Nano-Bio-Sensing Summer School @ EPFL
June 29 – July 3, 2009

Introduction to Optofluidics

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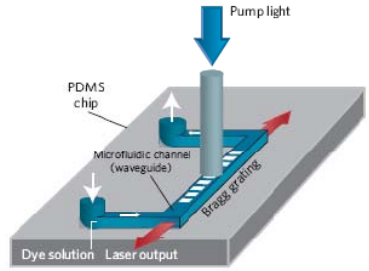
Optofluidics

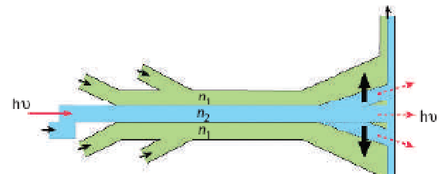
- Electrowetting optics
- Tunable lenses
- Electronic papers
- Optical trapping and manipulation
- Optofluidic lab-on-a-chip
- Microresonators
- Photonic crystals

Optofluidics

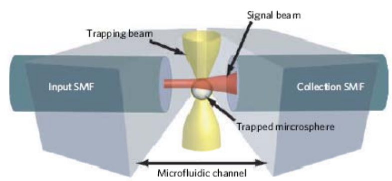
- Integration of optics and fluidics to synthesize novel functionalities
- Applications:
  - Use microfluidics to control light
    - Optical switches, tunable lenses
    - Display
    - Sensors
  - Use light to control microfluidics, micro/nanoparticles, cells, …
    - Optical trapping, sorting, and assembly
    - Non-invasive optical actuation



Li, et. al., *Opt. Express*, 2006



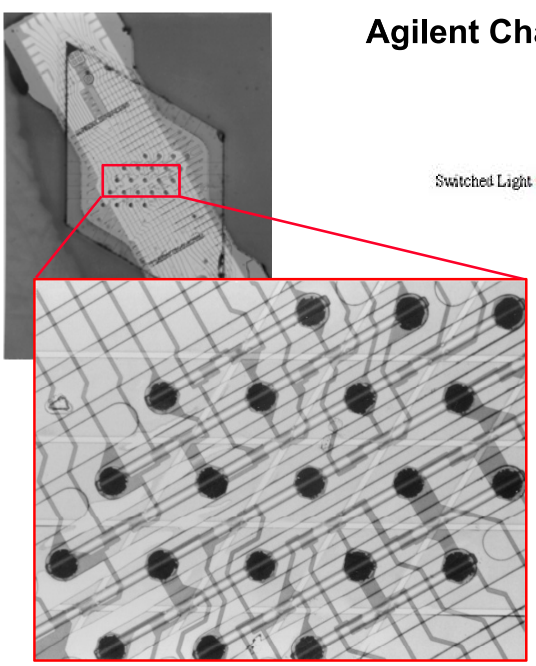
Wolfe, et. al., *Proc. Natl. Acad. Sci.* , 2004



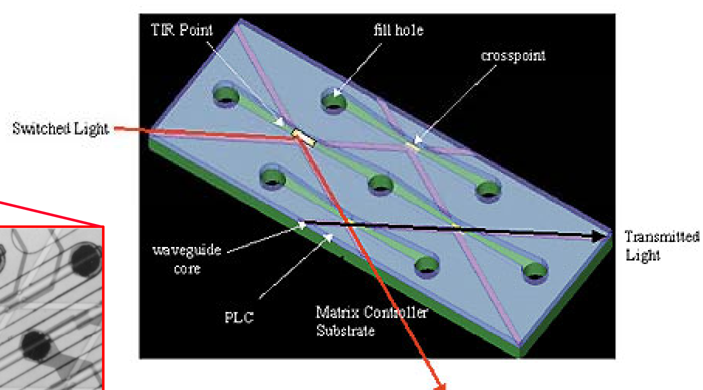
Domachuck, et. al., *Nature*, 2005

Psaltis, et. al., *Nature*, 2006

"Bubble" Switches



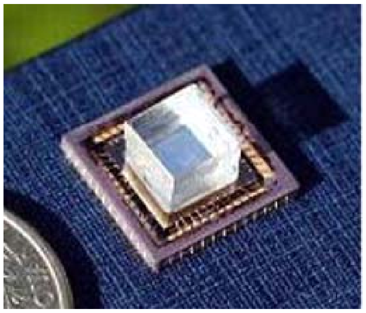
Agilent Champaign Switch

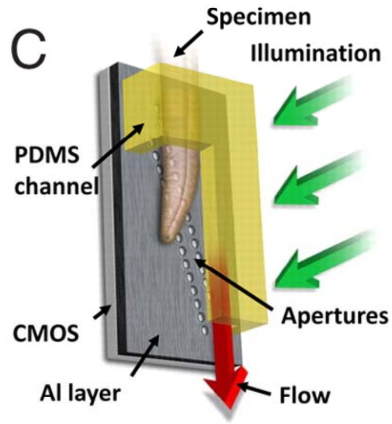


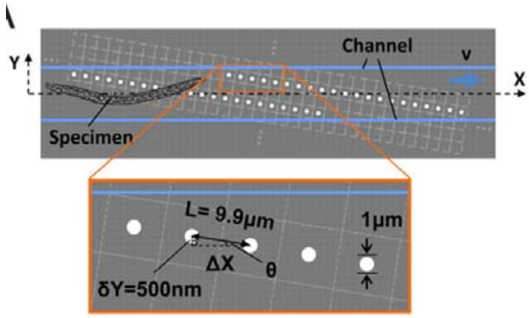
- Optical crossbar switch using total internal reflection by a thermally generated bubble
- 32x32 switches have been demonstrated

- J. E. Fouquet, "Compact optical cross-connect switch based on total internal reflection in a fluid-containing planar lightwave circuit," OFC 2006

Optofludic Microscopy



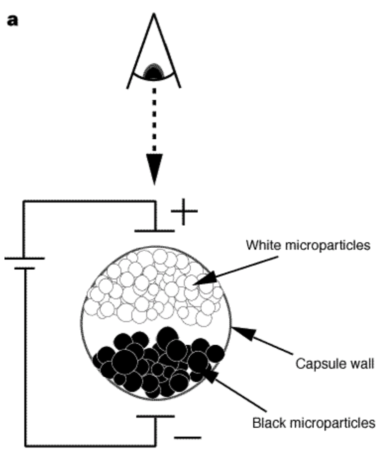


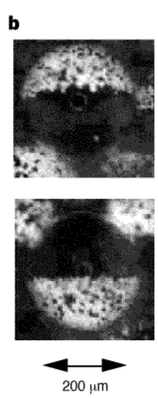


- **Low-cost, high-resolution (0.8 μm), lensless on-chip microscopes**
- **Use microfluidic flow to deliver specimens across apertures on a metal-coated CMOS sensor**

X. Cui, L. M. Lee, X. Heng, W. Zhong, P. W. Sternberg, D. Psaltis, and C. Yang, "Lensless high-resolution on-chip optofluidic microscopes for Caenorhabditis elegans and cell imaging," Proceedings of the National Academy of Sciences, vol. 105, p. 10670, 2008.

Electrophoretic Ink for All-printed Reflective Electronic Displays



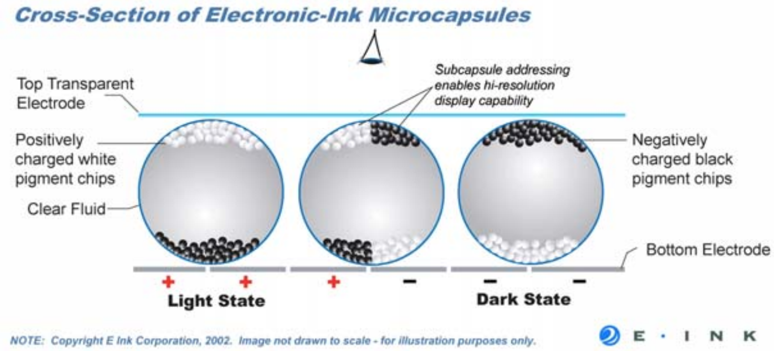


Joseph Jacobson co-founded E Ink

- **1 ~ 5um Charged microparticles**
  - **White: rutile titanium dioxide**
  - **Black: inorganic black pigment**
- **Particles acquire a surface charge due to the electrical double layer**
- **Microcapsule with diameter ~ 30 um**
- **Zero power consumption**

B. Comiskey, J. D. Albert, H. Yoshizawa, and J. Jacobson, "An electrophoretic ink for all-printed reflective electronic displays," ***Nature, vol. 394, pp. 253-255, 1998.***

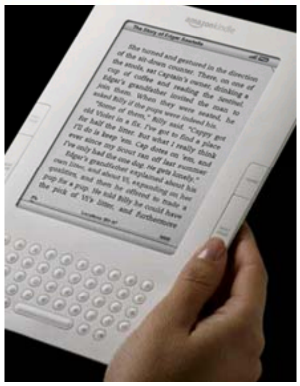
E-Ink
Electronic Paper Display (EPD)



www.eink.com

Portable Reader (600x800, 167 ppi)

Amazon Kindle



Flexible Wall Clock

Citizen

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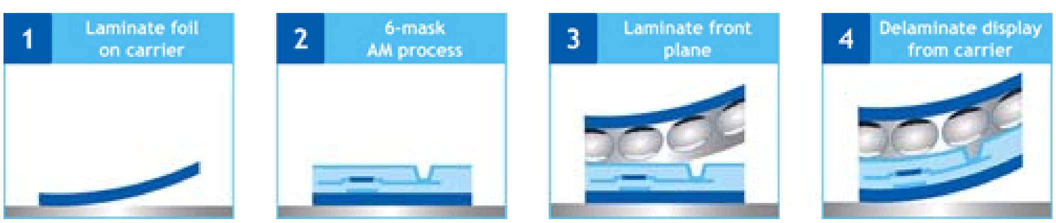
Polymer Vision's Rollable Display

Flexible display made in AM-LCD facility



Rollable Display

http://www.polymervision.com/site/page/15/26/37/Rollable_Displays

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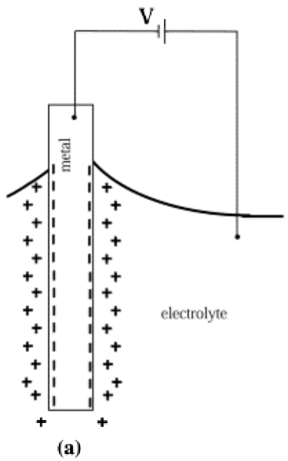
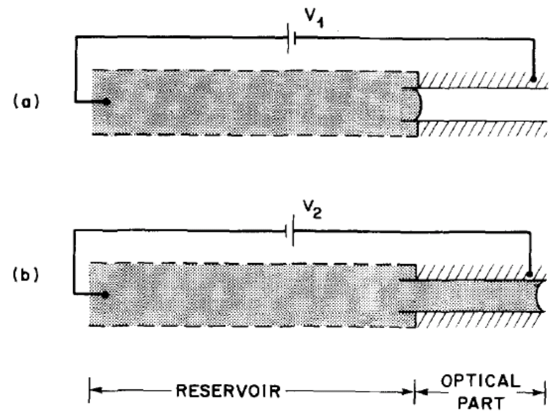
Electrowetting

Electrowetting (1875)
(Classical electrocapillarity)



G. Lippmann, Relation entre les phénomènes électriques et capillaires. *Ann. Chim. Phys.* 5 (1875), pp. 494–549.

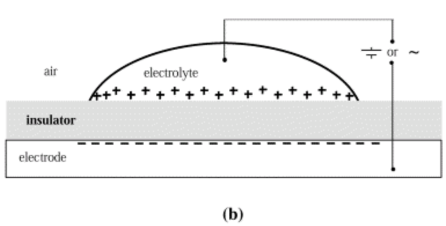
Electrowetting Display
(Bell Labs, 1981)



G. Beni and S. Hackwood, "Electro-wetting displays," *Applied Physics Letters, vol. 38, pp. 207-209, 1981.*

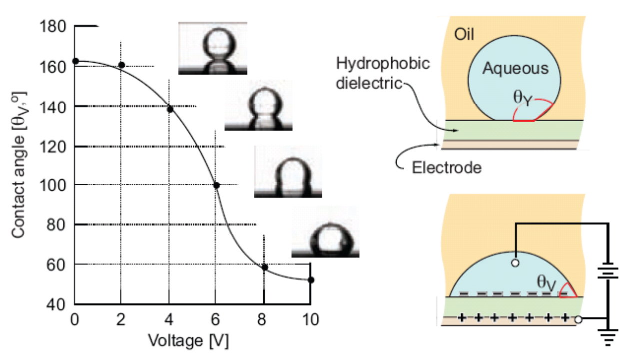
Electrowetting on Insulator Coated Electrodes (EICE)

Electrowetting on Insulator Coated Electrodes (EICE)



B. Berge, Electrocapillarité et mouillage de films isolants par l'eau. C.R.A.S. III 317 (1993), pp. 157–163.

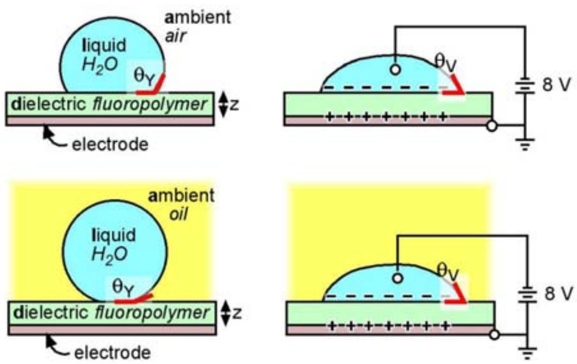
Reversible Change of Contact Angle



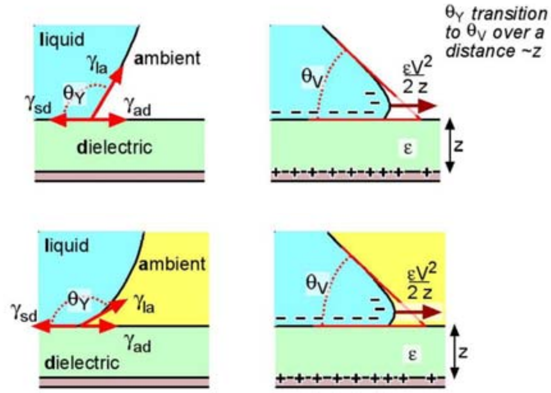
J. Heikenfeld, et al., « Recent progress in arrayed electrowetting optics, » Optics and Photonics News, 2009

Electrowetting on Dielectric

Macroscopic Picture



Microscopic Picture



$$\cos\theta_V = \cos\theta_Y + \frac{1}{\gamma_{LA}}\frac{CV^2}{2}$$

$$\gamma_{LD} = \gamma_{DA} - \gamma_{LA}\cos\theta_Y$$

$\gamma_{LA} \sim 73$ mN/m for air,
< 50 mN/m for oil

$\gamma_{DA} \sim 16$ to 20 mN/m

J. C. Heikenfeld, N. R. Smith, B. Sun, K. Zhou, L. Hou, Y. Lao, and B. Raj, "Flat electrowetting optics and displays," in *Proc. SPIE, Vol. 6887, 2008, p. 688705*

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Video of Electrowetting

http://www.varioptic.com/en/tech/technology-demos.php

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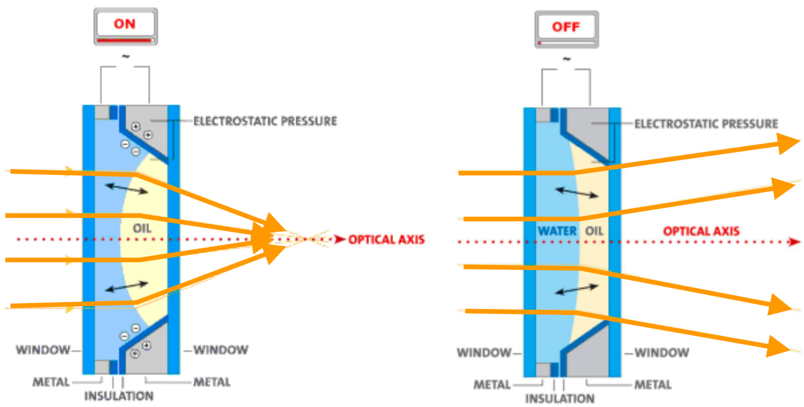
Tunable-Focus Liquid Lens

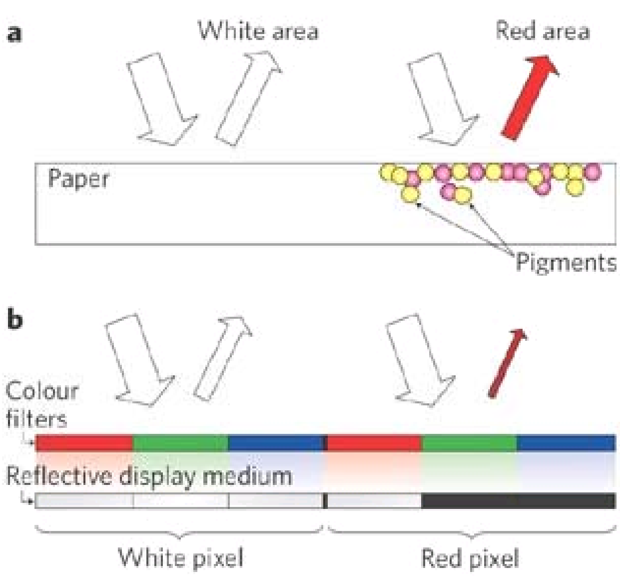
Compact auto-focus lens for cell phones, slim camera, webcam



- Auto focus
- Compact zoom lens

www.varioptic.com

Paper vs General Reflective Electronic Display

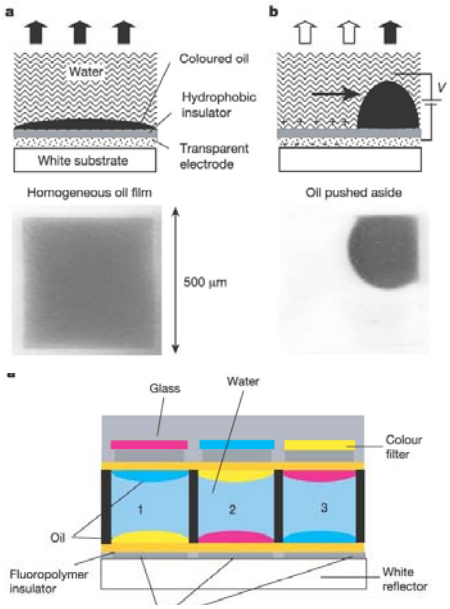


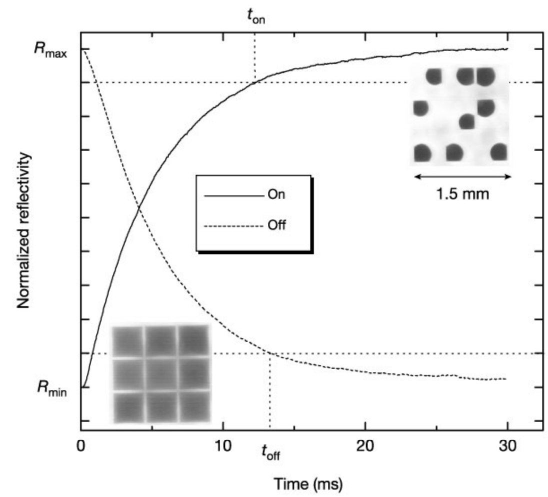
- Paper
  - Color pigments on white
  - Bright
- Reflective electronic display
  - RGB subpixels + color filters
  - Efficiency < 1/3
  - Not very bright

P. Drzaic, "Displays: Microfluidic electronic paper," Nat Photon, vol. 3, pp. 248-249, 2009.

Video-Speed Electronic Paper Based on Electrowetting

Philips Research Eindhoven (now Philips spin-off, Liquavista)





Robert A. Hayes & B. J. Feenstra, "Video-speed electronic paper based on electrowetting," *Nature* 425, 383 - 385 (2003).

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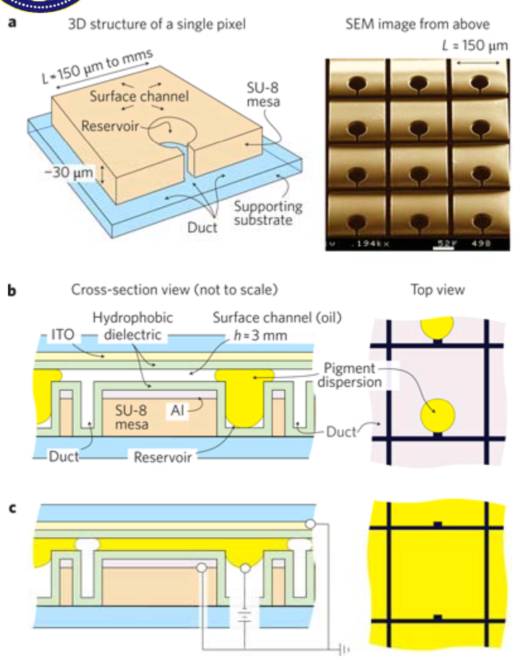
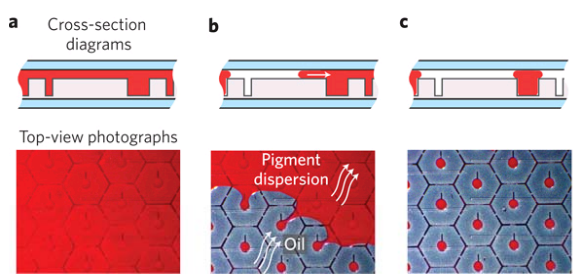
Electrofluidic Display



Self-Assembly of Pigment Liquid



Pigment Droplet

HeikenfeldJ, ZhouK, KreitE, RajB, YangS, SunB, MilarcikA, ClappL, and SchwartzR, "Electrofluidic displays using Young-Laplace transposition of brilliant pigment dispersions," Nat Photon, vol. 3, pp. 292-296, 2009.

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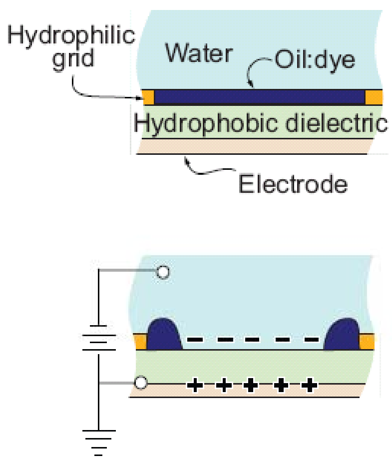
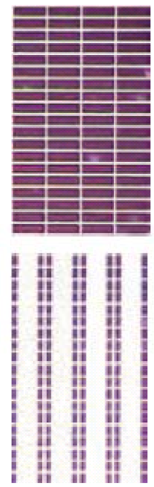
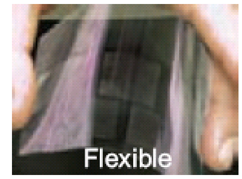
Electrowetting Display

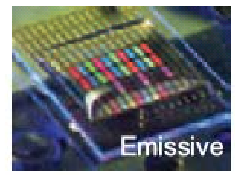
X-section diagram

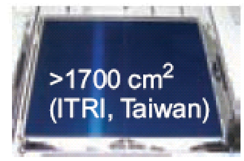


Top-view photo





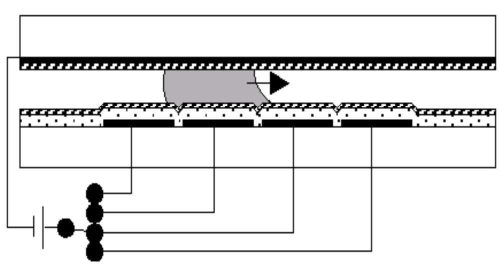




- **Emissive display using fluorescence oil with 400nm backlight**
- **ITRI has recently scaled the electro-wetting display fabrication process to greater than 1,700 cm^2 on an active matrix backplane, using standard LCD manufacturing equipment.**

Jason Heikenfeld, et al. "Recent Progress in Arrayed Electrowetting Optics," Optics & Photonics News 20, 20-26 (2009)

Digital Microfluidics Based on Electrowetting on Dielectric (EWOD)



Lippmann-Young equation

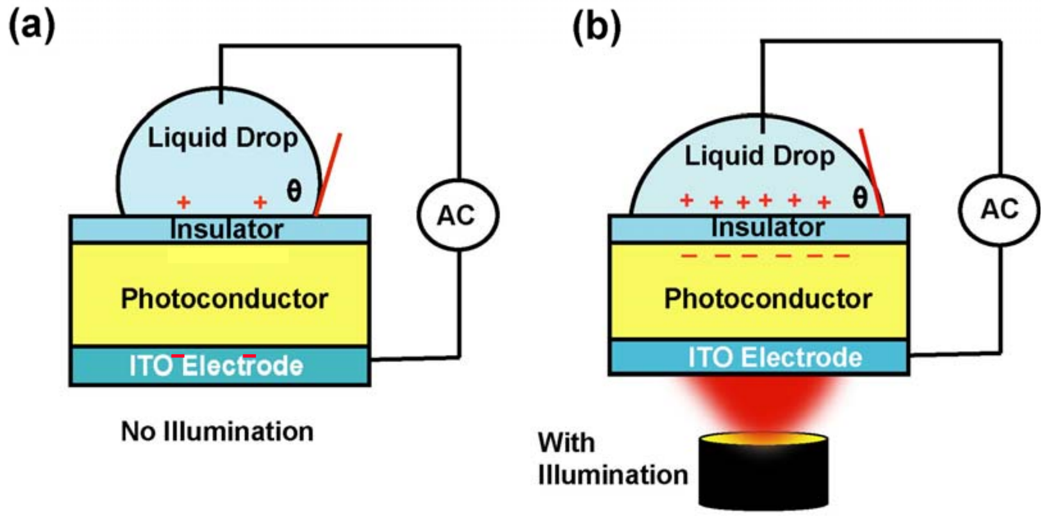
$$\cos\theta(V) = \cos\theta_0 + \frac{1}{\gamma_{LG}}\frac{1}{2}CV^2$$

C. J. Kim (UCLA)
S. K. Cho, H. Moon, and C. J. Kim, *J-MEMS2003.*

- **Manipulate discrete droplets instead of continuous flow liquid**
- **Droplet actuated by EWOD**
- **Eliminate the need for pumps or valves**
- **Require a large number of electrodes**

Richard Fair (Duke Univ)
M.G. Pollack, et al, *Applied. Phys. Lett.* 2000

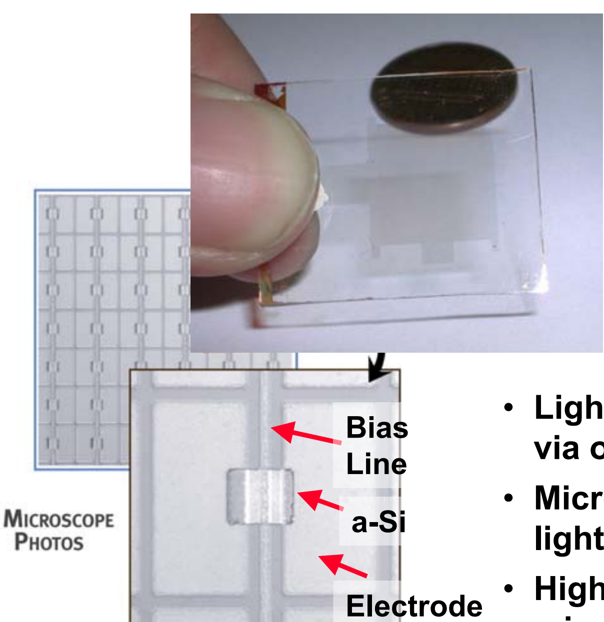
Optoelectrowetting (OEW)

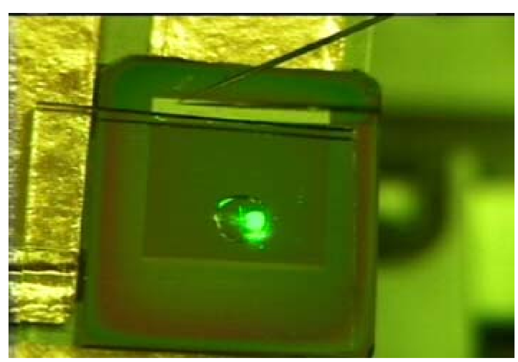


Applied AC frequency: 100Hz ~ 1kHz (determined by RC charging time)

P. Y. Chiou, H. Moon, H. Toshiyoshi, C.-J. Kim, and M. C. Wu, "Light actuation of liquid by optoelectrowetting," *Sensors & Actuators A-Physical, vol. A104, pp. 222-8, 15 May 2003.*

Opto-Electrowetting (OEW)

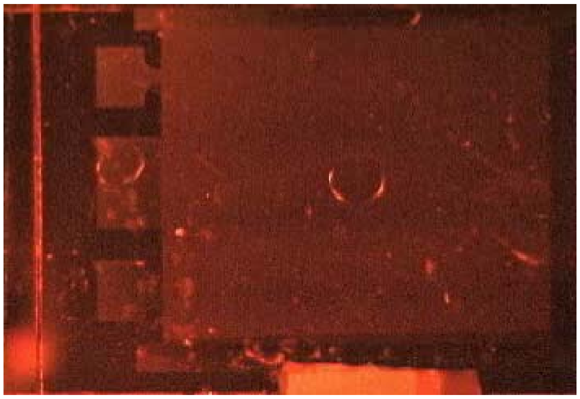




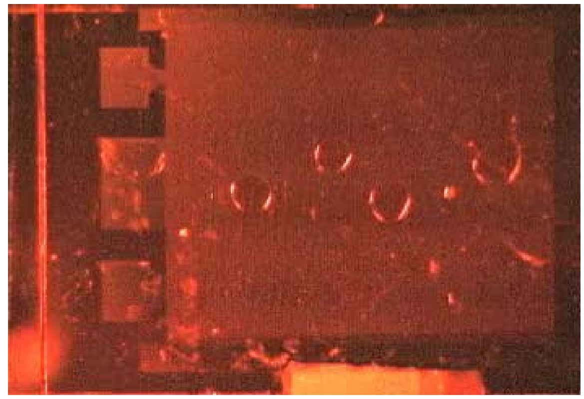
- **Light illumination changes contact angle via opto-electrowetting**
- **Microdroplets follow the movement of light**
- **Highly scalable, droplet volume from micro- to pico-liter**

P. Y. Chiou, Z. H. Chang, and M. C. Wu, "Droplet manipulation with light on optoelectrowetting device," *Journal of Microelectromechanical Systems, vol. 17, pp. 133-138, Feb 2008.*

OEW Microfluidic Functions



Droplet Separation



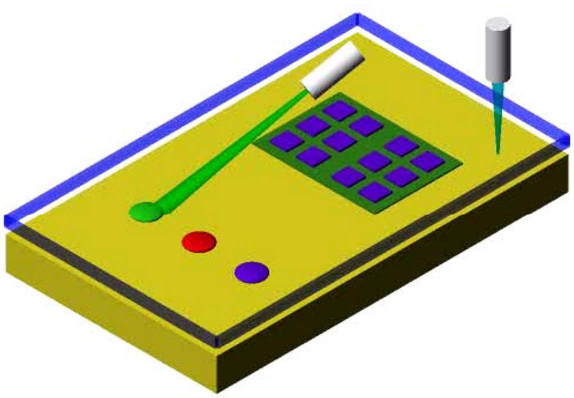
Multiple Droplet Manipulation

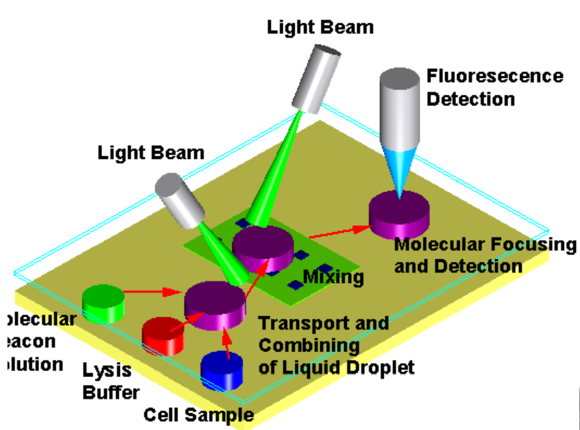
Droplets manipulation using 2 scanning laser beams

Light-Actuated Microfluidic Circuits

- Lab-on-a-Chip
  - Ease-of-use
  - Speed of analysis
  - Low sample and reagent consumption
  - Standardization and automation

- Light-actuated lab-on-a-chip
  - Optical detection
  - Optically actuation (droplets, cells, nanoparticles, DNAs)
- Low-cost, disposable “Bio-FPGA”

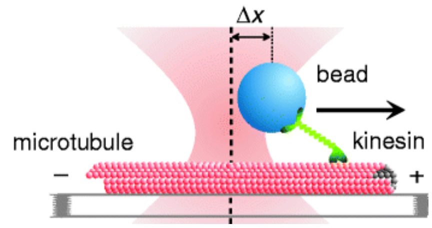




Tools for Manipulating Cell and Micro/Nano Particles

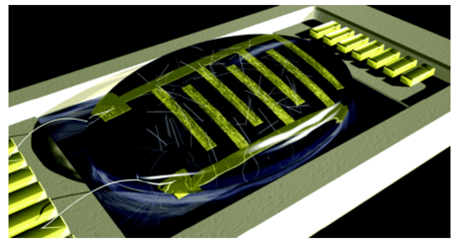
- Highly sought of in fields of biological and colloid science
  - Trapping
  - Sorting
  - Addressing
- Tools Available
  - Optical Tweezers
  - Dielectrophoresis (DEP)

- Molecular Force Clamp



Visscher , Nature, 1999

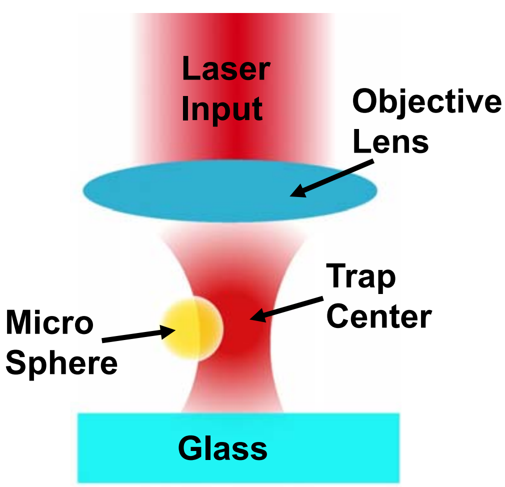
- Separation of Carbon Nanotubes



Krupke, Science, 2003

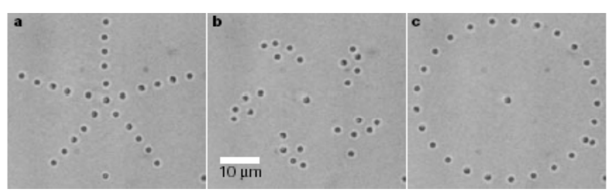
Optical Tweezers

Optical Tweezers



Ashikin, *Opt. Lett.*,1986

Holographic Optical Tweezers

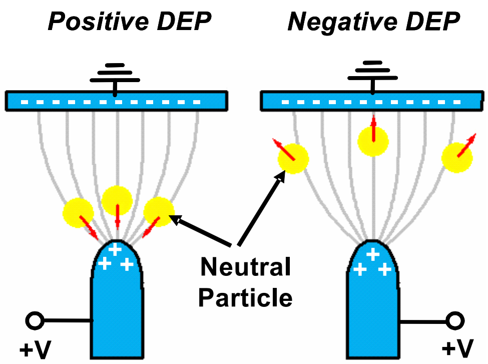


Curtis, et al., *Optics Comm.*, 2002 (Univ. of Chicago)

Limitations:

- Small manipulation area (< 100 µm)
- High optical power (laser power ~ Watt)

Dielectrophoresis (DEP)



- **Motion of polarisable particles (charged or uncharged) in non-uniform AC electric fields**
- **Coined by Pohl in 1951**

$$F_{dep} = 2\pi a^3 \varepsilon_m \,\mathrm{Re}[K^*(\omega)] \nabla(E^2)$$

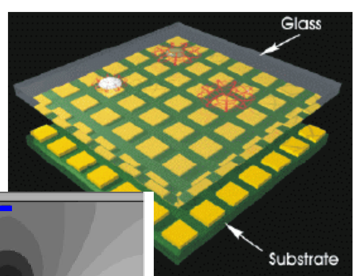
$$K^*(\omega) = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}, \quad \varepsilon^* = \varepsilon + \frac{\sigma}{j\omega}$$

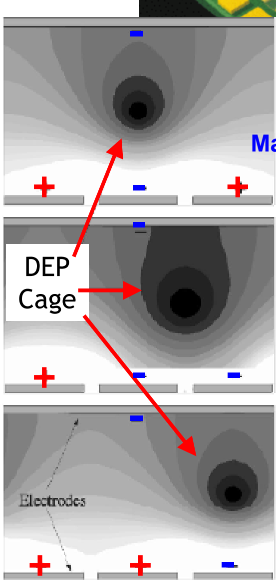
ε_p^* : Dielectric Constant of Particles

ε_m^* : Dielectric Constant of Media

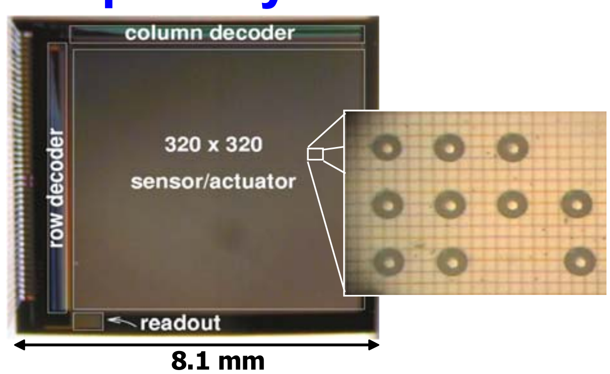
- **Unlike optical gradient force, DEP can be positive or negative**
  - **Positive DEP: particle attracted to field maximum**
  - **Negative DEP: particle attracted to field minimum**
- **Polarity depends on the dielectric function and bias frequency**

2-D DEP Trap Array





Manaresi, *ISSCC*, 2003



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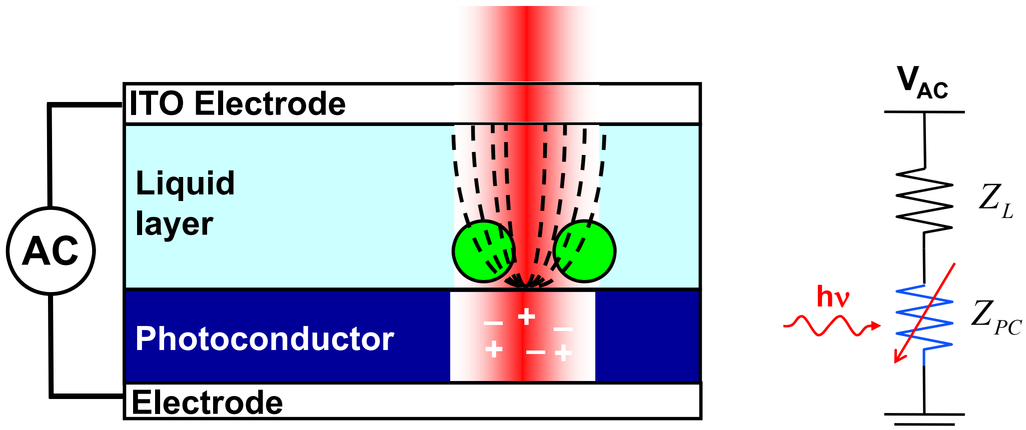
- **Programmable DEP cage on CMOS array**
  - **Massively parallel individual-cell operation**
  - **Programmable**
  - **Embedded sensors**
  - **Channel-less**
  - **Contactless movement**
  - **Pitch (~ 20μm) limited by circuit area**
  - **Expensive**

http://www.siliconbiosystems.com/technology/index.htm

Optoelectronic Tweezers Principle

- **Based on light-induced dielectrophoresis (DEP)**
- **Illumination creates virtual electrodes**



$$Z_L > Z_{PC}$$

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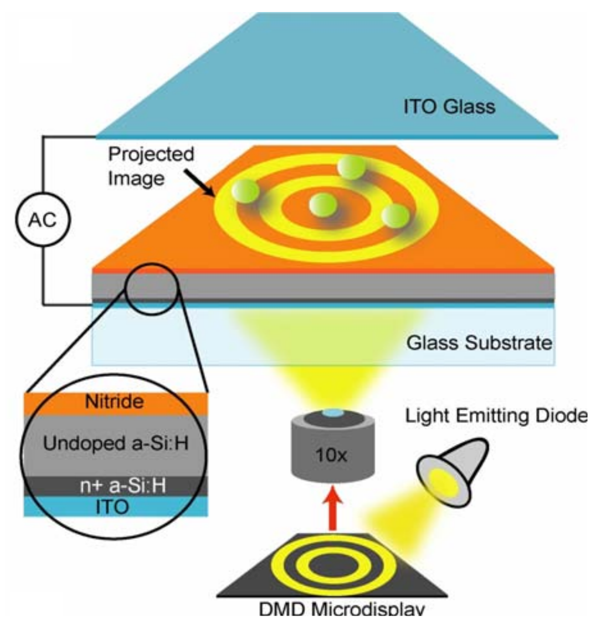
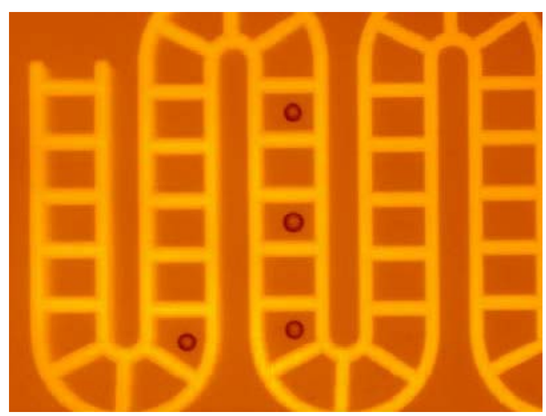
Optoelectronic Tweezers



P.Y. Chiou, A.T. Ohta, M.C. Wu, *Nature,* 2005

Optical Conveyor Belt



- **Programmable: Trapping and manipulation using a digital projector**
- **10,000x lower power than conventional optical tweezers**
- **Massively parallel: 30,000 individually controlled traps**

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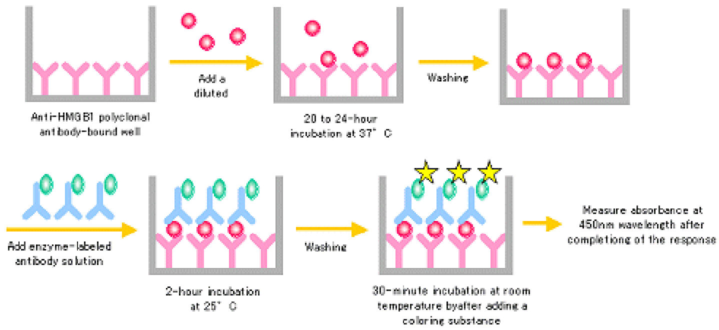
Nanophotnics and Bioanalysis systems

- High-Q microresonators
- Photonic crystals
- Plasmonics
- Optical antennas
- Resonance-enhanced biochemical sensors
- Surface Plasmon resonance (SPR)
- Surface-enhanced Raman spectroscopy (SERS)

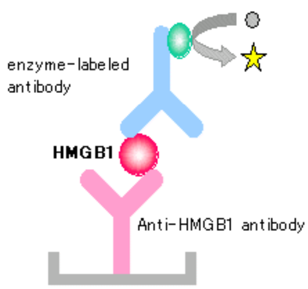
Optical Biosensors

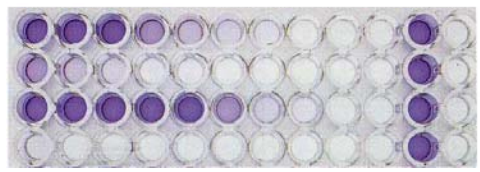
- Fluorescence-based detection
  - Target molecules are labeled with fluorescent tags (e.g., dyes)
  - "Label" behaves as "amplifier" for weak signal
  - Labeling increase time and cost of detection
- Examples
  - ELISA
  - Microarray
- Label-free detection
  - Target molecules are detected in their natural forms without labeling or altering
  - Faster assay development times; accurate,
  - Less interference from labels
- Examples
  - Surface plasmon resonance (SPR)
  - Whispering gallery mode (WGM)

ELISA
(Enzyme-Linked ImmunoSorbent Assay)

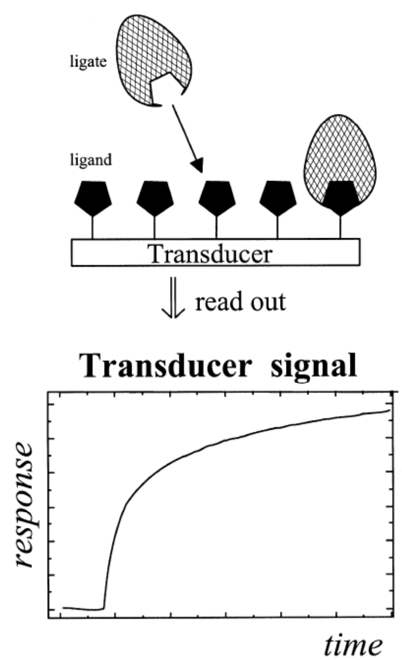


- Measure antigen-antibody binding
- Detect antibody
  - anti-HIV
- Detect antigen
  - hormones, enzymes, microbial antigens, illicit drugs



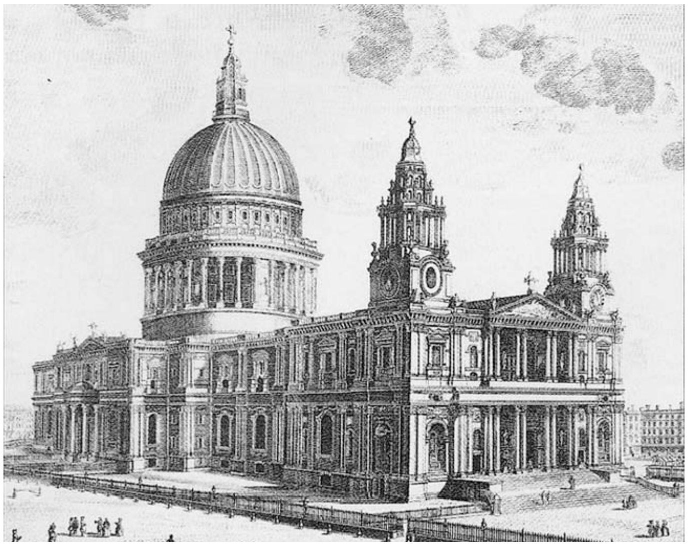


Label-free Detection Of Biomolecular Interaction

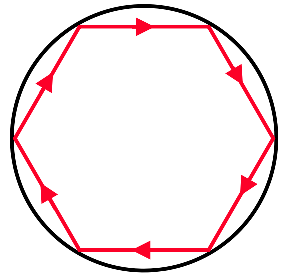


H. M. Haake, A. Schütz, and G. Gauglitz, "Label-free detection of biomolecular interaction by optical sensors," *Fresenius'Journal of Analytical Chemistry, vol. 366, pp. 576-585, 2000*

Whispering Gallery Mode (WGM)

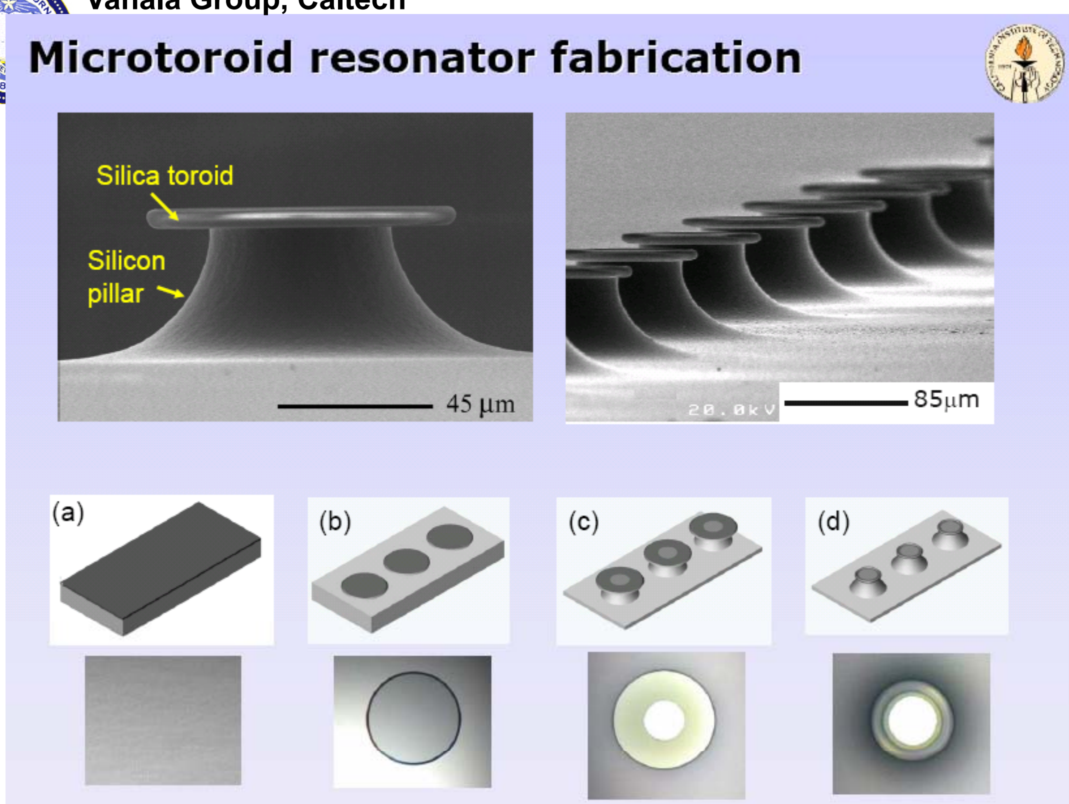


St Paul's Cathedral, London



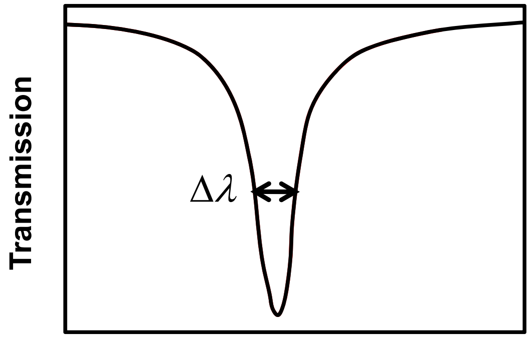
- WGM first explained by Lord Rayleigh in 1910
- Used in
  - Acoustic waves
  - Microwaves
  - Optical waves

Vahala Group, Caltech



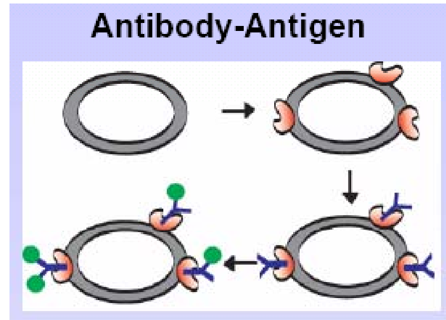
http://www.its.caltech.edu/~vahalagr/BPS2007Armani.pdf

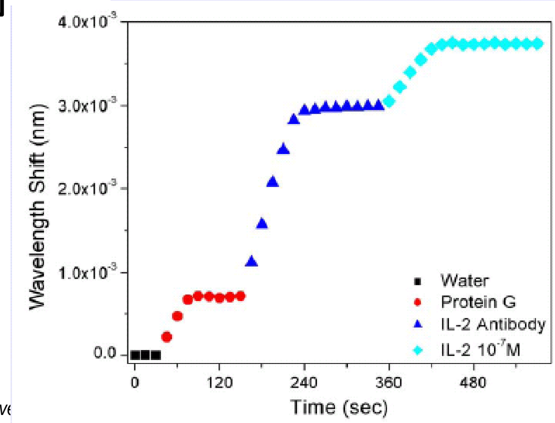
High-Q Microresonator for Biosensing



$$Q = \frac{\lambda}{\Delta\lambda}$$

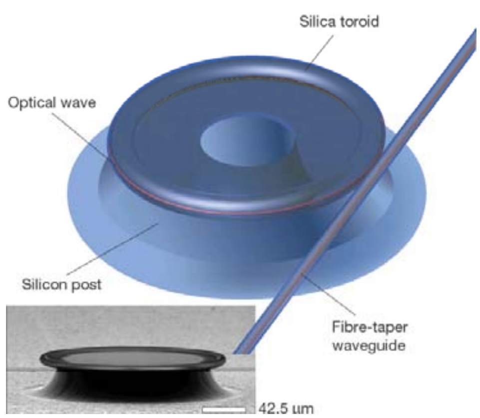
High Q → High Sensitivity

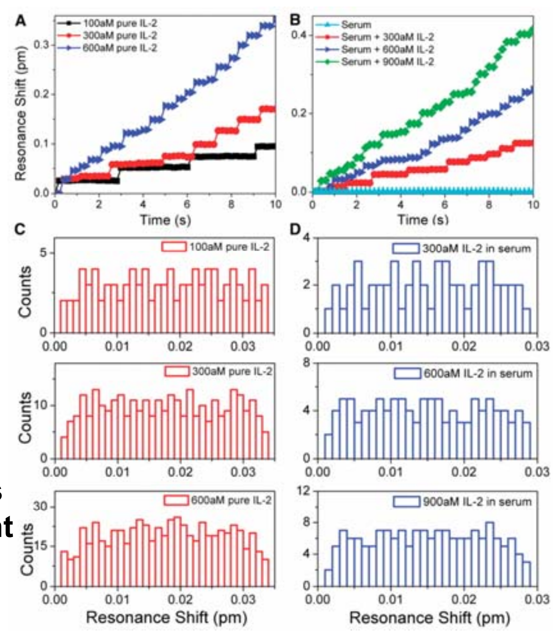




http://www.its.caltech.edu/~vahalagr/BPS2007Armani.pdf

Single Molecule Detection with WGM



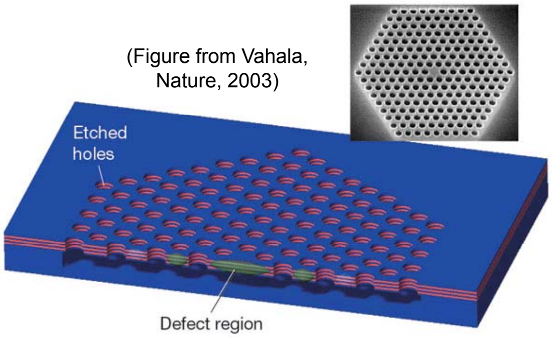


- **Label free**
- **Functionalized to bind target molecules**
- **Observed single molecule binding event that shifts resonance frequency**
- **High sensitivity due to high quality factor (Q > 10^8)**

A. M. Armani, R. P. Kulkarni, S. E. Fraser, R. C. Flagan, and K. J. Vahala, "Label-Free, Single-Molecule Detection with Optical Microcavities," *Science, vol. 317, pp. 783-787, August 10, 2007*

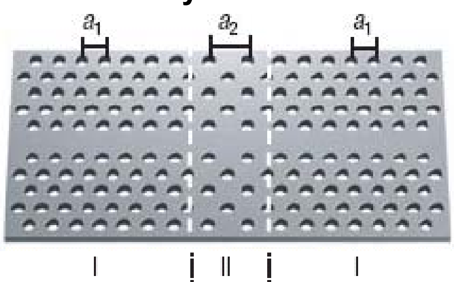
Photonic Crystals

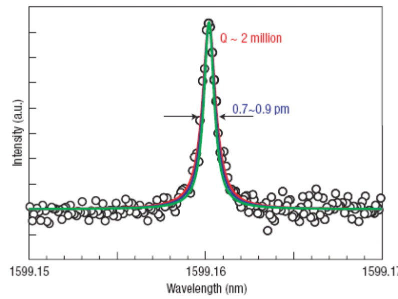
(Figure from Vahala, Nature, 2003)



- "Semiconductor of light"
- Tight optical confinement
  - Wavelength-scale optical cavity
- High Q ~ 10^6 and large Q/V ratio

Photonic Crystal Heterostructure

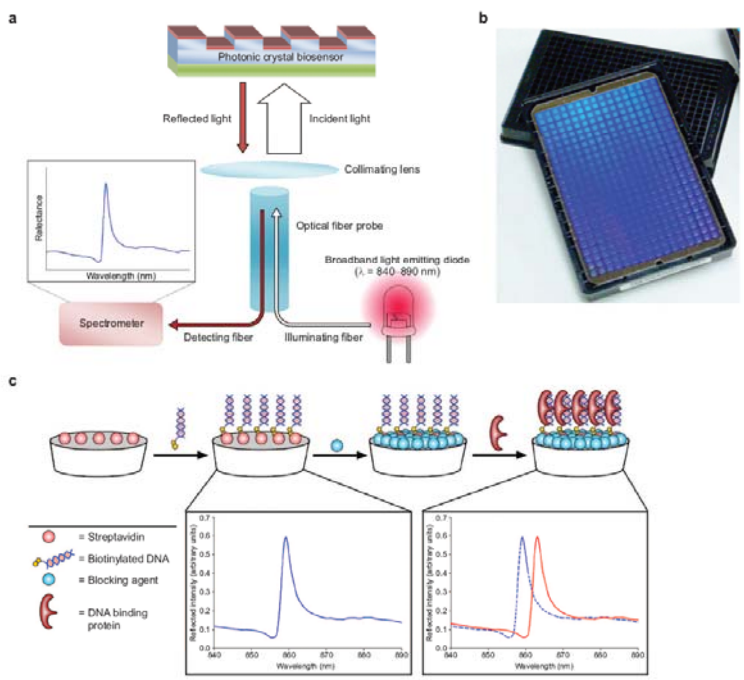




Noda, et al., Nature 2007

BSAC

Photonic Crystal Biosensor for Protein-DNA Interaction



L. L. Chan, M. Pineda, J. T. Heeres, P. J. Hergenrother, and B. T. Cunningham, "A General Method for Discovering Inhibitors of Protein- DNA Interactions Using Photonic Crystal Biosensors," *ACS Chemical Biology, vol. 3, p. 437, 2008*

Summary

- **Optofluidics is a powerful platform for biosensing**
  - High-Q microresonator, photonic crystals as label-free biosensor
  - Single molecule sensitivity demonstrated
  - Plasmonics, SERS, LSPR, optical antenna
- **Integrated platform**
  - Both microfluidics and optics can be integrated on a chip
  - "All-optical" lab-on-a-chip
- **Consumer market (display, zoom lens, etc) can accelerate the technology development**

Thank You !