Last Week's Lab

Printing chemical indicators with an inkjet printer…

Photographs of copper electrodes, organic transistors, and polymer LED displays removed due to copyright restrictions.

PLED Display from Philips Research, 2004

Copper electrodes → Circuits ← Organic transistors

J.S. Kang et al, J Mater Sci: Mater Electron, vol 21 (2010)

S. Chung et al, Jpn. J. Appl. Phys., vol. 50 (2011)

Polymer LEDs → Displays

B. –J. de Gans et al, Adv. Mat., vol. 16 (2004)

… a wide range of other functional materials can be printed as well!

Nanomaker

Lab #6: PDMS/Glass Microfluidics

Optical micrograph of the microfluidic comparator chip removed due to copyright restrictions.

Refer to: Fig. 3A in Thorsen, T., S. J. Maerkl, et al. "Microfluidic Large-Scale Integration." *Science* 298, no. 5593 (2002): 580–84.

Published by AAAS

T Thorsen et al. Science 2002;298:580-584

Polydimethylsiloxane (PDMS)

PDMS Microfluidics

Navier-Stokes' Equation

Polydimethylsiloxane (PDMS)

Photo of silly putty removed due to copyright restrictions.

Photo courtesy of Achim Hering on Wikimedia Commons.

This image is in the public domain.

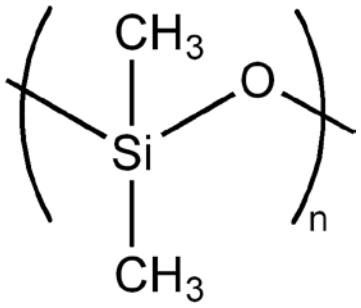
Photo courtesy of oskay on Flickr.

Silly Putty

Silicone sealant

Defoaming agent for foods

Transparent encapsulant for LEDs



- **Strong, flexible** Si-O-Si backbone
- Low intermolecular force between CH_3 groups – **low surface tension**, allowing it to fit into small gaps

Nanoreplication Using PDMS

Process diagram of "Microcontact Printing" removed due to copyright restrictions.
Refer to article, page 42.

The PDMS precursor (Sylgard 184 and curing agent) can be poured over a pattern, left to solidify, and peeled off as a negative copy of the pattern.

Images from: G. Whitesides and J. Christopher Love, *Scientific American sp* **17**, 12 - 21 (2007)

Nanoprinting Using PDMS

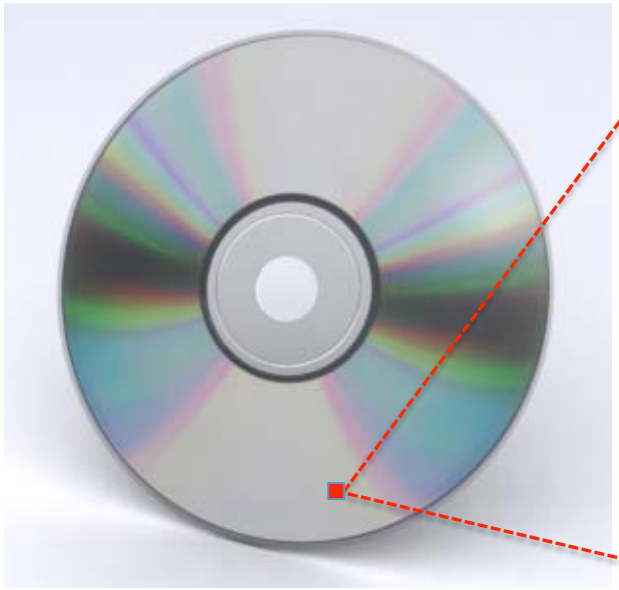
Process diagram of "Making an Electric Stamp" removed due to copyright restrictions.
Refer to article, page 42.

The PDMS negative can also be inked, just like a rubber stamp, and pressed against another surface to print the pattern.

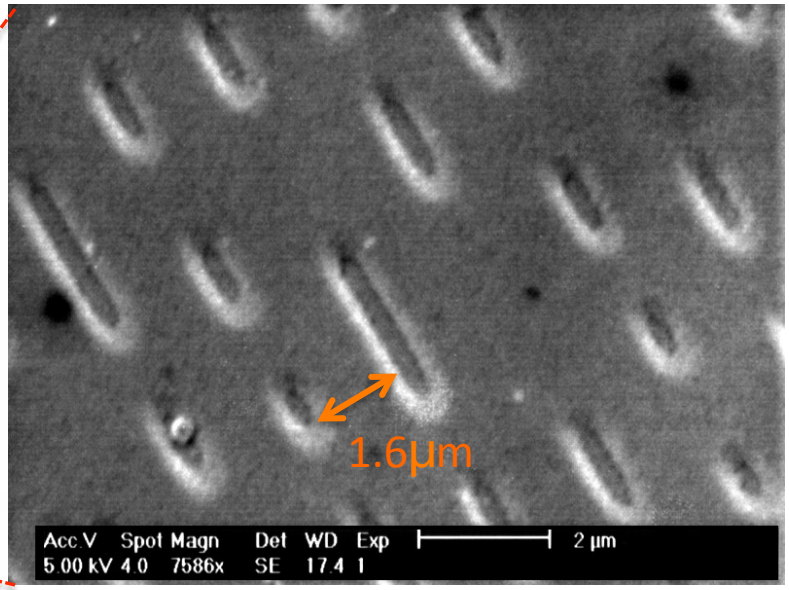
Images from: G. Whitesides and J. Christopher Love, *Scientific American sp* **17**, 12 - 21 (2007)

PDMS Stamping Example: Compact Disk

CD-R



SEM (7500x magnification)



- A CD is made up of a spiral track that is 1.6µm wide (total write area = 0.0025m^2)
- Total length of track is 1.54km (0.96 miles)
- Optical diffraction from the tightly-spaced adjacent tracks in the spiral are what produce the lovely rainbow pattern.

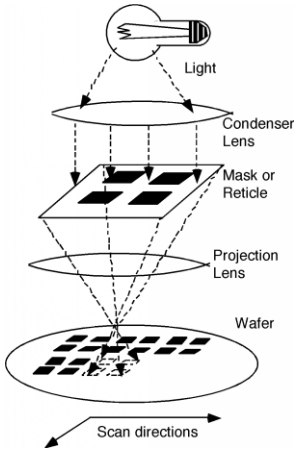
- The PDMS precursor can easily conform to the surface to replicate the pits of the CD, and cure to form a rubber stamp.
- Diffraction from the stamp is easy to observe, and can be distorted by stretching the PDMS

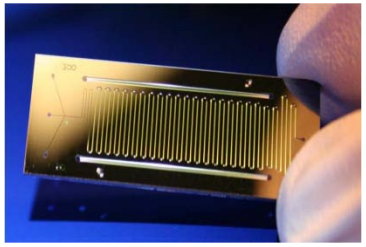
Polydimethylsiloxane (PDMS)

PDMS Microfluidics

Navier-Stokes' Equation

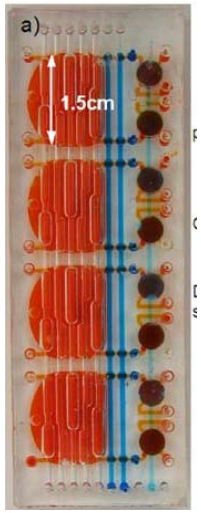
Varieties of Microfluidics



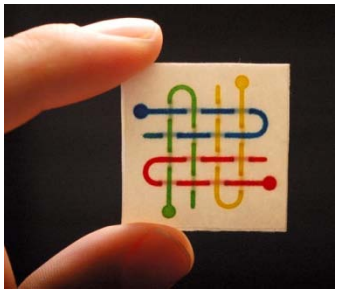


Glass or Silicon microfluidics, patterned using photolithography

Inkjet printed microfluidics in Shrinky Dinks (polystyrene) and Silicone rubber



Milled microfluidics in Polycarbonate

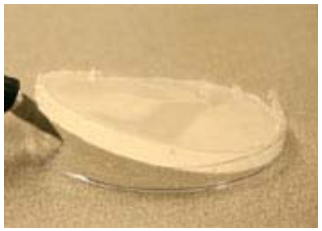


Printed wax microfluidics on filter paper

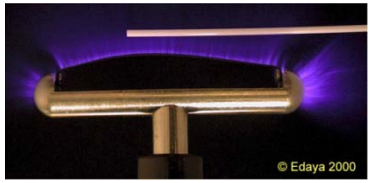
Fabrication Process

Design

Print wax microfluidic channels on ***transparency***

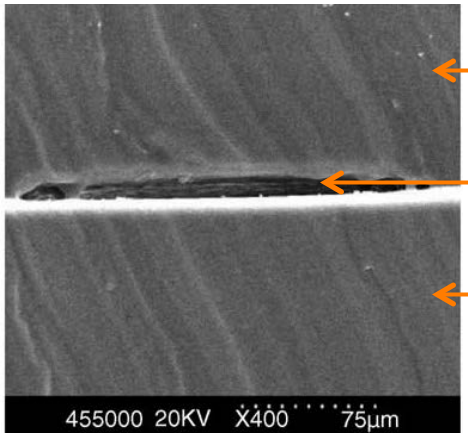


Pour PDMS precursor onto transparency, allow to cure



Courtesy of Edaya. Used with permission.

Corona treat PDMS and bond to glass slide



PDMS

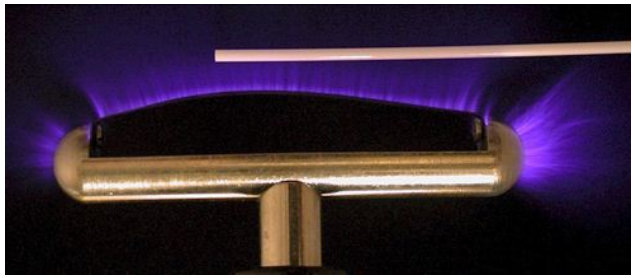
Microfluidic channel

PDMS (replaced by glass slide in our process)

Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

N. Bao et al, J of Chromatography A, vol 1089 (2005)

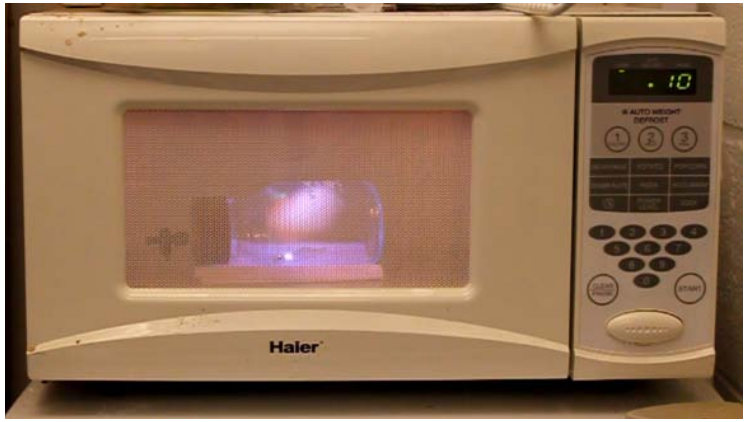
Corona Treatment



Courtesy of Edaya. Used with permission.

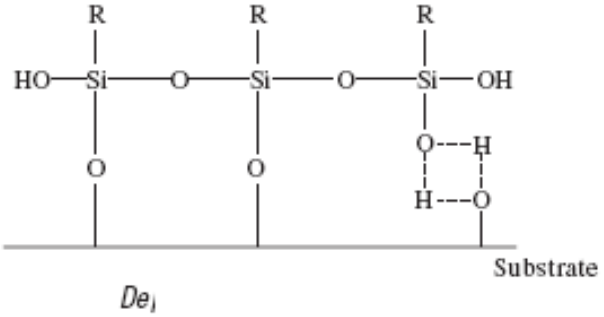
Corona: High voltage generates ionized gas, ozone (O_3), and UV light

OR



A plasma can also be generated in a microwave oven

Surface modification and bonding



<u>Corona turns the surface of PDMS into glass</u>

-Methyl groups get knocked off via energy from UV, ion bombardment…

-OH groups attach to the Si-O backbone to form silanol groups (SiOH), the same as the surface of glass (and hydrophilic like glass)

-PDMS is now brought into contact with glass, and water is released as the two bond together

Polydimethylsiloxane (PDMS)

PDMS Microfluidics

Navier-Stokes' Equation

Navier-Stokes' Equation

The Navier-Stokes' equation for <u>incompressible flow</u>:

constant density everywhere

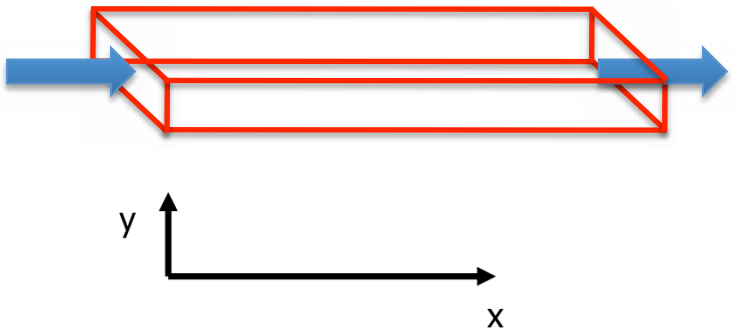
$$\rho \frac{dU}{dt} = \eta \nabla^2 U - \nabla P$$

U = velocity
P = pressure
t = time
ρ = fluid density (10^3 kg/m^3 for water)
η = Viscosity (10^{-3} Pa-s for water)

Simplify Our Problem

- No time dependence
- Flow is constant in x-direction and zero in z-direction
- Pressure is only a function of x

$$\rho \frac{dU}{dt} = \eta \nabla^2 U - \nabla P$$

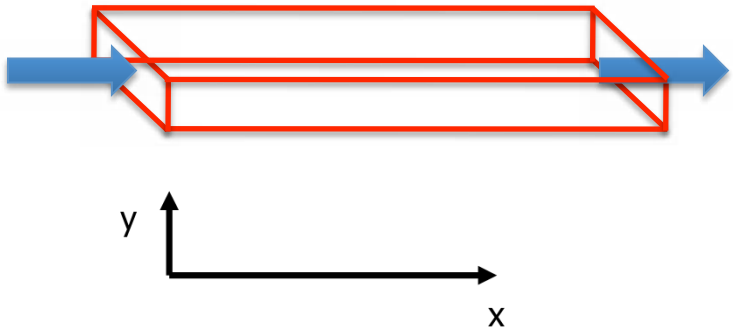


$$\frac{\partial^2 U_x}{\partial y^2} = \frac{K}{\eta} \qquad \frac{dP}{dx} = K$$

Poiseuille Flow

- Assume width >> height
- Neglect entrance effect
- No slip boundary condition!

zero velocity relative to the boundary



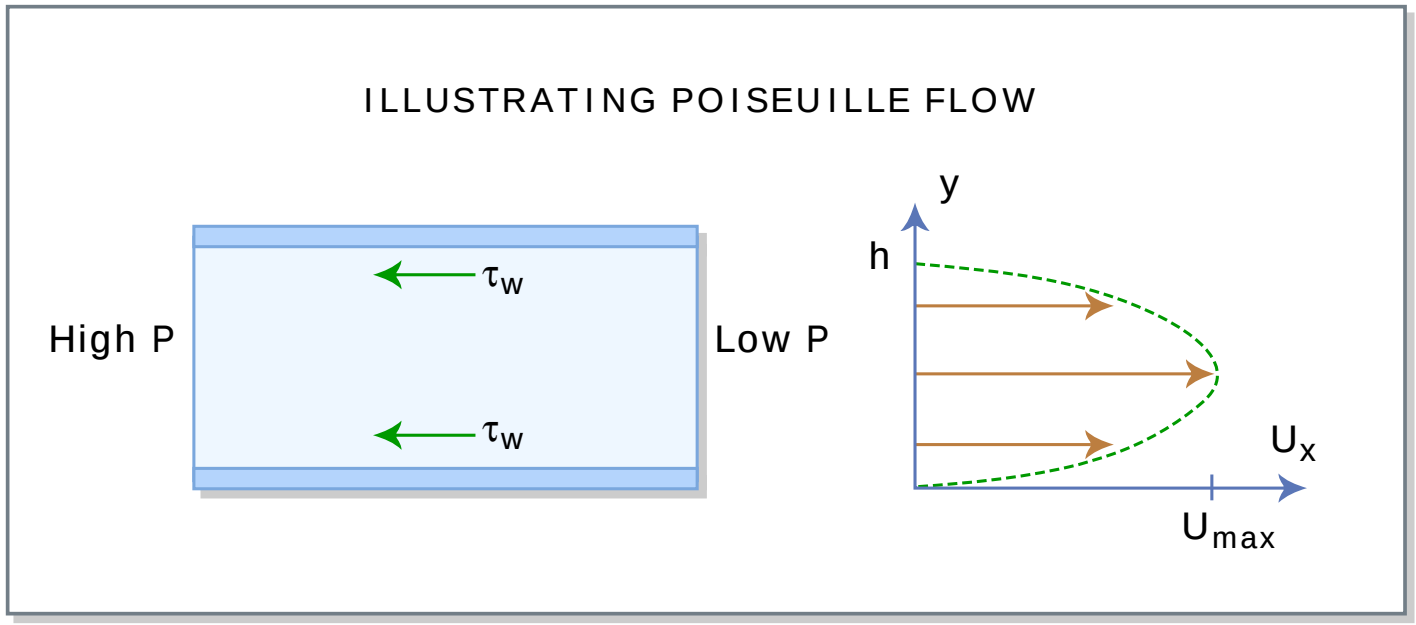


Figure by MIT OCW.

Solution

- Parabolic profile: $U_x = \frac{1}{2}[y(h \quad y)]K$
- Maximum velocity: $U_{max} = \frac{h^2}{8}K$
- Average velocity: $U_{ave} = \frac{2}{3}U_{max}$
- Flow rate: $Q = \frac{Wh^3}{12}K$

$$\frac{dP}{dx} = K$$

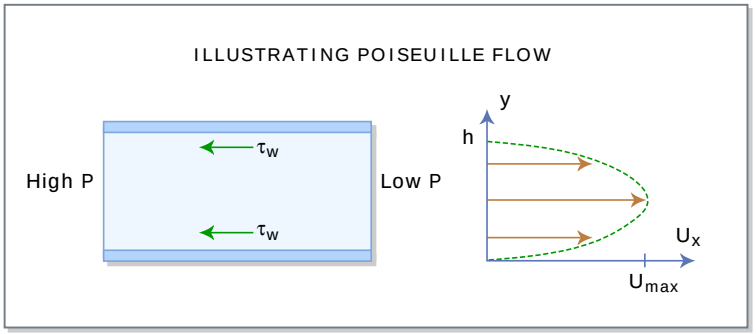
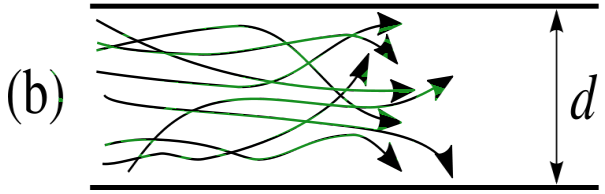


Figure by MIT OCW.

Laminar vs Turbulent Flow

Reynold's number <2300

- **Smallest Fish ~ 1**
- **Blood flow in brain ~ 100**
- **Blood flow in aorta ~ 1000**



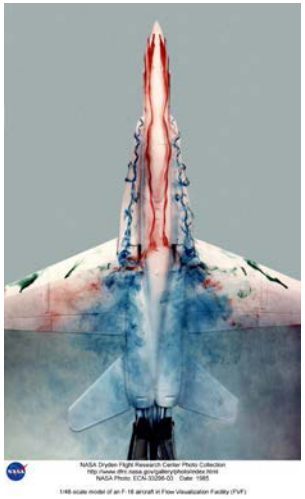
Reynold's number >4000

- **Typical pitch in MLB~ 2×10^5**
- **Person swimming ~ 4×10^6**
- **Blue Whale ~ 3×10^8**
- **A large ship ~ 5×10^9**

Reynold's number = inertia force/ viscous force

$$Re = \frac{\rho V L}{\mu}$$

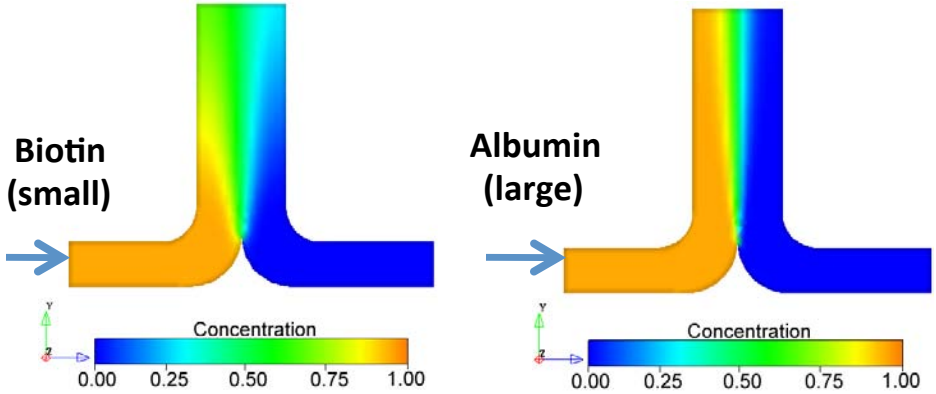
ρ: density
V: mean velocity
L: characteristic linear dimension
μ: viscosity



For small channels and flows, viscous forces dominate and flow is laminar.

Applications of Laminar Flow

Separation using Diffusion

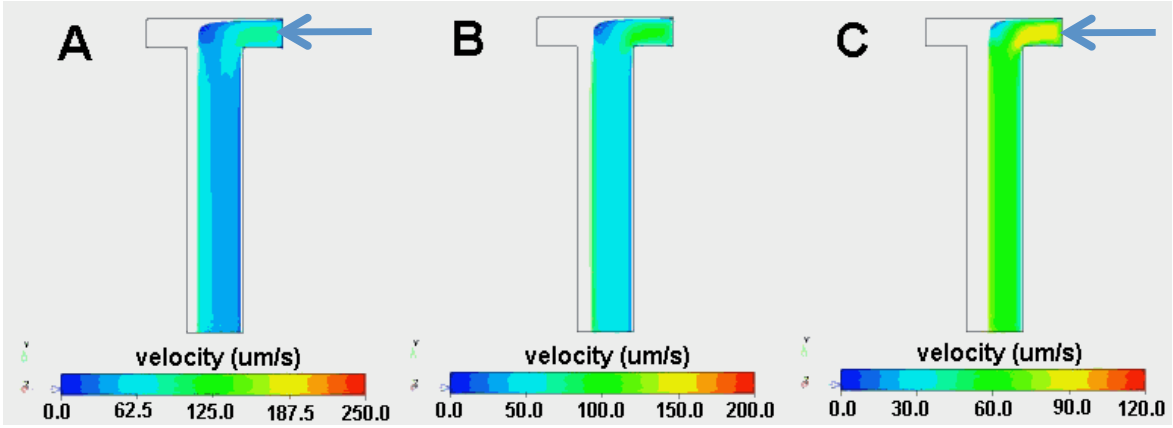


$$Re = \frac{\rho V L}{\mu}$$

Viscosity and Channel Width

High viscosity

Low viscosity



Yager Group, University of Washington

6.S079 Nanomaker

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