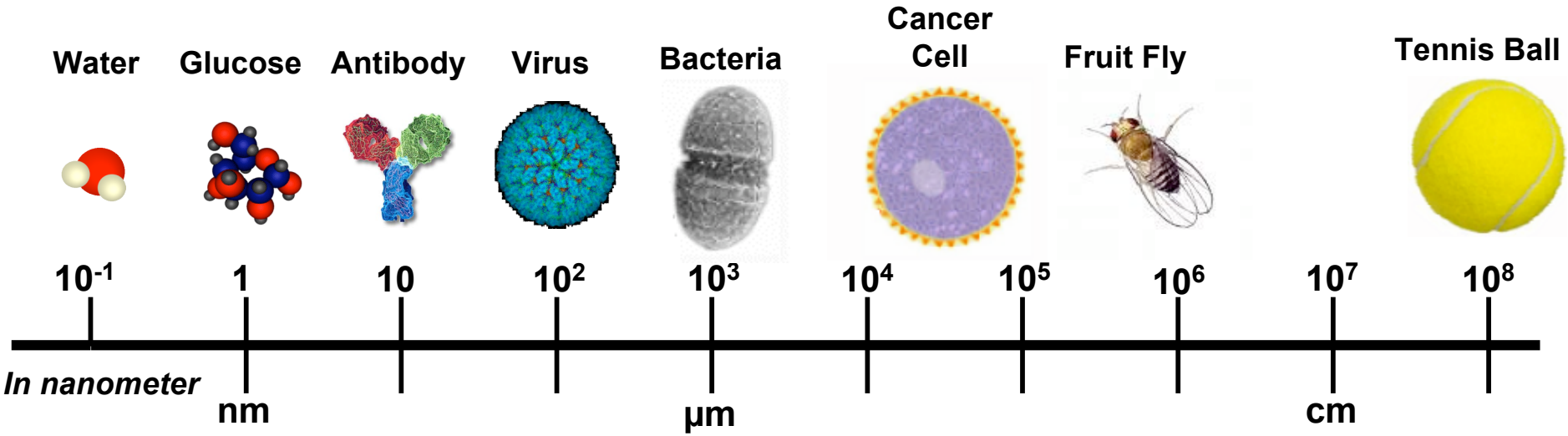
Center for Future Health

University of Rochester

With: **Dr. Huimin Ouyang, Mindy Lee, and Prof. Ben Miller**

Support: **NSF BES**

Bio Meets Nano



Objectives and Results

- Develop *label-free* biosensors capable of detecting the presence of harmful pathogens, including public health hazards and biowarfare agents.
- The photonic crystal microcavity platform is capable of detecting sub-Angstrom thick layers or a single biological object.
- Demonstrate robustness and practical implementations

Outline of the Talk

- **1-D Platform:**
  - Porous silicon
  - Photonic Crystal Microcavities
- **Biosensing Results:**
  - Proteins, E-coli
  - Performance and tradeoffs
- **2-D Platform:**
  - Fabrication and protein detection
  - Toward single biomolecule detection

How can silicon be useful for biosensing?

- As a substrate for biology, SiO_2 is much better understood than Si ➔ coat Si with a thin oxide layer

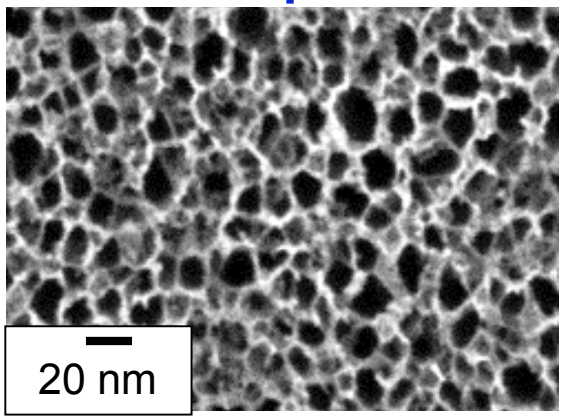
- Ease of use implies label-free and no multiplication

  ➔ more capture sites/cm^2

  ➔ resonances or E-field enhancement

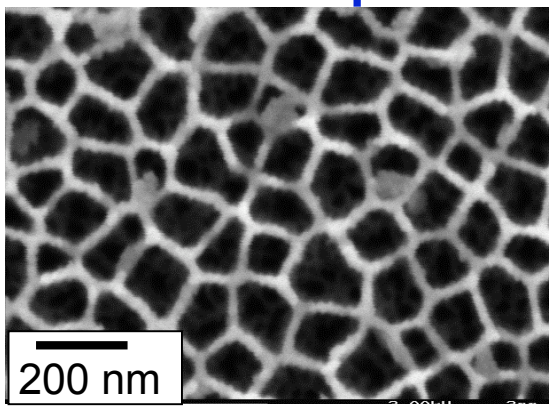
1-D Material: Porous Silicon

Mesopores



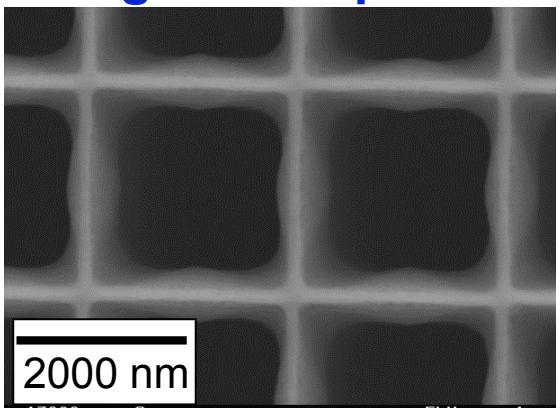
Chemicals, short DNA strands, small molecules

Small Macropores



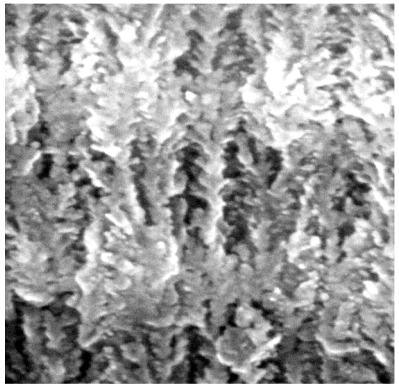
Macromolecules, proteins

Large Macropores

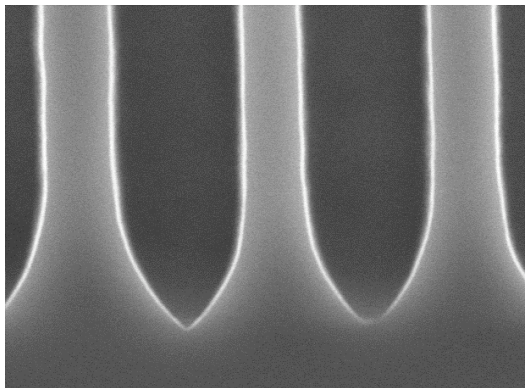


Viruses, bacteria

SEM top views



SEM cross-sections



Control of the Refractive Index

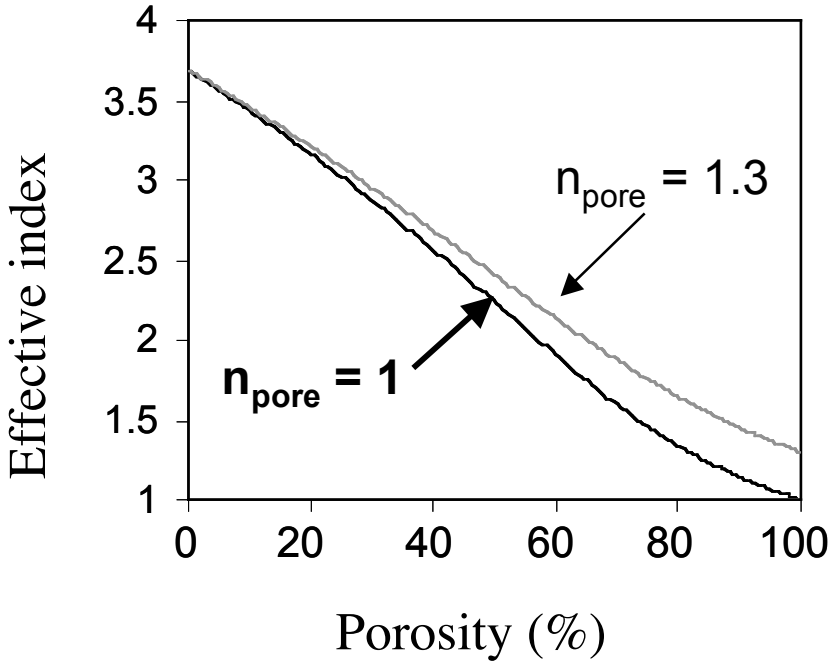
Porous silicon is an effective medium. Its refractive index is described by the Bruggeman approximation.

The effective refractive index is a function of:

*** porosity**

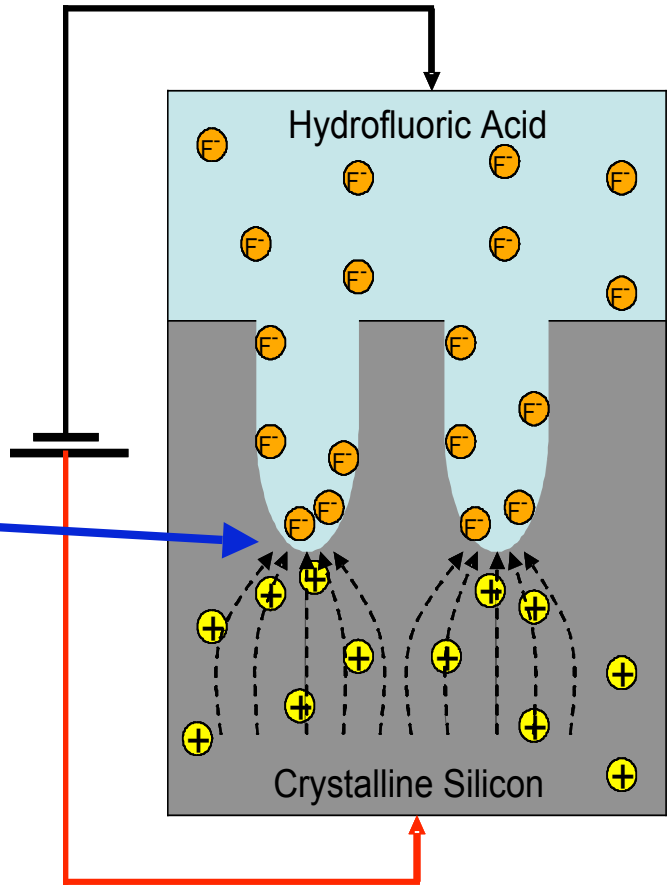
* refractive index of silicon

*** refractive index inside the pores**

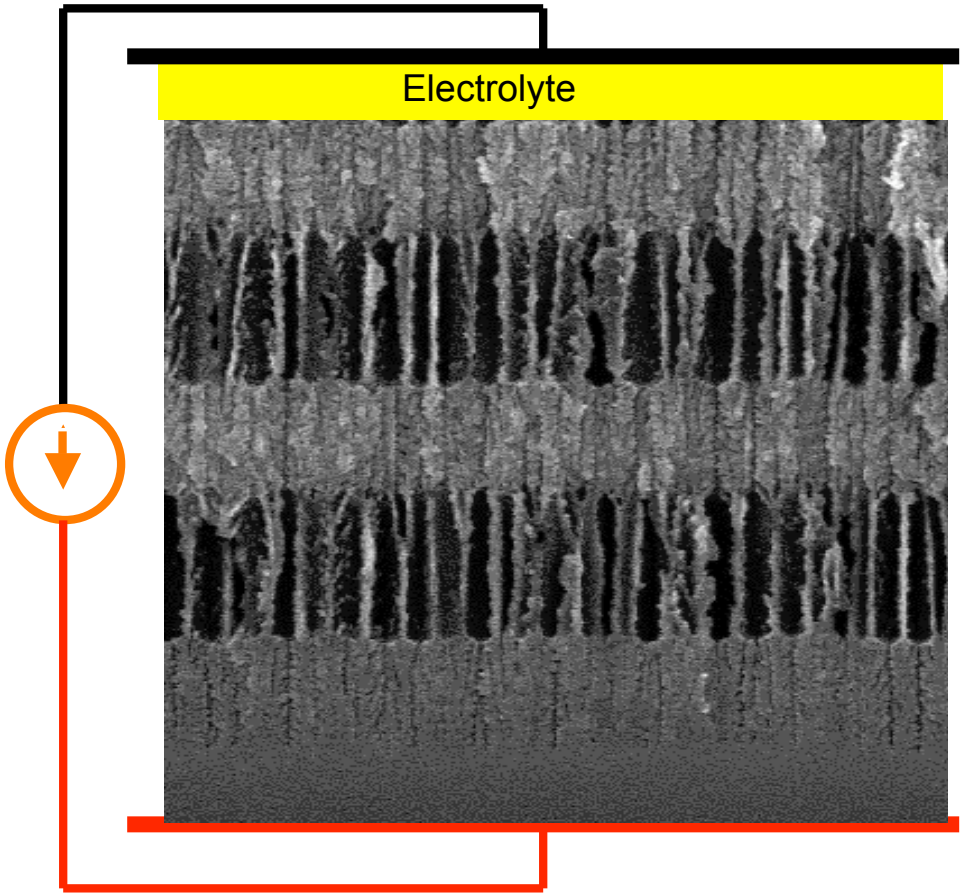


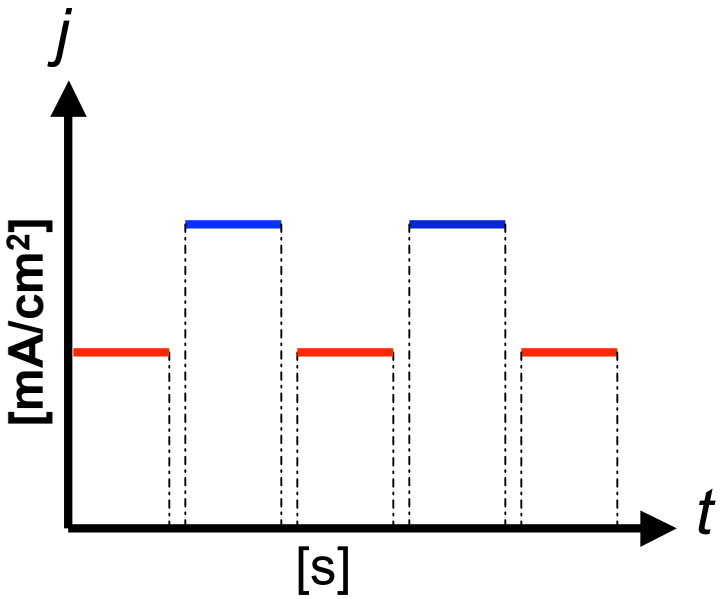
Porous Silicon: Etching Mechanism

Etching occurs at the pore tips only



Multilayer Structures





High index contrast Bragg reflector

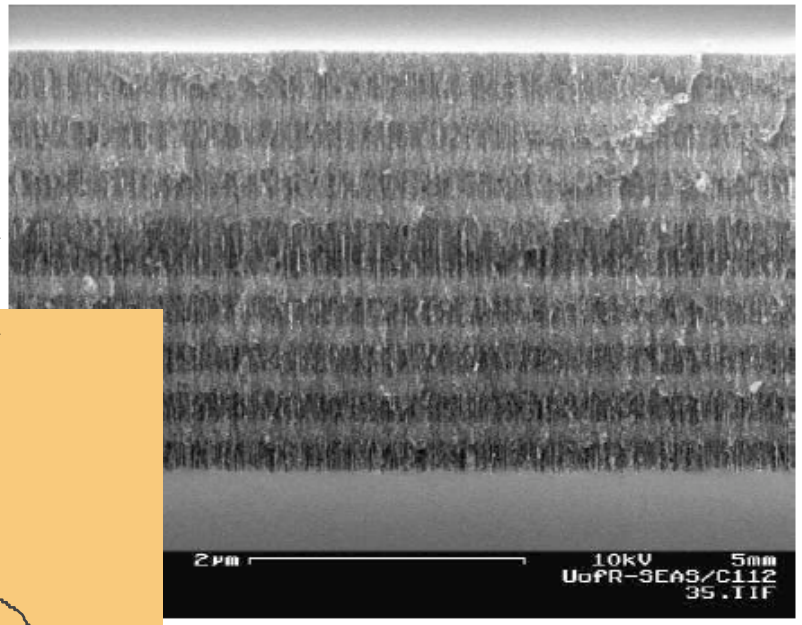
High-Quality Microcavities

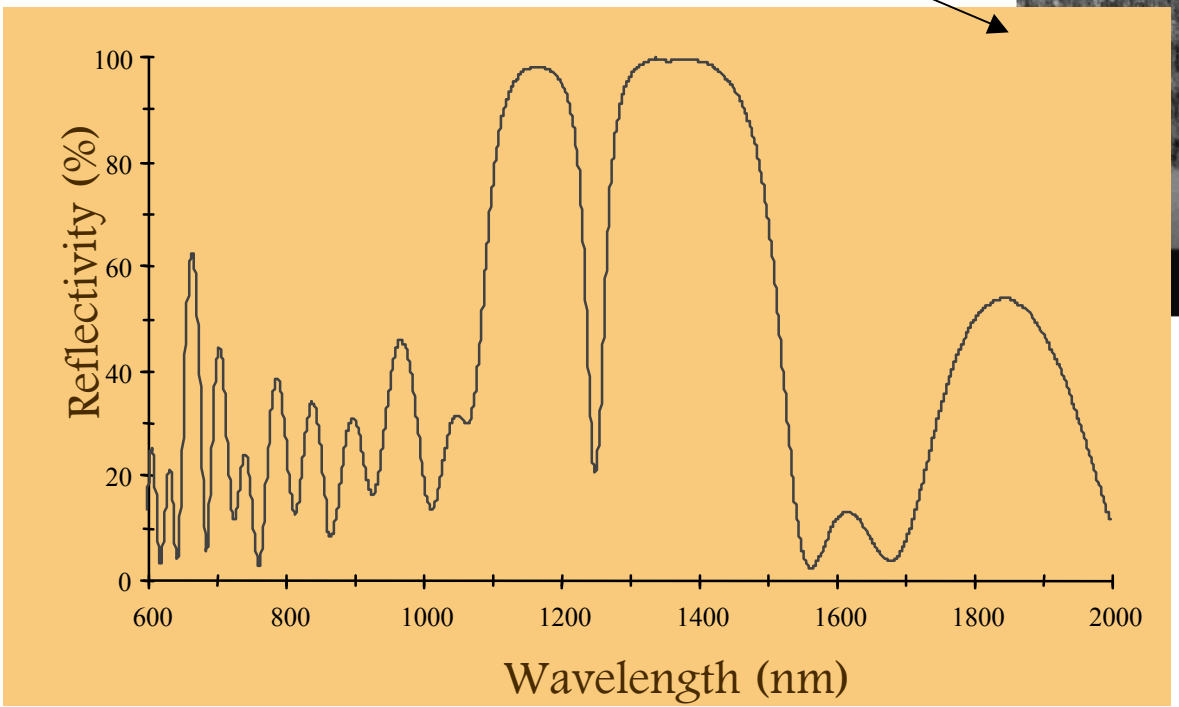
Large index of refraction contrast (from >2.5 to <1.3)

Bragg Reflector

"Defect" layer

Bragg Reflector





Quality Factor $\lambda/\Delta\lambda$ can be much larger than 1000

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  - Some with proteins
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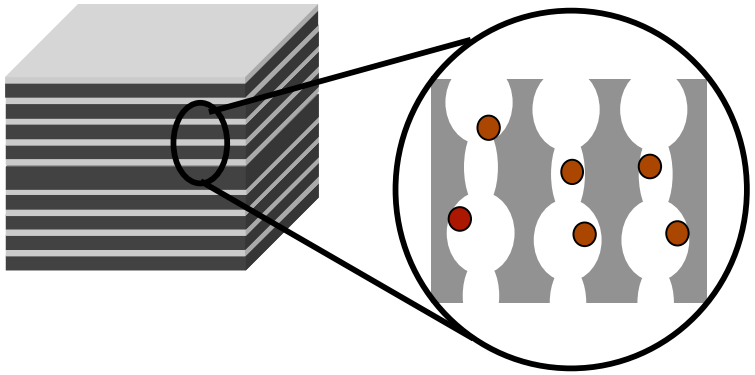
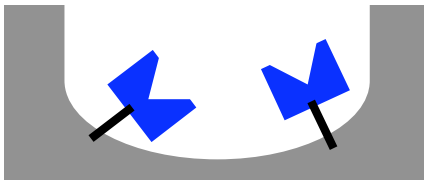
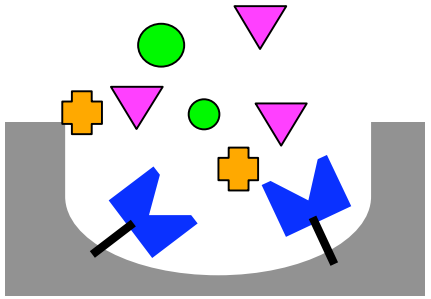
Sensing Principle



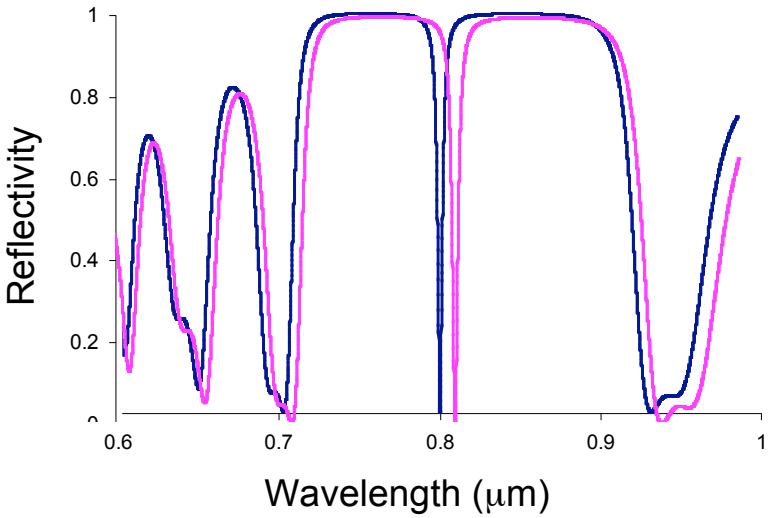
$n \rightarrow n + \Delta n$



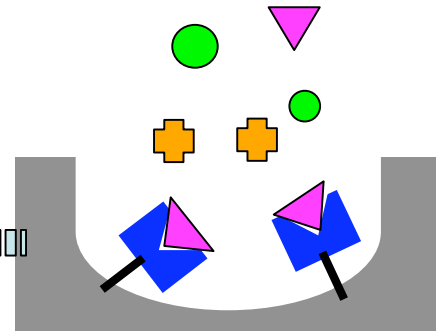
Internal surface modification



Exposed to species

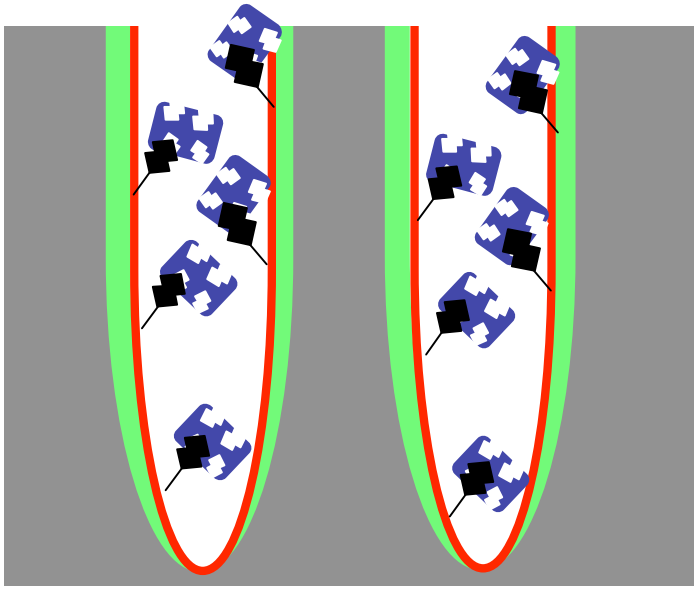


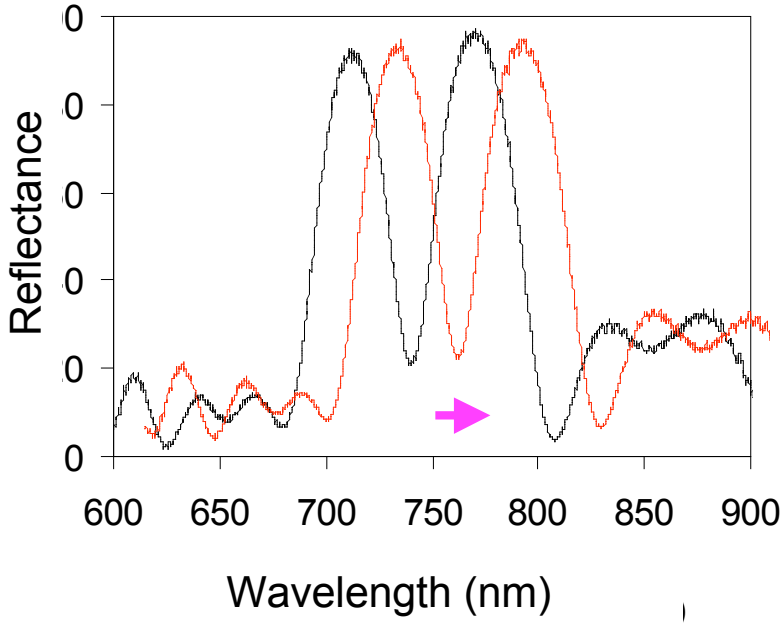
Red shift



Specific binding

Biosensing: Biotin-Streptavidin

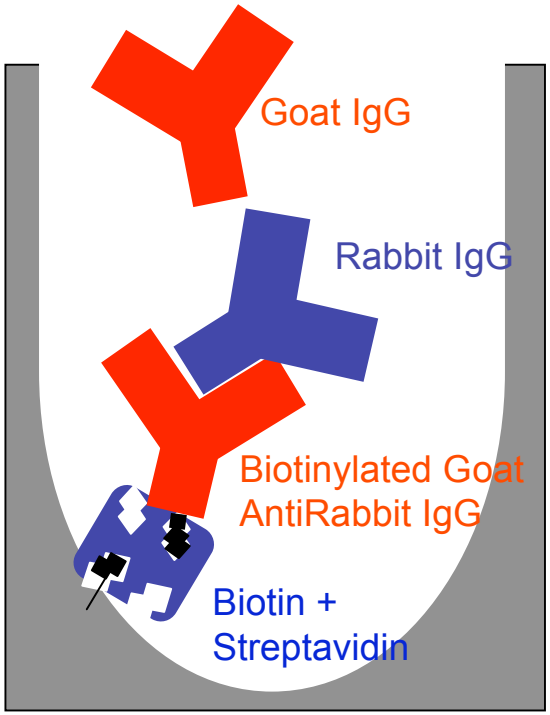


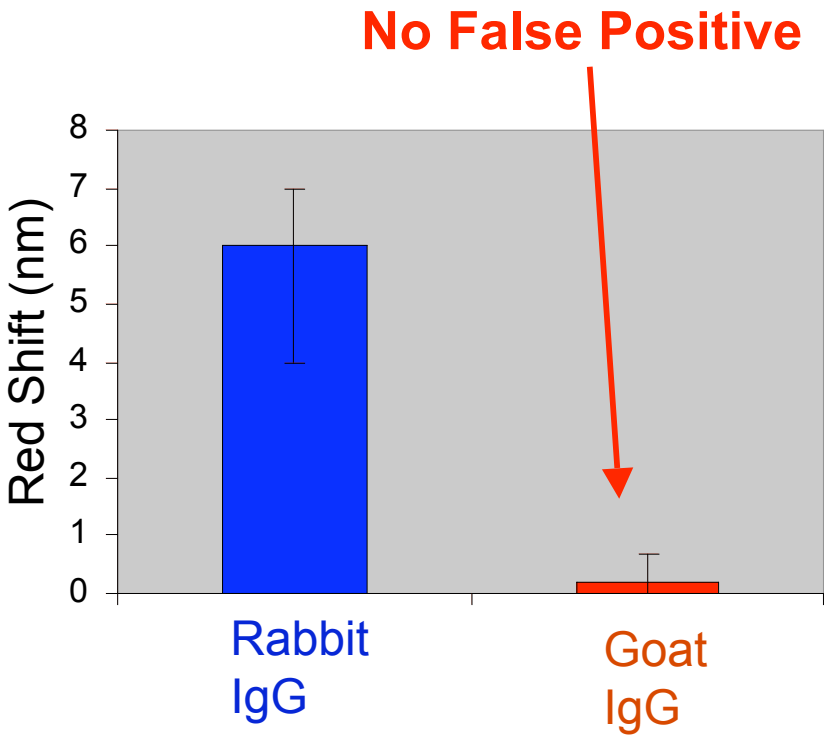


1. **Thermal oxidation**
2. **Amino silane**
3. **Sulfo-NHS-LC-LC-Biotin**
4. **Streptavidin**

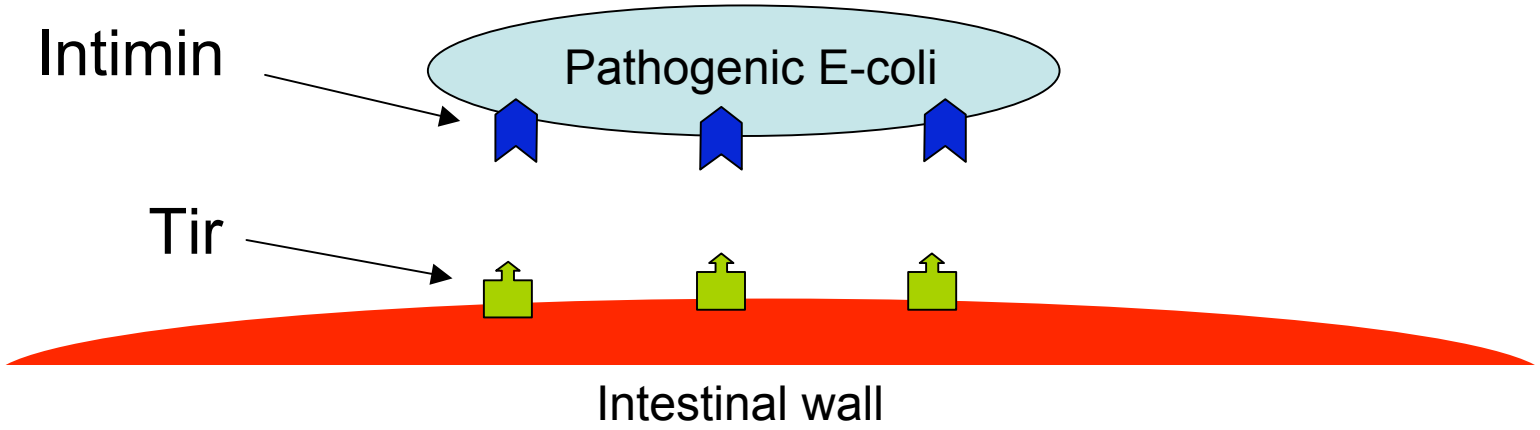
Sensitivity: ~ 10 - 30 pg/mm^2 on the internal surface of the pores (~ 20,000 mm^2).

Immunoglobulin G (IgG)



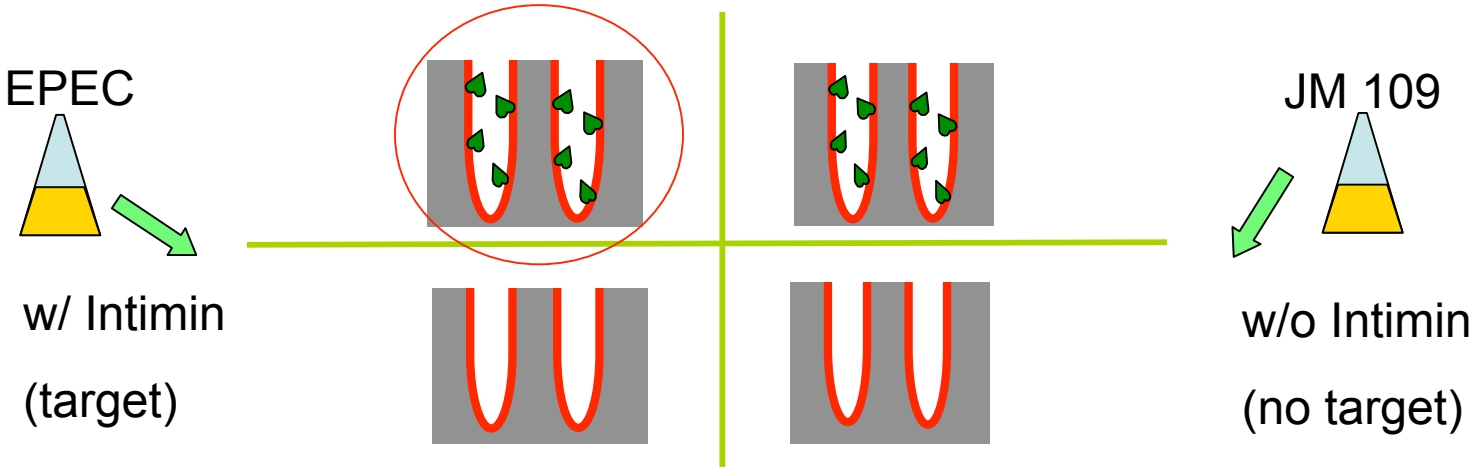


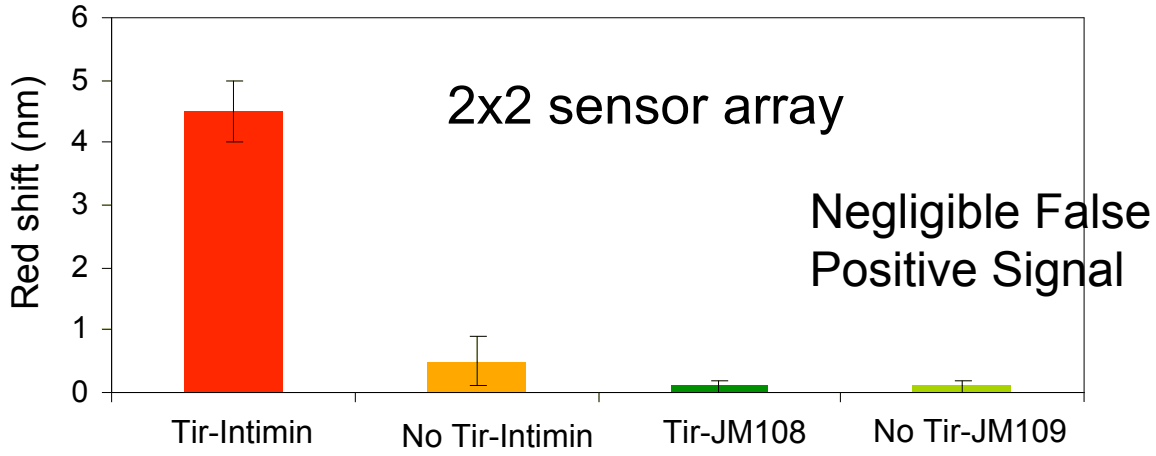
EHEC Detection via Intimin-Tir Binding



*Y. Luo et al. Nature Vol **405**, 1073 (2000)*

E-coli Cells from Culture



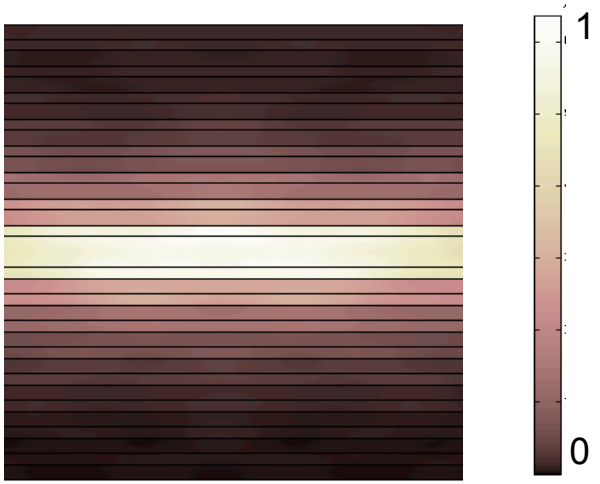


H. Ouyang et al., Anal. Chem. 79, 1502 (2007)

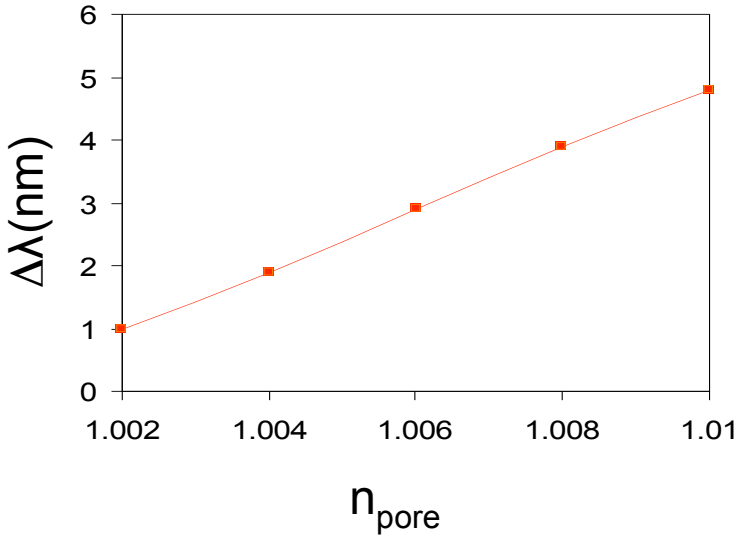
Optimum Design Considerations

Key advantage of this technology: Large overlap between the field inside the microcavity and the analyte

Field confinement in 1-D Microcavity



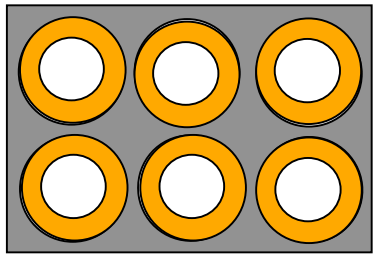
Δλ/Δn ~ 400 nm



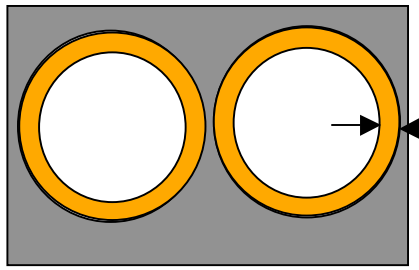
Much better than microring cavity using evanescent field **Δλ/Δn ~ 33 nm**

J. Scheuer et al., Opt. Lett. 29, 2641 (2004).

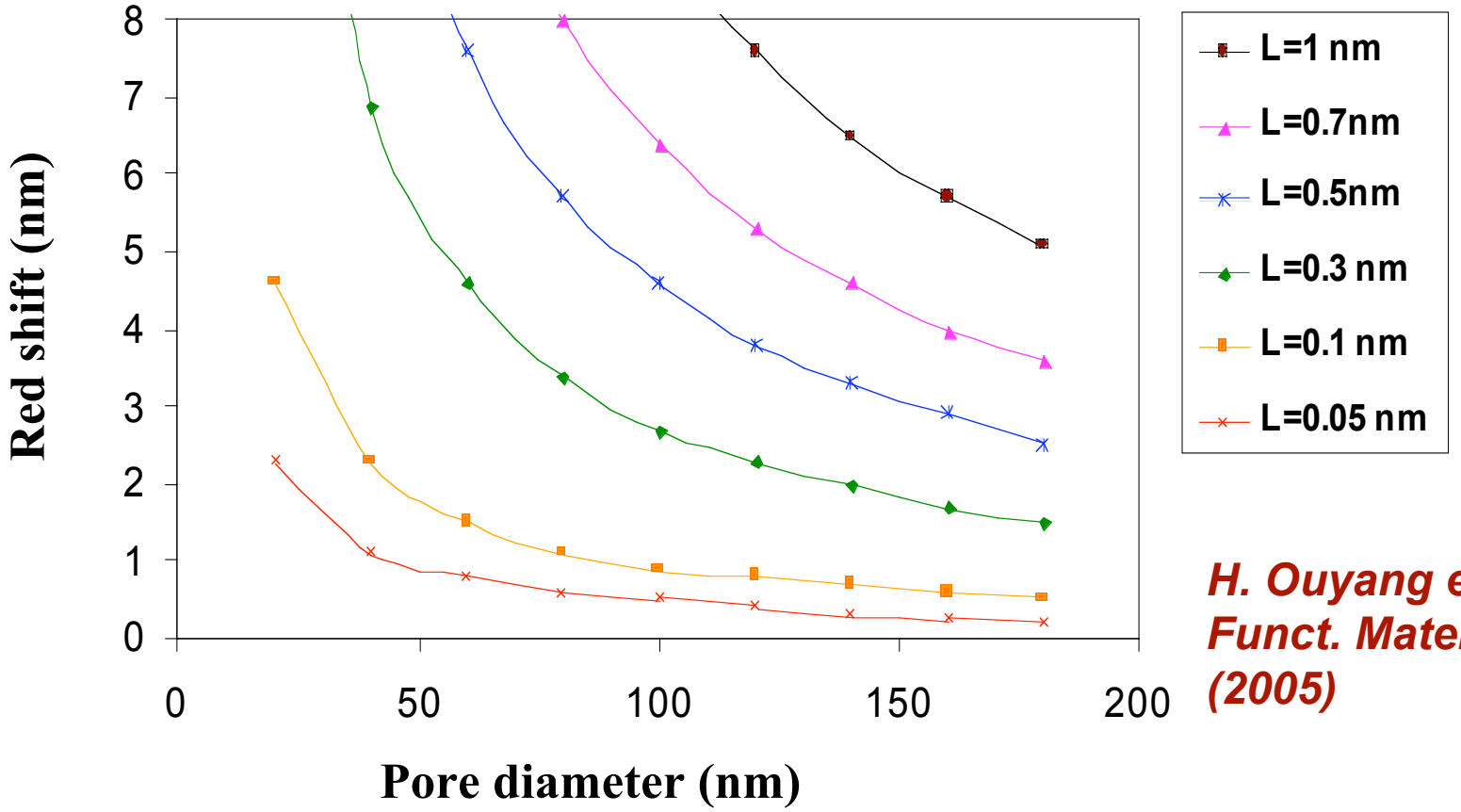
Nanostructures and Sensitivity



20 nm pores
Sensitivity:
~15 pg/mm^2



120 nm pores
Sensitivity:
~50 pg/mm^2

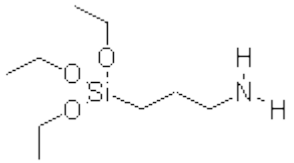


H. Ouyang et al., Adv. Funct. Mater.15, 1851 (2005)

Nanostructures and Sensitivity

(Experiment)

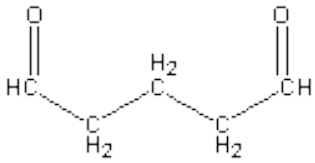
3-Aminopropyltriethoxysilane



0.7 nm

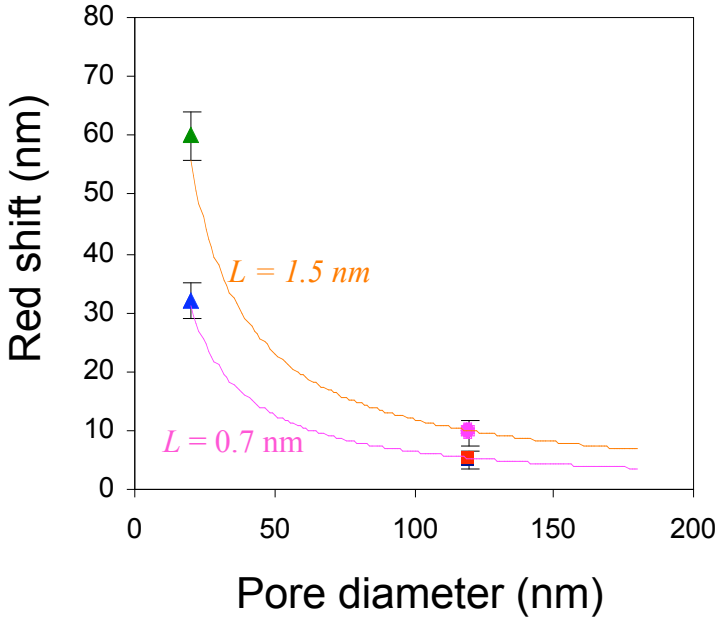
+

Glutaraldehyde



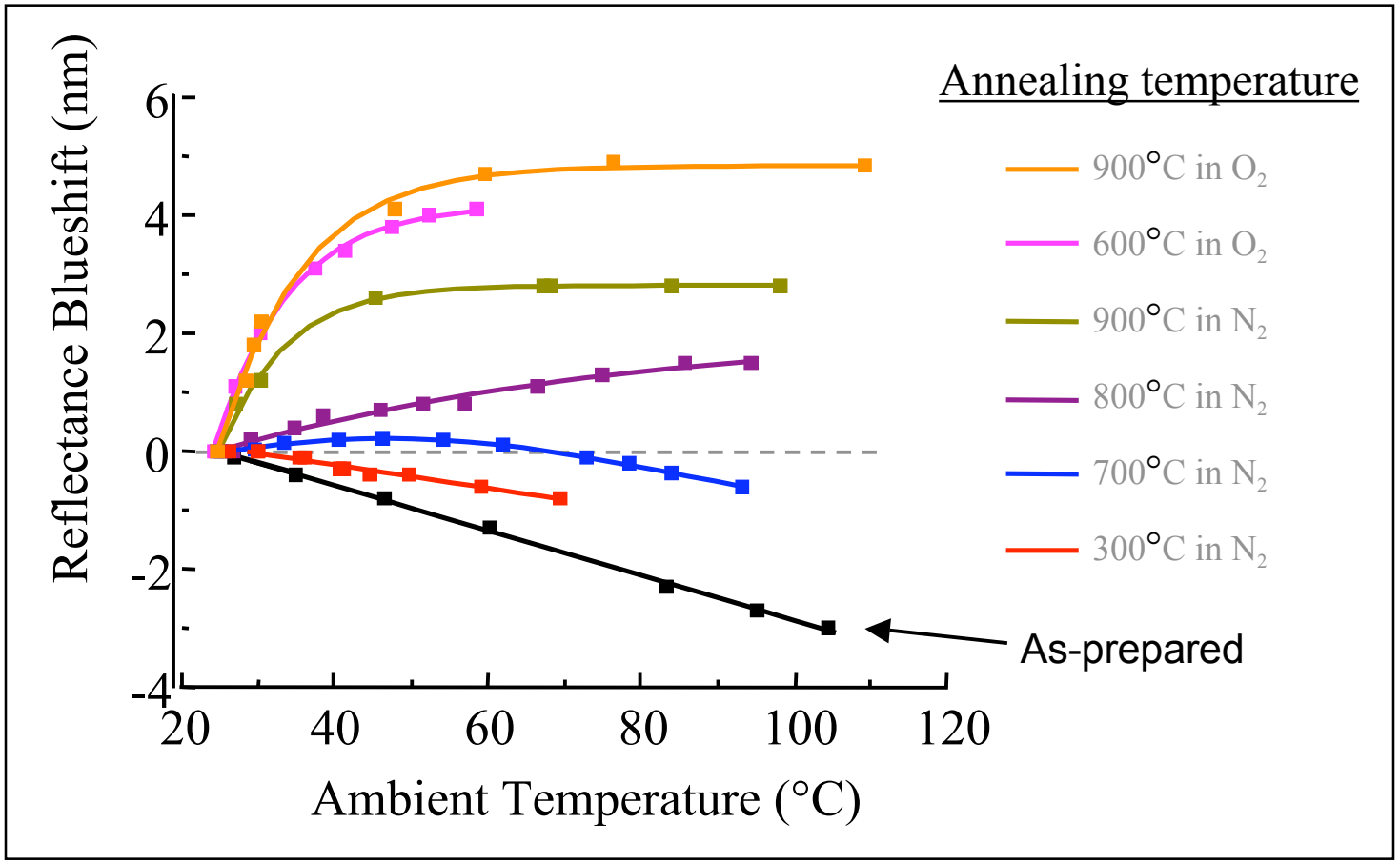
0.8 nm

(measured by ellipsometry on planar surface)



H. Ouyang et al., Appl. Phys. Lett. 88, 163108 (2006)

Beating the Temperature Sensitivity



S.M. Weiss et al, Appl. Phys. Lett. 83, 1980 (2003)

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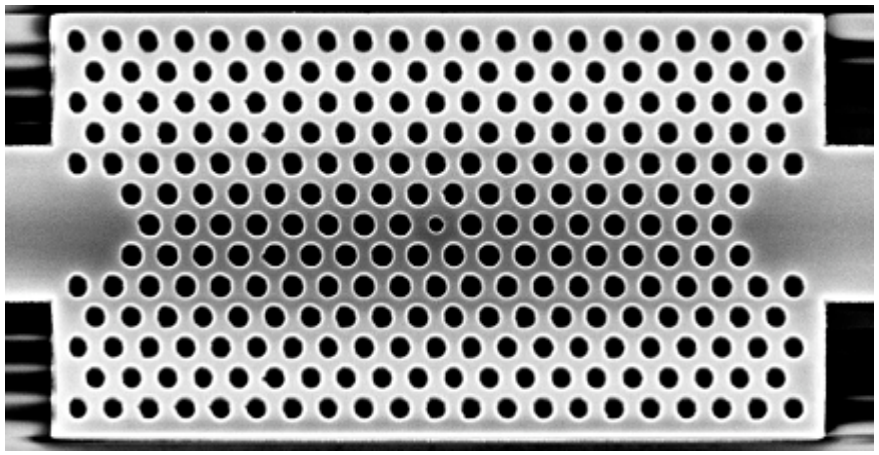
2-D Photonic Crystal Sensor

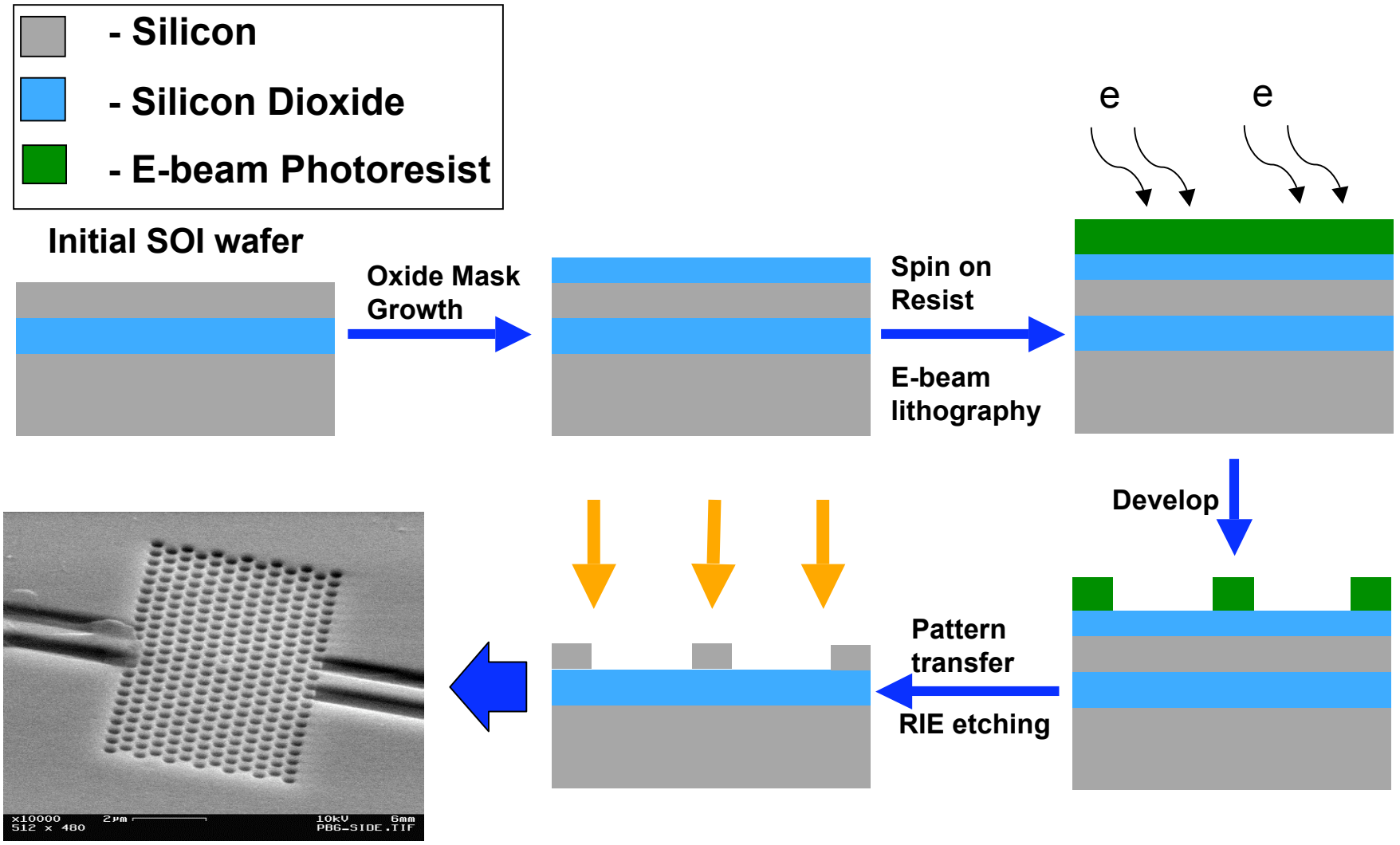
- **Integratable** Ultra-compact (< 100 μm^2) with potential of integration with waveguides and microfluidic channels for “lab on chip” devices
- **Sensitive** Capable of detecting sub-femtogram of biological matter or a single particle.

Light in

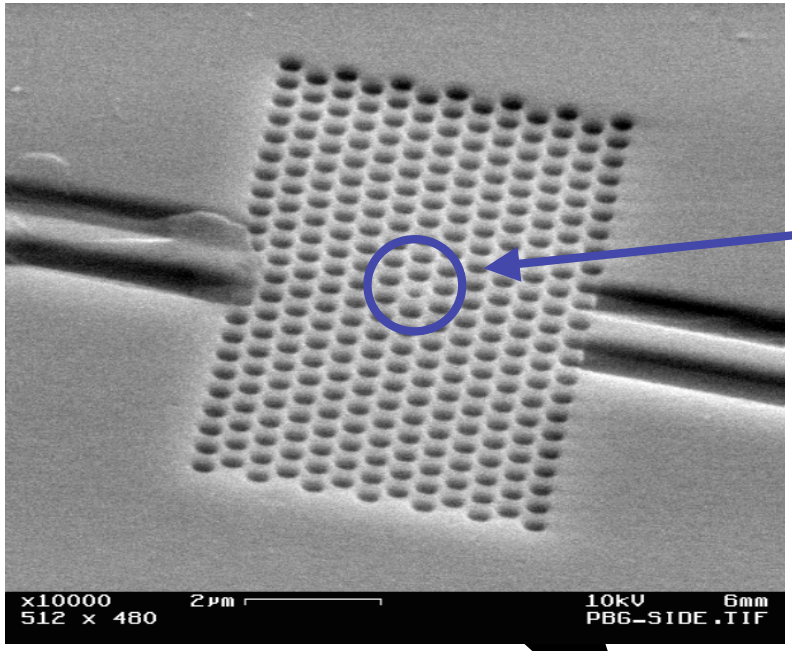


Light out

2-D PhC Microcavity on SOI



Experimental setup (waveguide)



smaller or larger hole

Tunable laser 1440~1590nm

Polarization controller

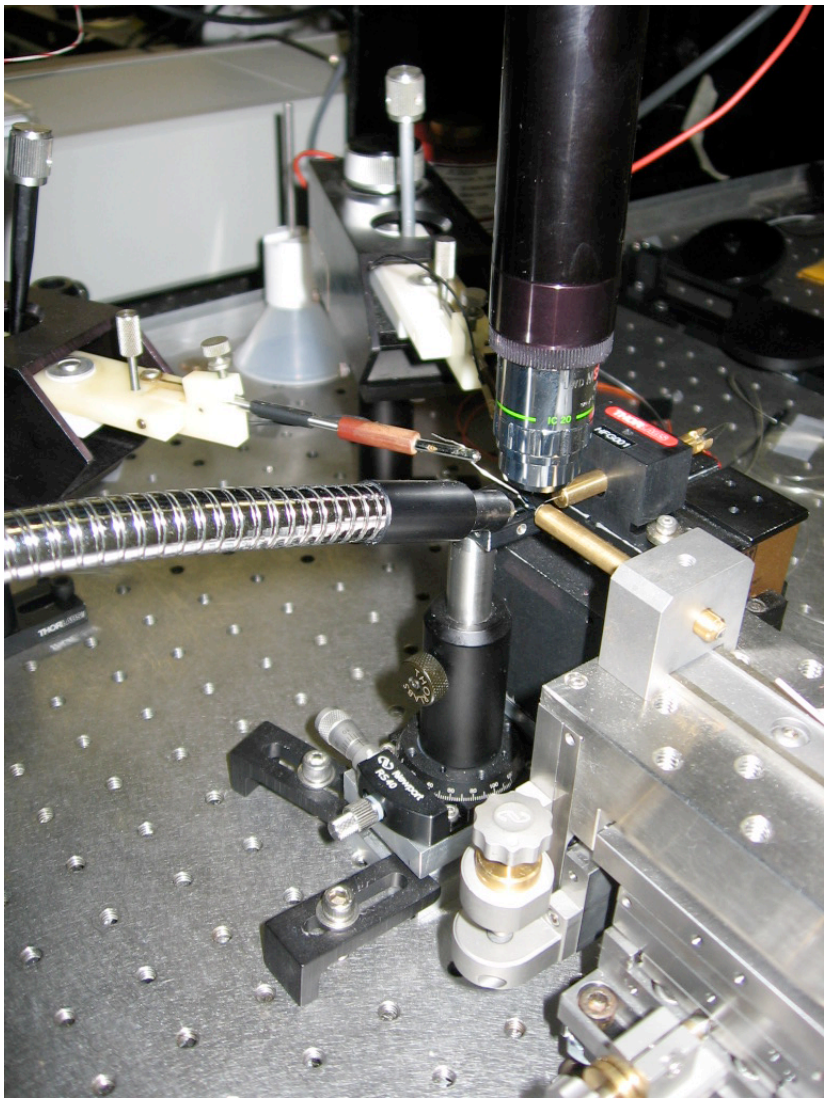
TE

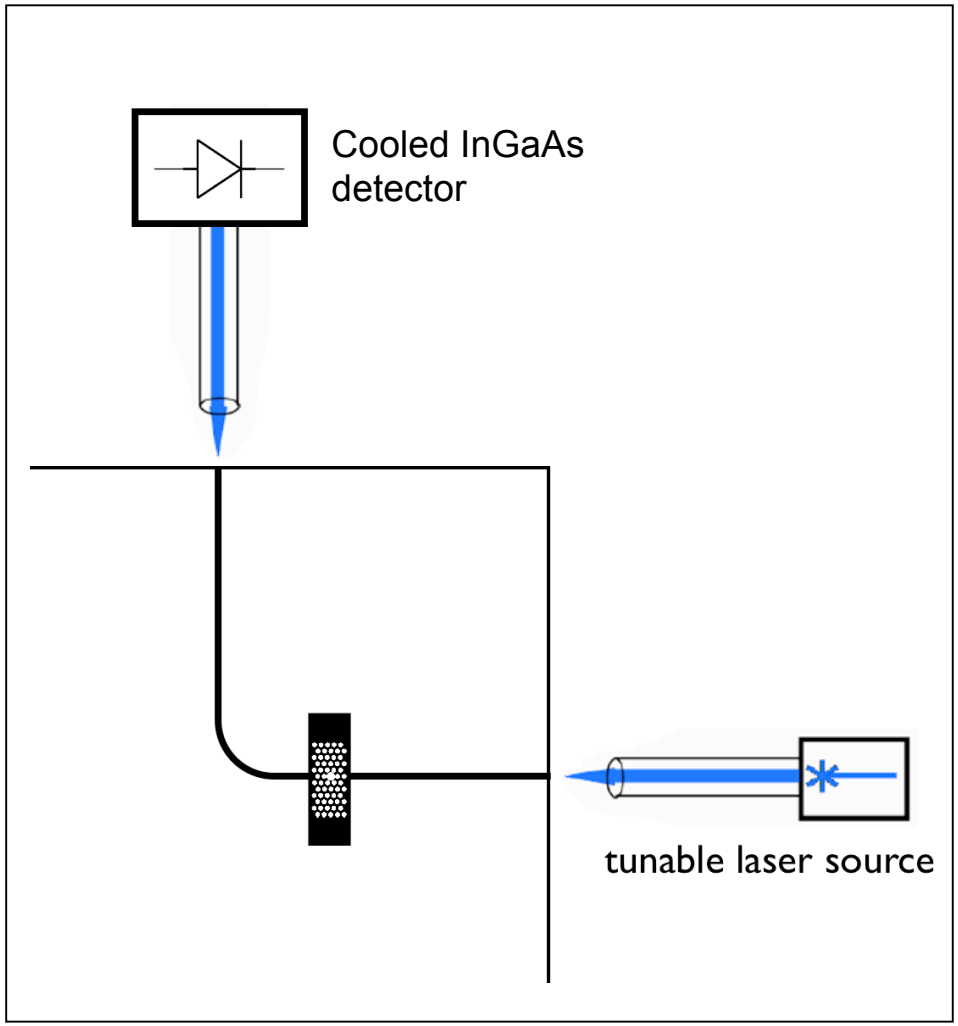
Polarizer

Sample

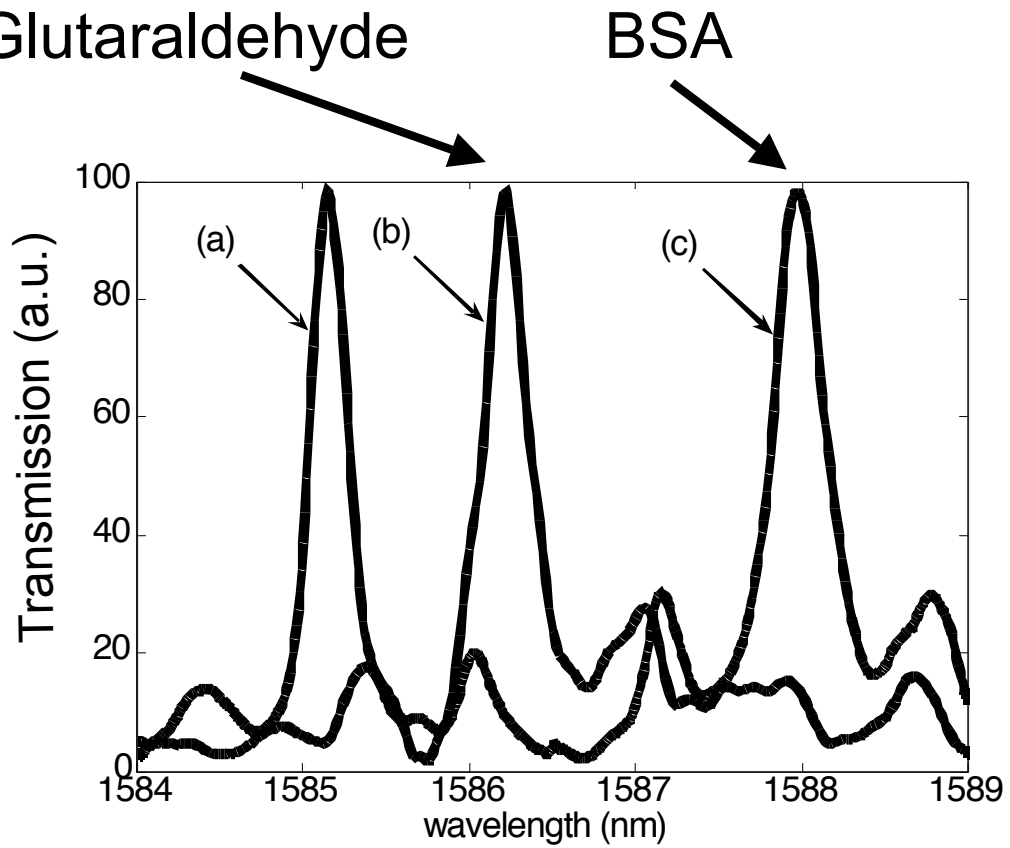
Detector

Experimental arrangement





Experimental Demonstration

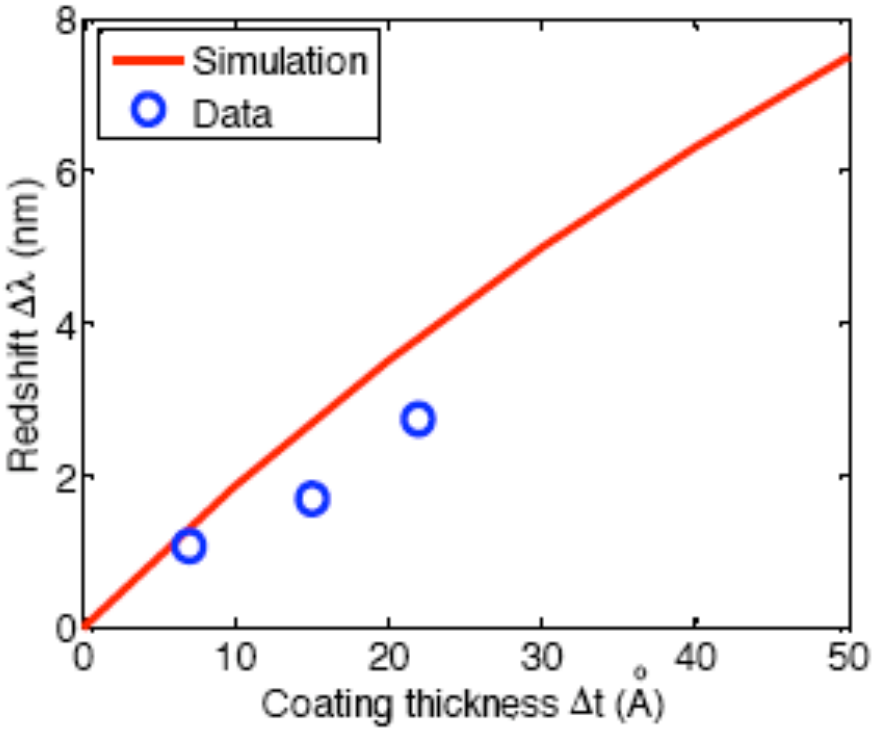


Exposure to Glutaraldehyde, then BSA

Comparison with theory

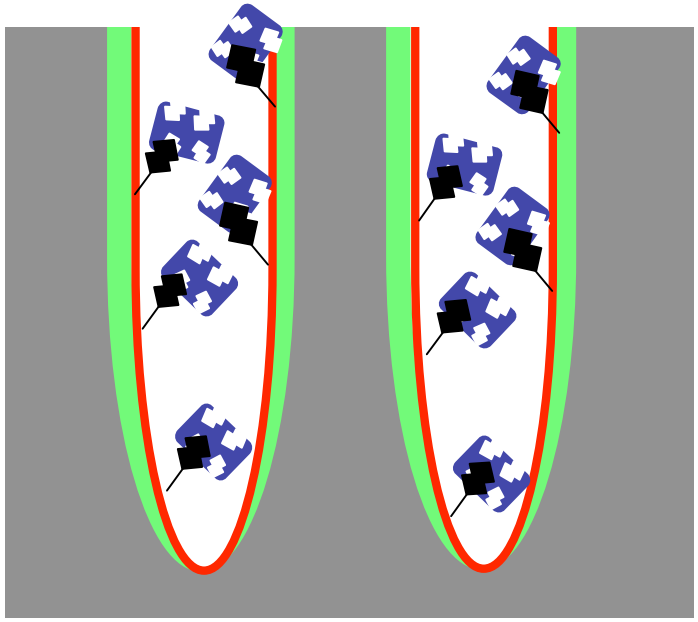
Detection Limit using the current devices:

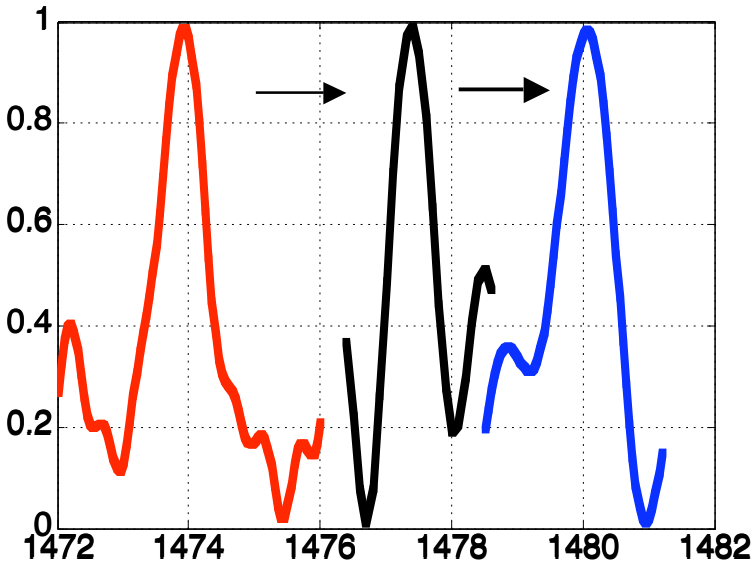
~2 fg for complete device, ~ 0.05 fg in defect only



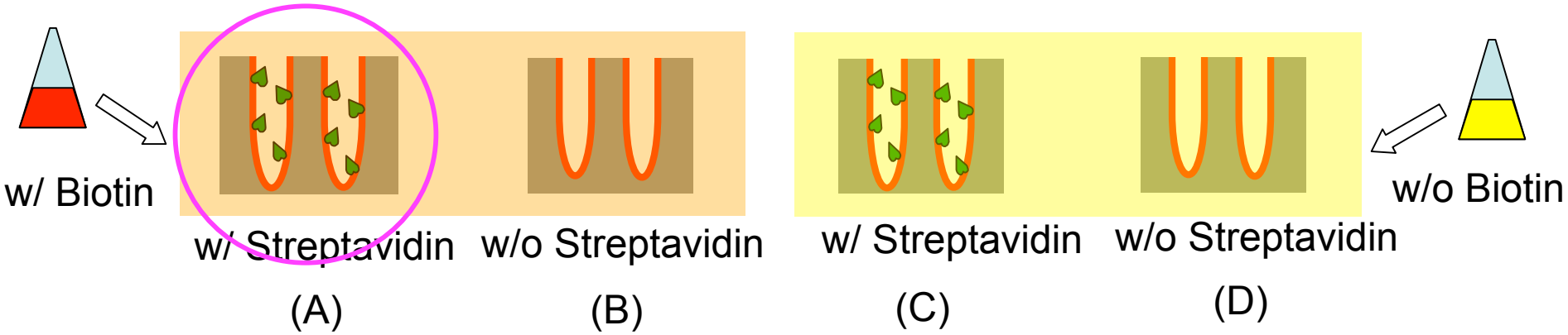
Specific Binding: Biotin-Streptavidin

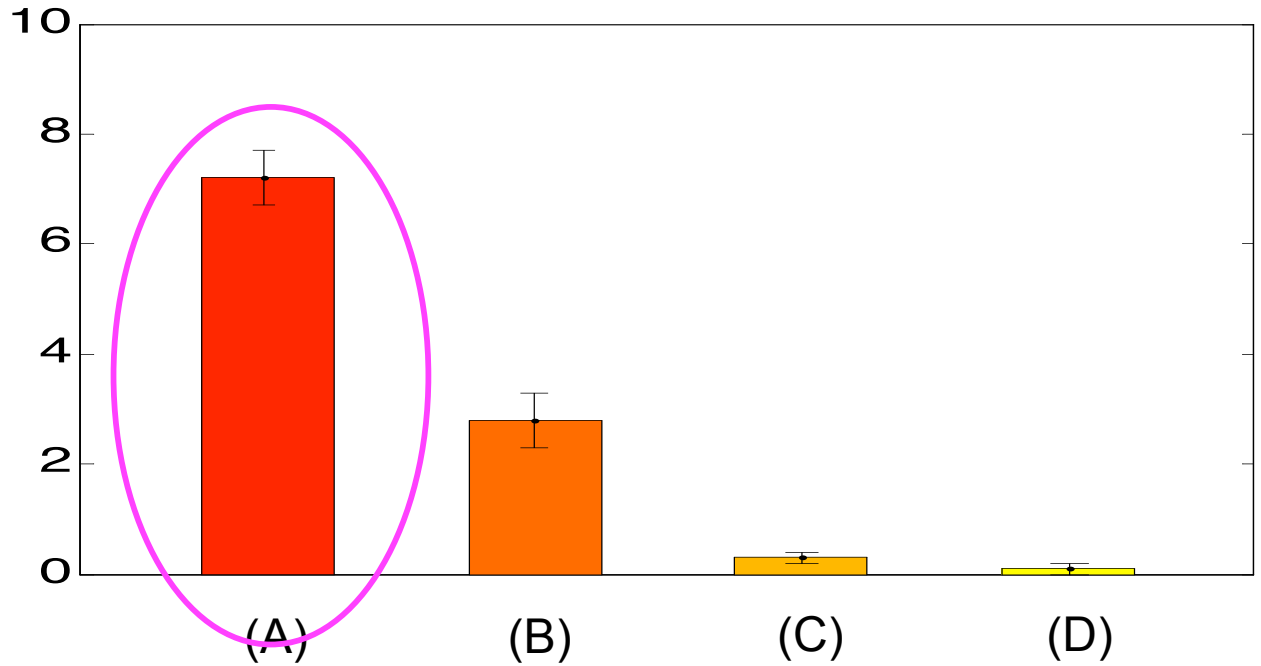
Step 1: Thermally oxidize at 800°C ;
Step 2: Drop 5µl of 2% aminopropyltrimethoxysilane,
Step 3: Post-bake at 100°C;
Step 4: Drop 5µl of 0.5 mg/ml NCF-biotin;
Step 5: Drop 5µl of 1 mg/ml Streptavidin.





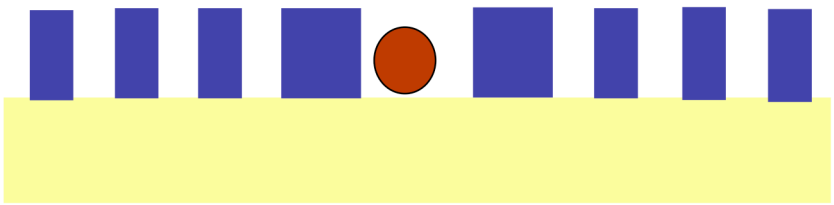
Selective Detection

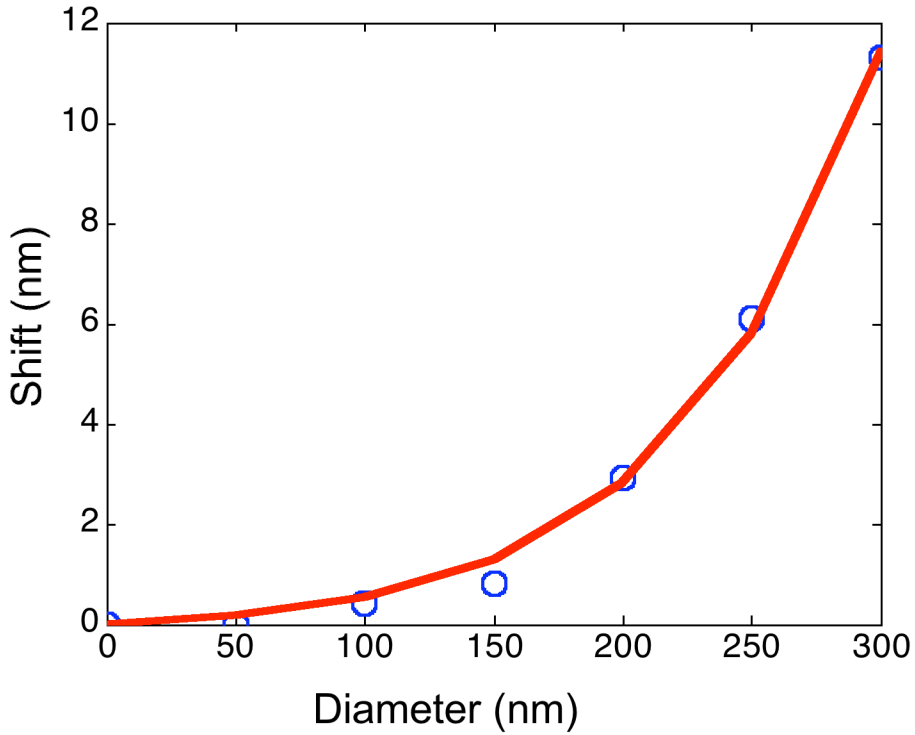




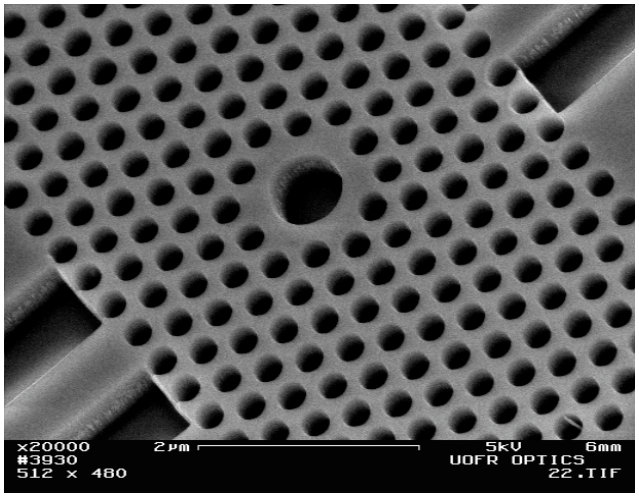
M. Lee and P.M. Fauchet, Opt. Express 15, 4530 (2007)

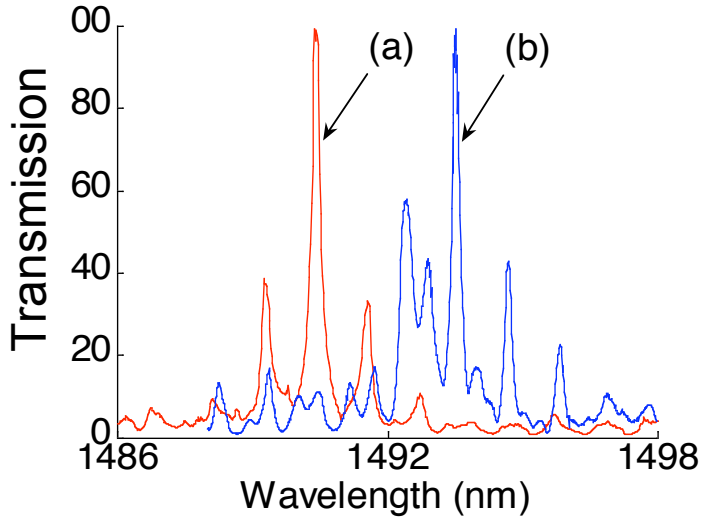
Single Biomolecule Detection

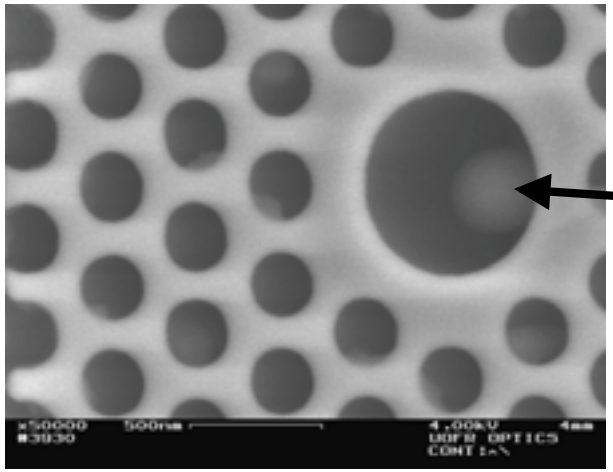




Single Particle Detection







Single latex microphere

M. Lee and P.M. Fauchet, CLEO 2007

Not in the outline: Toward integration with microfluidics

Key Issue: Filtration and Pre-Concentration

Demonstration:

C.C. Striemer et al., Nature 445, 749 (2007)

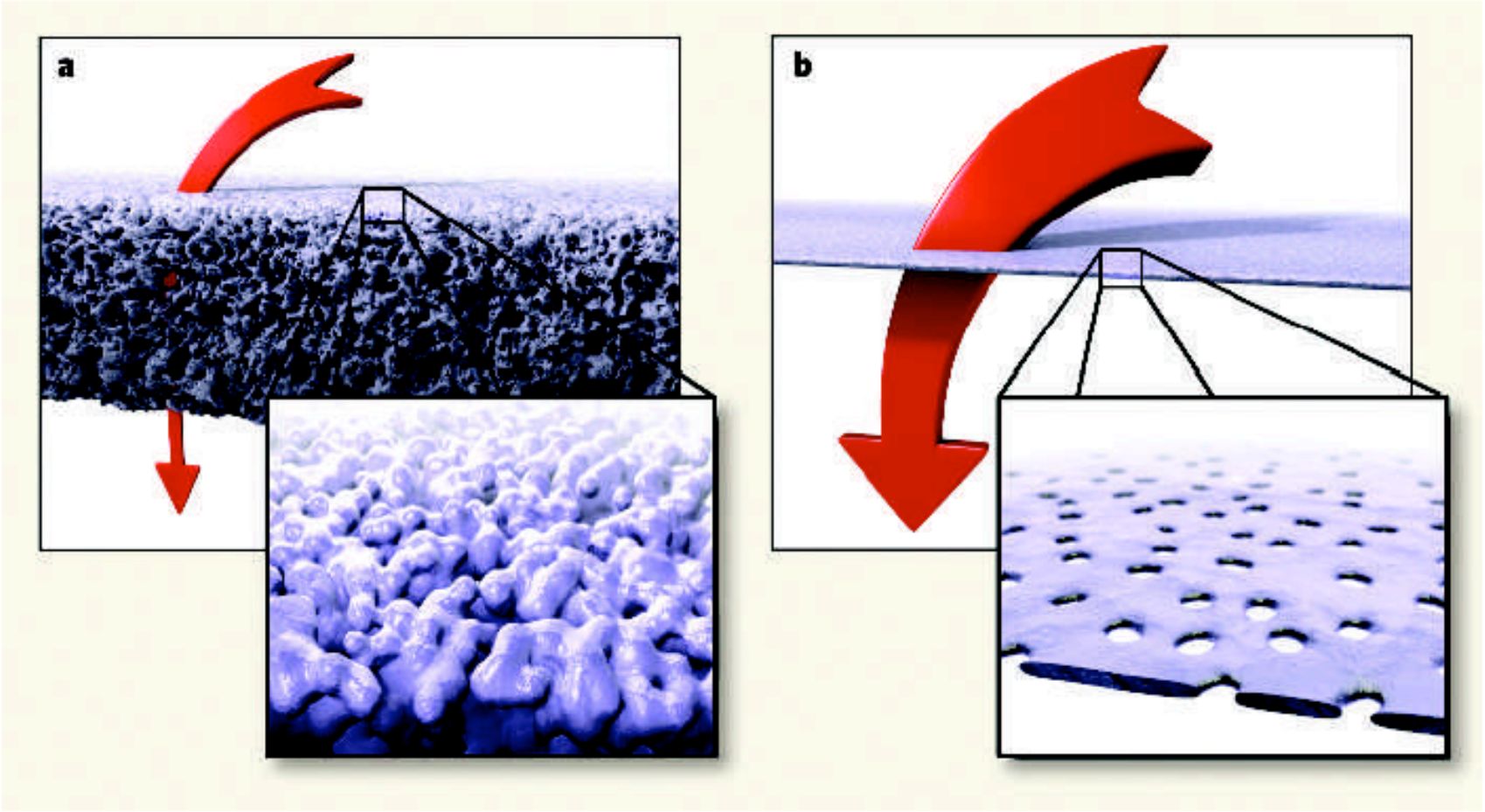
Commercialization:

SiMPore Inc.

Ultrafiltration membranes

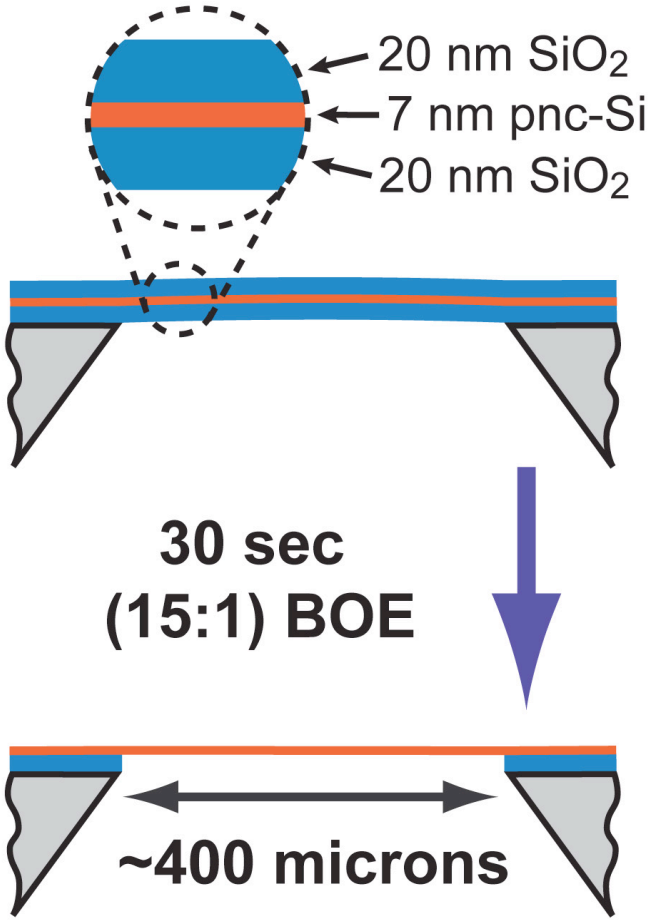
Conventional

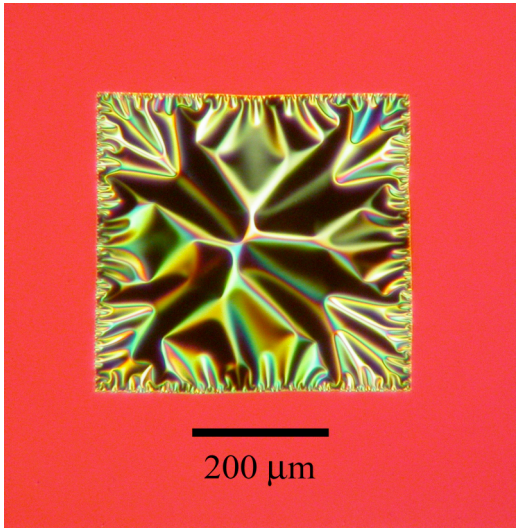
Ideal



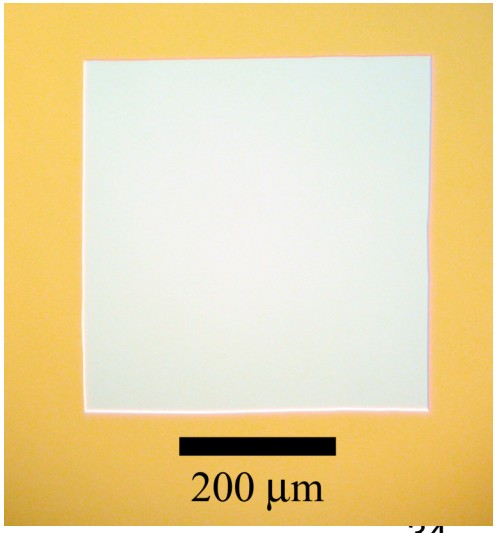
Nanometer-thick Si membranes

After KOH etching to remove the Si wafer, a buffered oxide etch removes the oxide, exposing the Si membrane



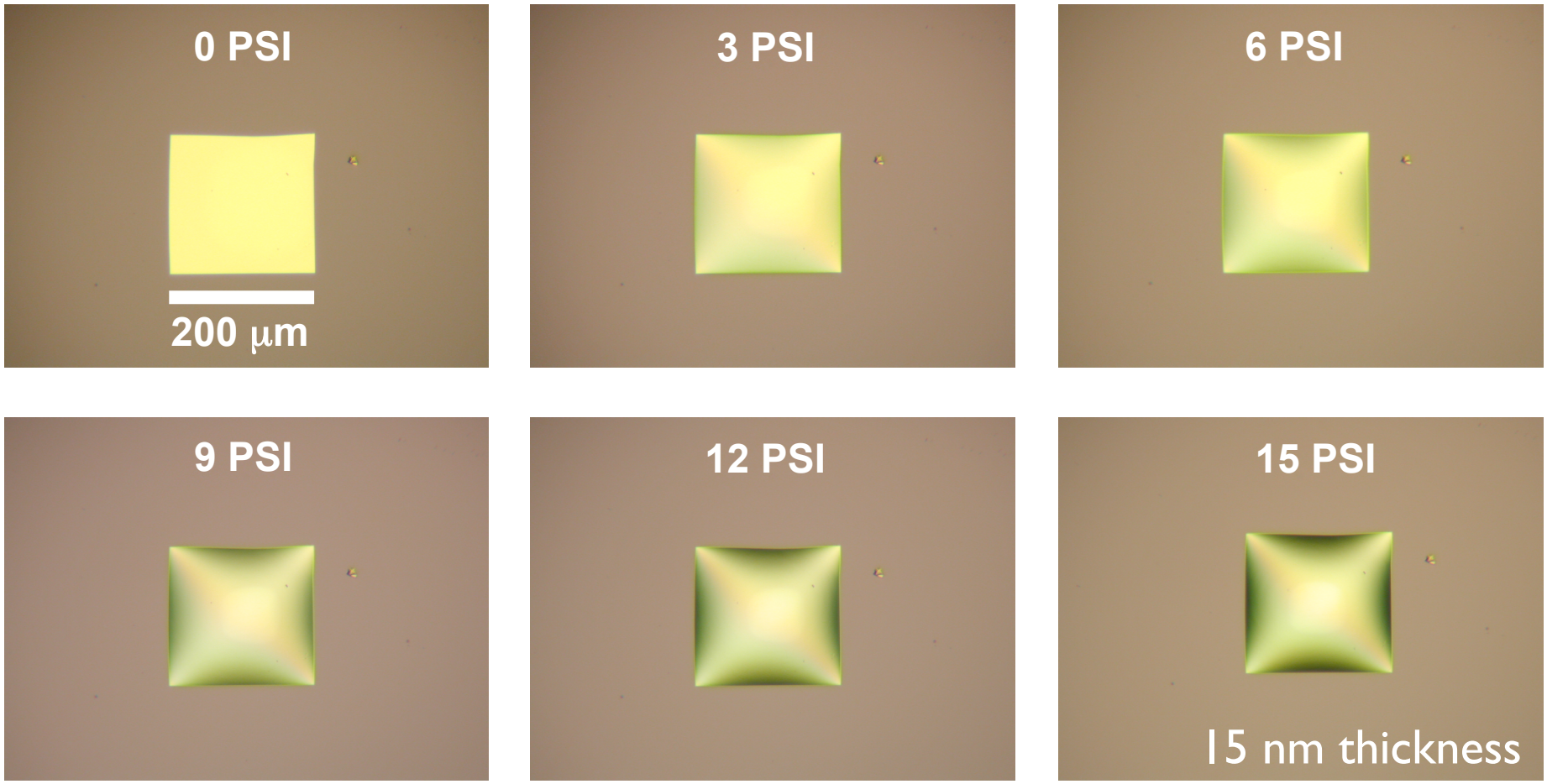


pnc-Si/SiO_2 sandwich



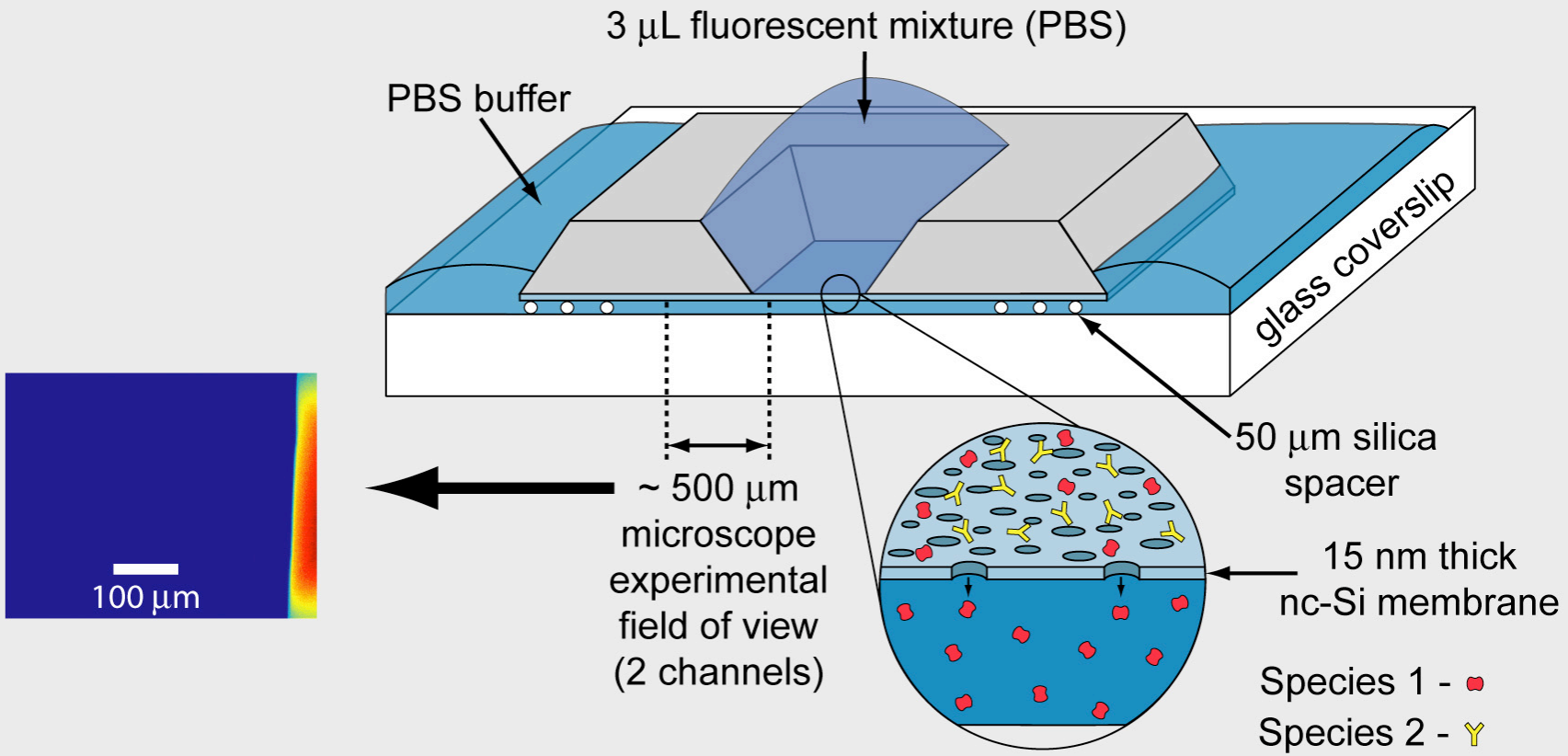
7 nm pnc-Si

The membranes are strong

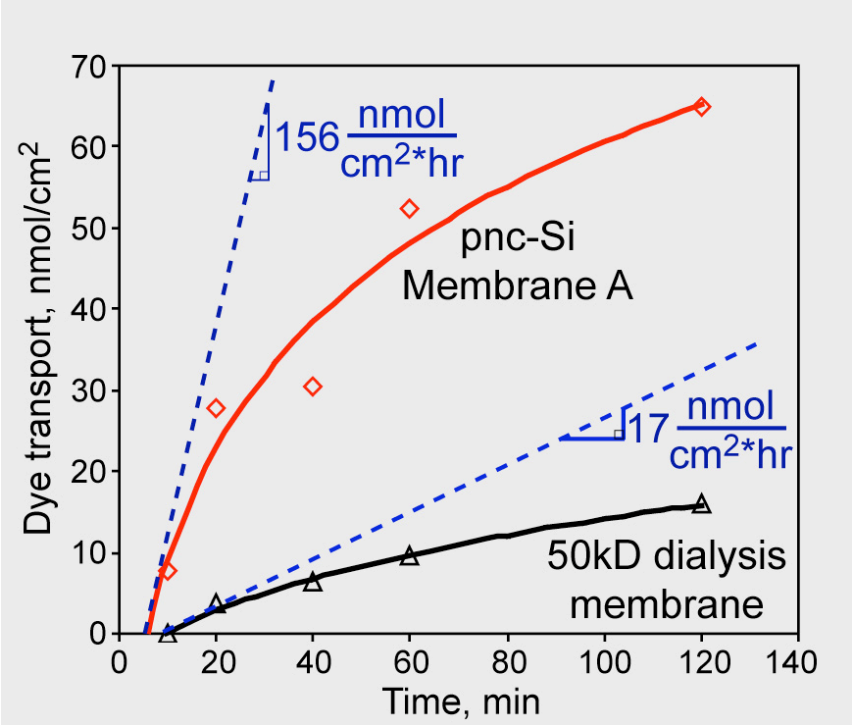


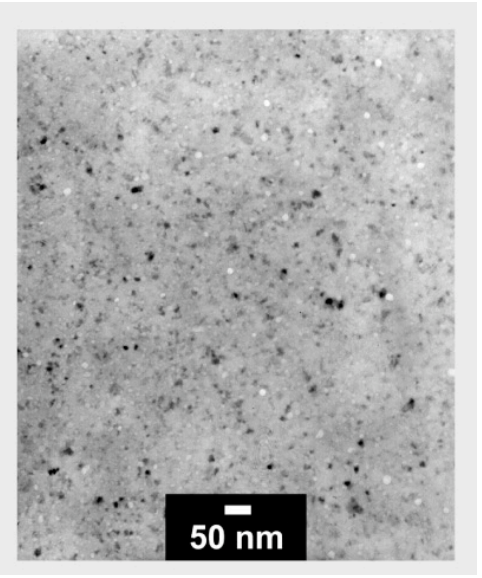
Elastic deformation without rupture

Molecular separation



Dye transport rate comparison





porosity = 0.2%

The diffusion rate of dye through pnc-Si is 10X that of a commercial dialysis membrane with 50 kDa cutoff

Conclusions

- 1D and 2D PhC microcavities can be used as highly sensitive optical label-free sensors
- Silicon 1-D microcavity biosensors with different nanostructures have been fabricated
- The devices have been used for detecting DNA segments, entire DNA strands, proteins, and bacteria, with sub-Angstrom sensitivity
- 2D PhC microcavities can detect sub-fg of material or a single object