Lec 3. Flow control

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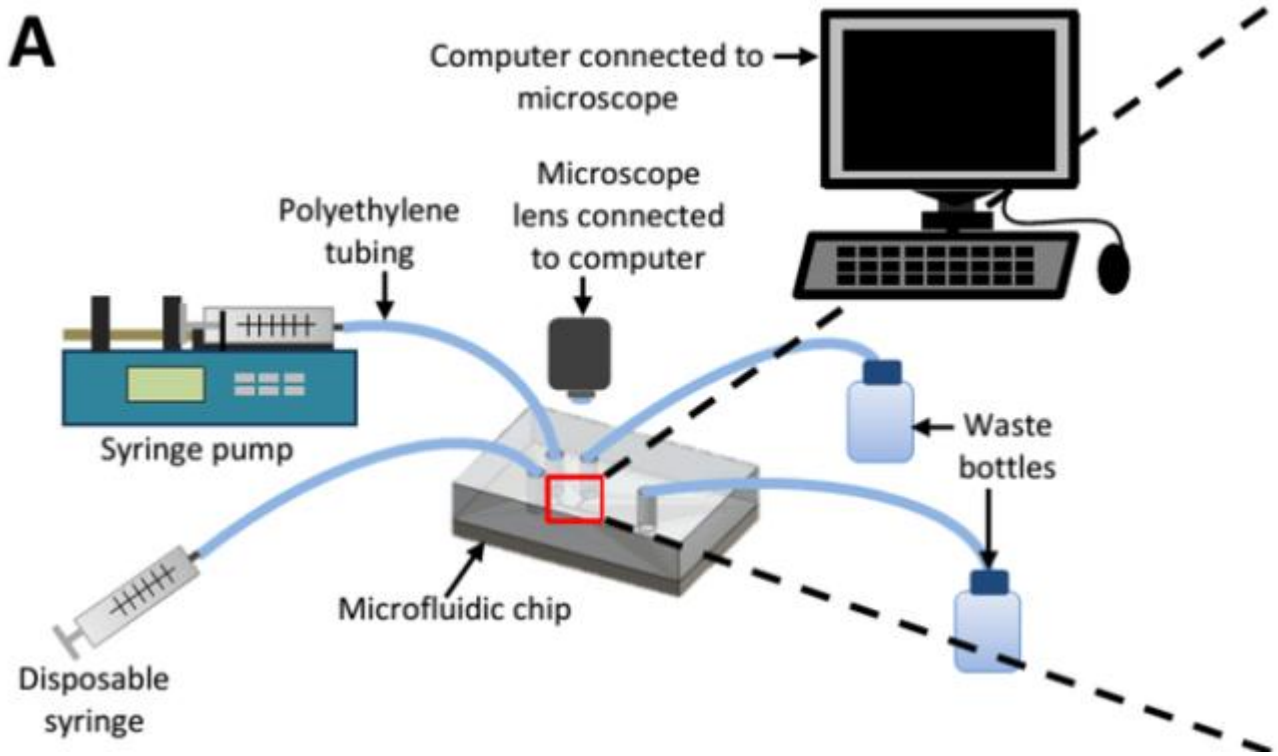
Lecture overview

1. External control
    1. Syringe pump
    2. Pressure pump
2. Internal control
    1. Pneumatic valves
    2. Check valves (check valve pump)
    3. Surface acoustic waves
    4. Dieletrophoresis
    5. Electrowetting on dieletric
    6. Opto-Electrical Positioning (OEP)

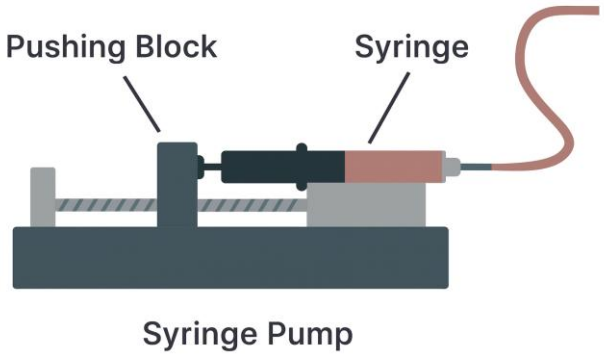
Experimental setup



Syringe pump

- **Principle**
- A syringe pump uses a motor-driven plunger to precisely displace liquid from a syringe.
- Flow rate is controlled by the motor speed, and volume is determined by syringe size and plunger movement.

How is flow rate determined



$$Q = \pi r^2 s f$$

$$f_{\text{pulse}} = \frac{4Q}{\pi D^2 s}$$

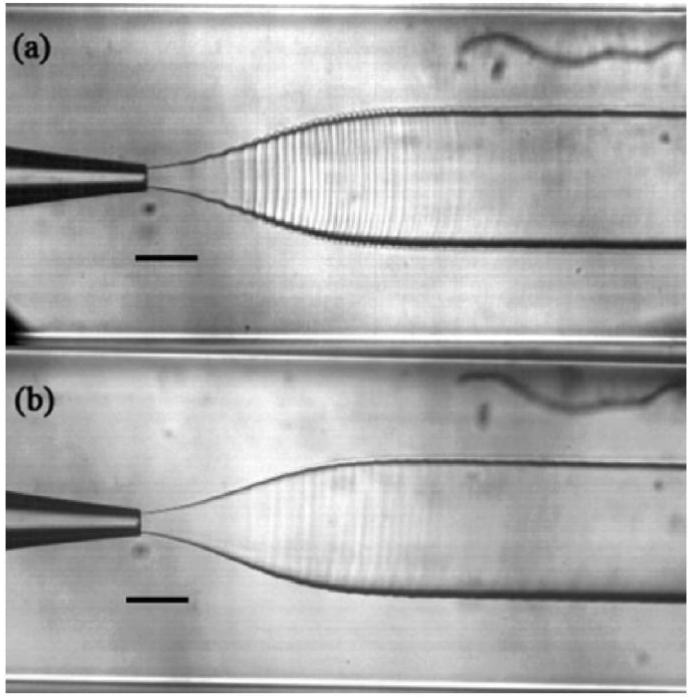


Fig. 1 Optical microscope image of an inner jet surrounded by a continuous phase. The inner phase is a 15 wt% tripotassium phosphate (K_3PO_4) solution, and the outer phase is a 17 wt% polyethylene glycol (PEG, MW = 8000) solution. (a)The fluids are driven by syringe pumps (LSP01-2A), and the flow rates of the inner and outer phases are Q_{in} = 4 mL h^{-1} and Q_{out} = 7 mL h^{-1}, respectively. (b) The fluids are driven by pressure-driven pumps. The estimated flow rates are Q_{in} = 3.6 mL h^{-1} and Q_{out} = 4.9 mL h^{-1}. Scale bars are 200 μm.

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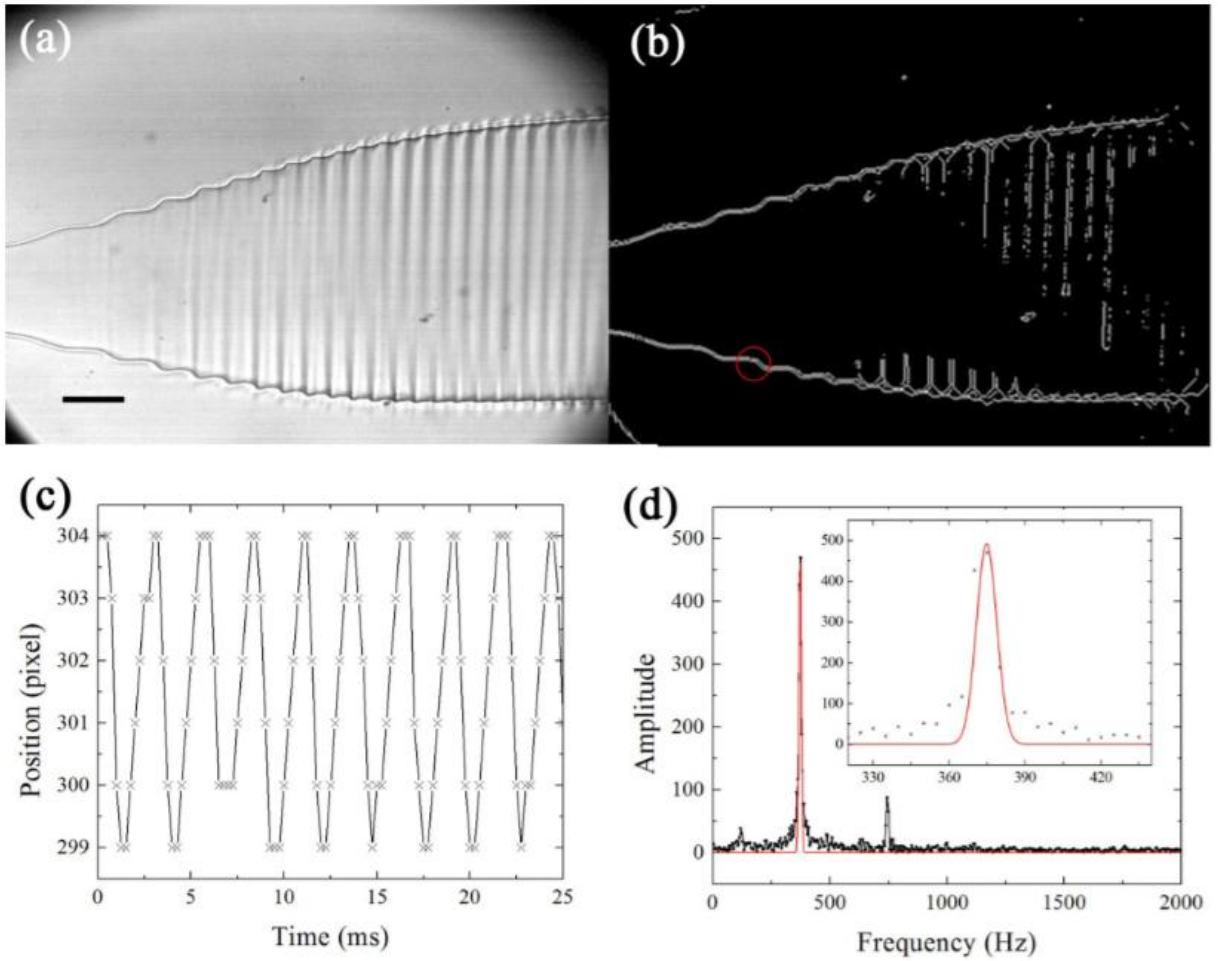

(a)
(b)
(c)
Position (pixel)
304
303
302
301
300
299
0
5
10
15
20
25
Time (ms)
(d)
Amplitude
500
400
300
200
100
0
0
500
1000
1500
2000
Frequency (Hz)
330
360
390
420

Advantages

- Very **accurate and stable** flow rates (typically in the nL/min to mL/min range).
- Well-suited for experiments requiring **precise dosing**, such as single-cell studies or chemical gradients.
- Easy to program for **continuous or pulsed** flow delivery.

Limitations

- **Discrete volume**: limited to the syringe capacity, requiring refills for long experiments.
- **Dead volume** and tubing length can introduce delays.
- Flow can be slightly pulsatile depending on mechanics.

Applications in Microfluidics

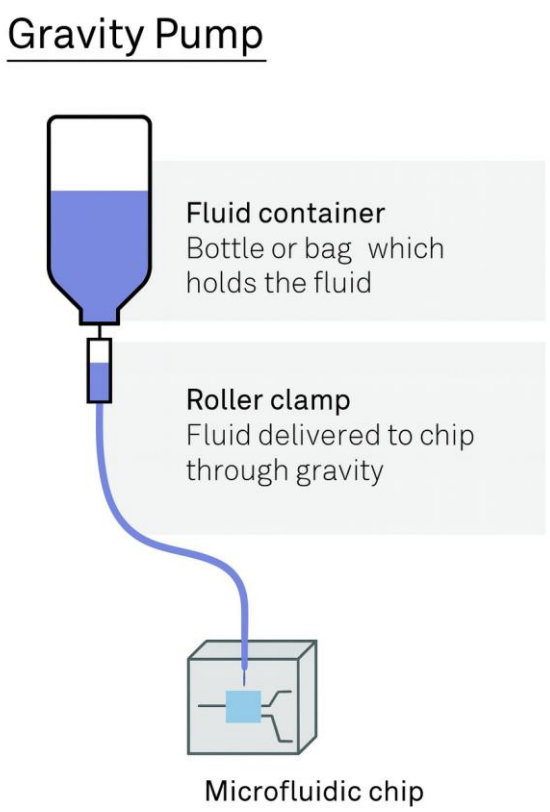
- Controlled reagent injection in **lab-on-chip systems**.
- Drug delivery studies with precise dosing.
- Creating chemical gradients for biological assays.

Pressure pump

Principle

- Pressure pumps regulate flow by applying controlled **air pressure** to a fluid reservoir, pushing liquid into microchannels.
- Flow rate depends on applied pressure and channel resistance (Poiseuille's law).

Simplest pressure pump



Gauge pressure at the chip inlet

If the fluid surface in the reservoir is Δh above the chip inlet,

$$P_{\text{in}} = \rho\, g\, \Delta h$$

- ρ = fluid density (kg·m⁻³)
- $g \approx 9.81\ \text{m}\backslash\text{cdotps}^{-2}$
- Δh = vertical height difference between the *free surface* and the chip inlet (m)

This is **gauge** pressure (relative to atmosphere). Absolute pressure is $P_{\text{abs}} = P_{\text{atm}} + P_{\text{in}}$.

Handy conversions (water, 20 °C):

- 1 cm height → $\approx 98\ \text{Pa} = 0.98\ \text{mbar}$
- 1 m height → $9.81\ \text{kPa} \approx 98.1\ \text{mbar} \approx 1.42\ \text{psi}$

Example: Δh = 0.50 m with water →

$P_{\text{in}} = 1000 \times 9.81 \times 0.50 \approx 4.9\ \text{kPa} \approx 49\ \text{mbar} \approx 0.71\ \text{psi}.$

Flow rate from the pressure

Flow follows Poiseuille's law:

$$Q = \frac{\Delta P}{R_h}$$

where hydraulic resistance R_h depends on channel geometry and viscosity μ.

- **Circular tube (radius r, length L)**:

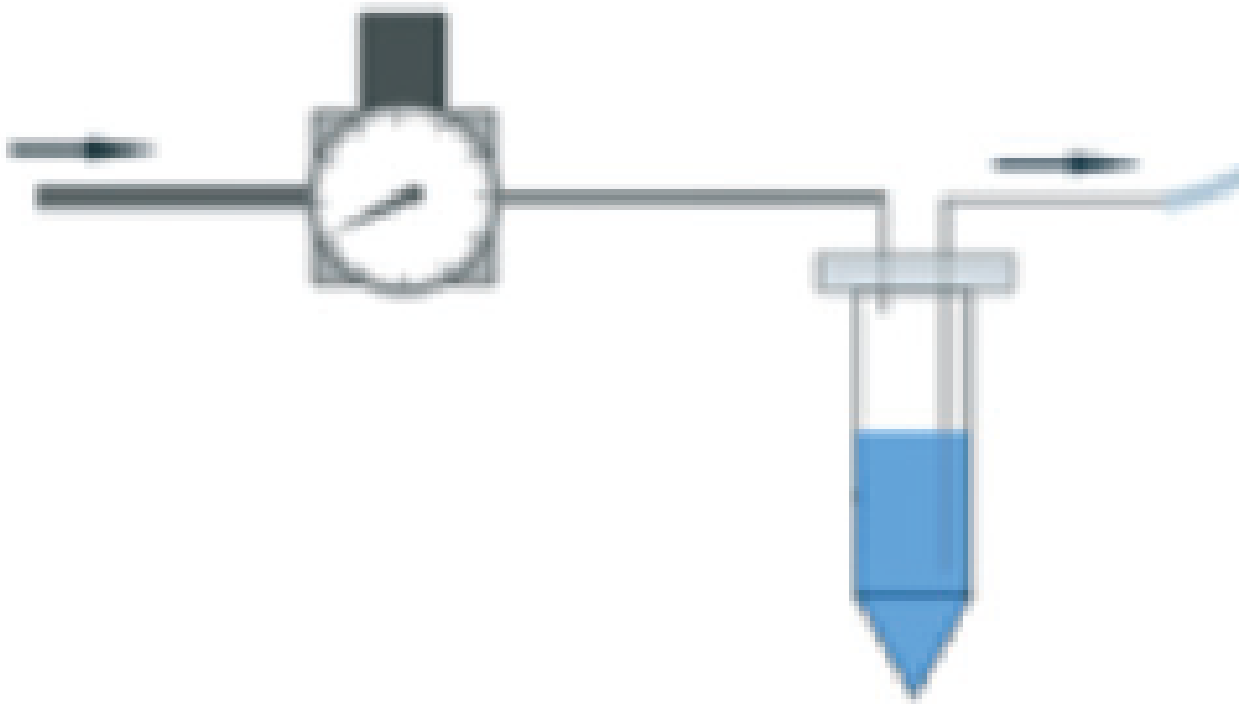
$$R_h = \frac{8\mu L}{\pi r^4}$$

- **Rectangular microchannel** ($w \geq h$):

$$R_h \approx \frac{12\mu L}{w\, h^3 \left[1 - 0.63(h/w)\right]}$$

Total R_h is the sum of resistances of tubing + chip + filters, etc.

Simplest pressure pump

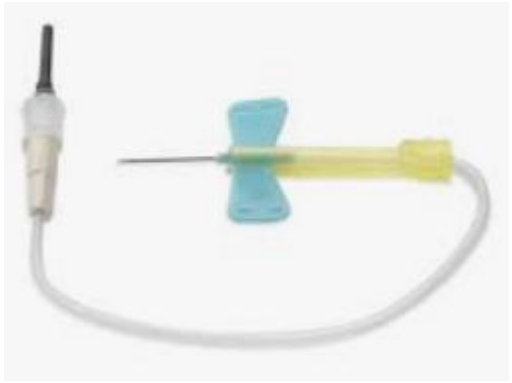


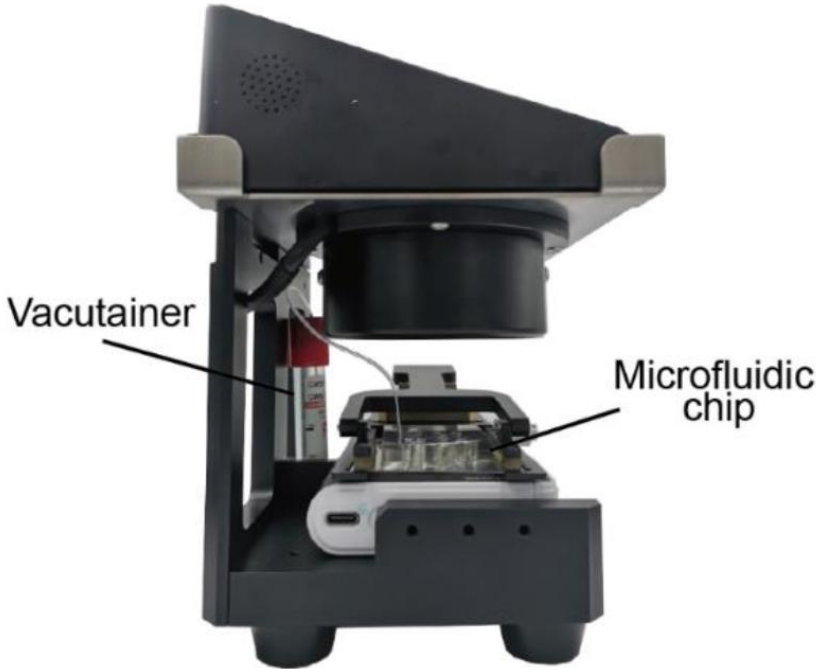
Simplest pressure pump

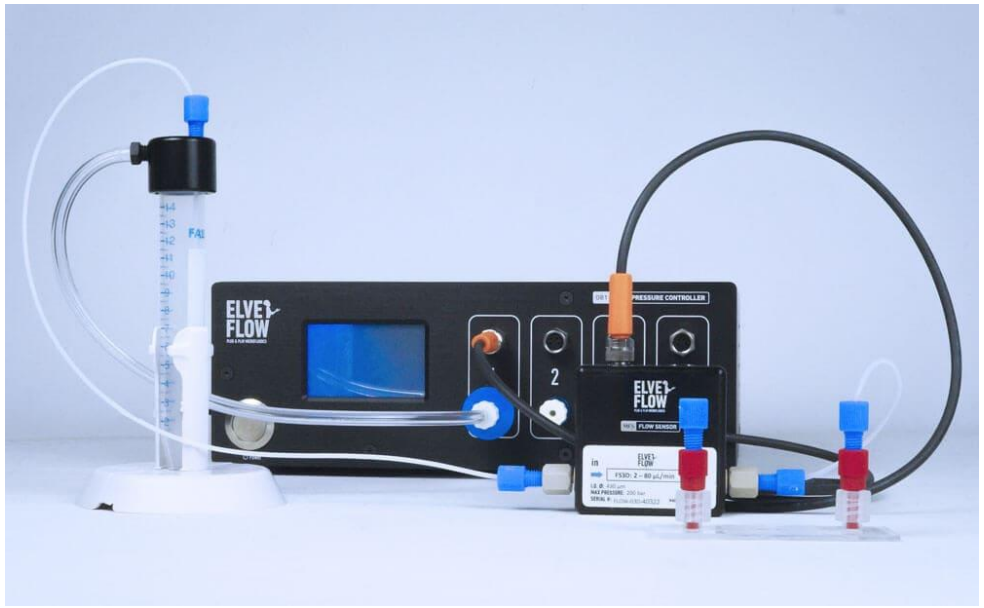
Microfluidic chip

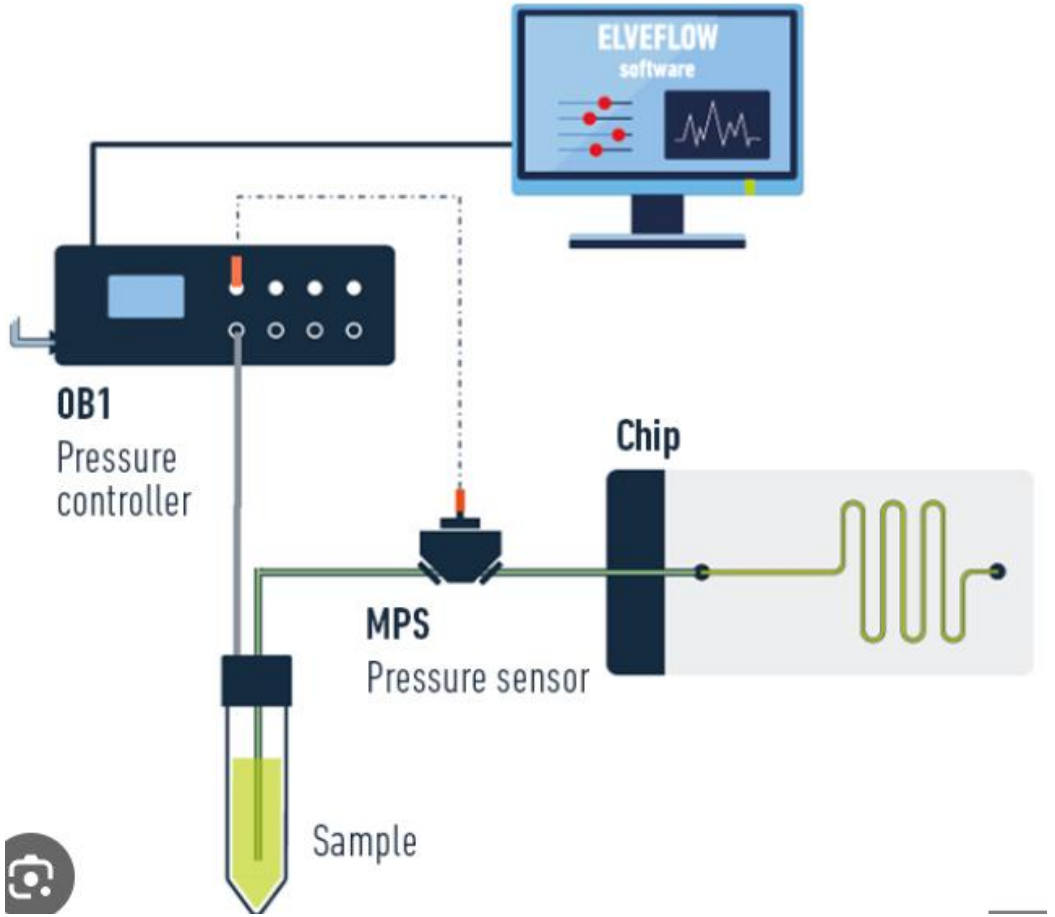
Syringe puller for negative pressure generation

Simplest pressure pump






ELVE1 FLOW
2


ELVEFLOW
software
OB1
Pressure
controller
Chip
MPS
Pressure sensor
Sample

Advantages

- Provides **continuous flow** (no syringe refill issue).
- Can deliver **multiple fluids** simultaneously using pressure controllers.
- Fast response time — suitable for applications needing rapid flow switching.

Limitations

- Requires a **compressed air source** and pressure regulators, making setup more complex.
- Flow rate is less direct — must be calibrated using channel geometry and fluid properties.
- More costly than syringe pumps.

Applications in Microfluidics

- Long-term experiments (cell culture, organ-on-chip) where continuous flow is needed.
- Multiplexed systems with multiple inlets.
- Applications where rapid fluid switching is required (e.g., chemical stimulation of cells).

Pneumatic valves

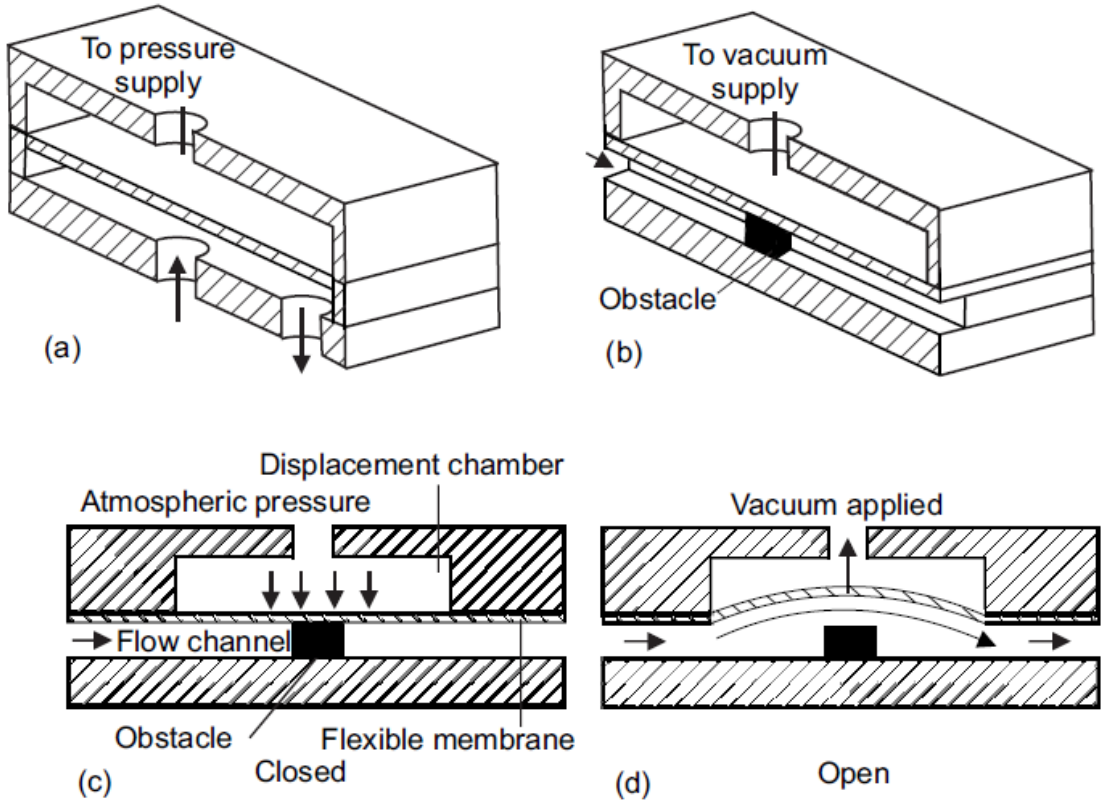


Figure 6.1 Two design examples of microvalves: (a) normally open valve (NO); (b) normally closed valve (NC); (c) side view of the normally closed valve once it is closed; and (d) side view of the normally closed valve once it is open.

Actuation principles

- Pneumatic microvalves;
- Thermopneumatic microvalves;
- Thermomechanical microvalves;
- Piezoelectric microvalves;
- Electrostatic microvalves;
- Electromagnetic microvalves;
- Electrochemical and chemical microvalves;
- Capillary force microvalves.

Pros and cons of different actuators

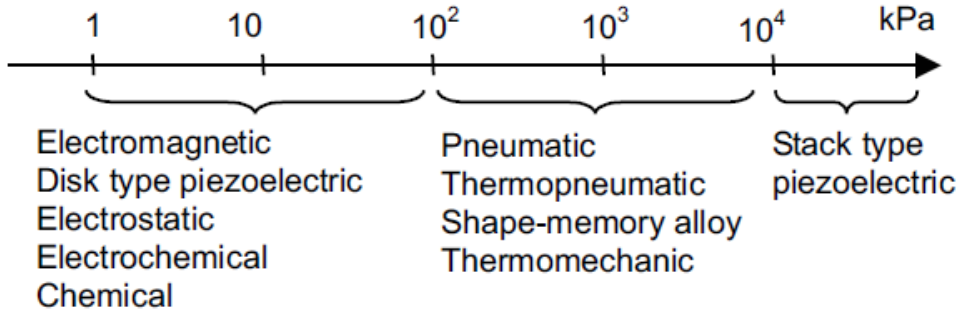


Figure 6.3 Pressure range of different actuators used in microvalves.

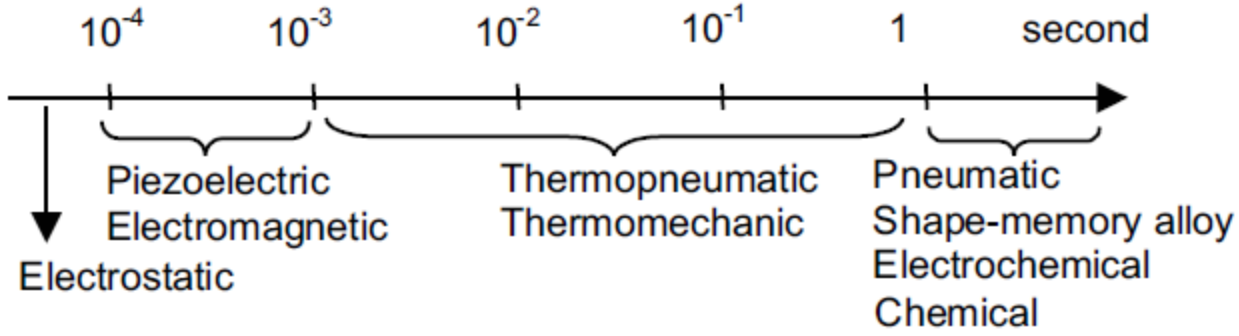


Figure 6.4 Time response range of different actuators used in microvalves.

Basic actuation concepts for an active microvalve

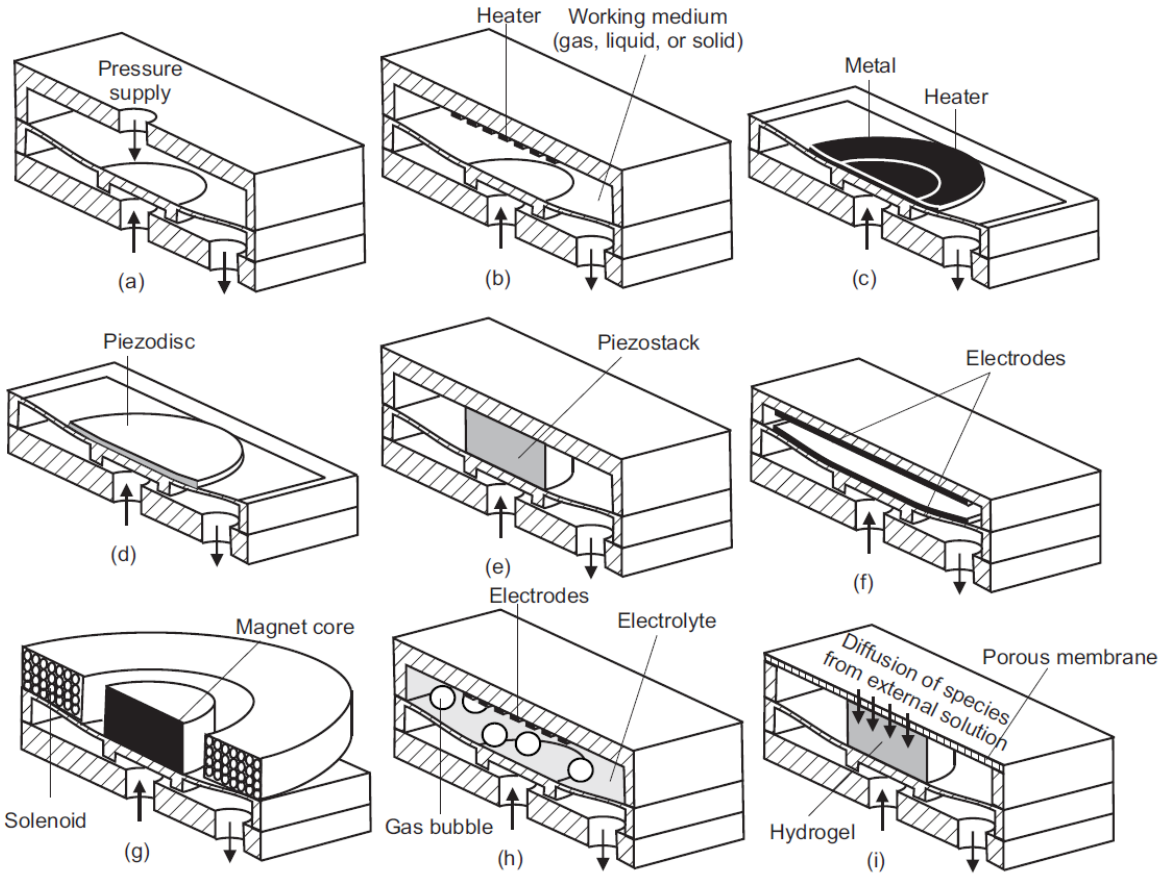
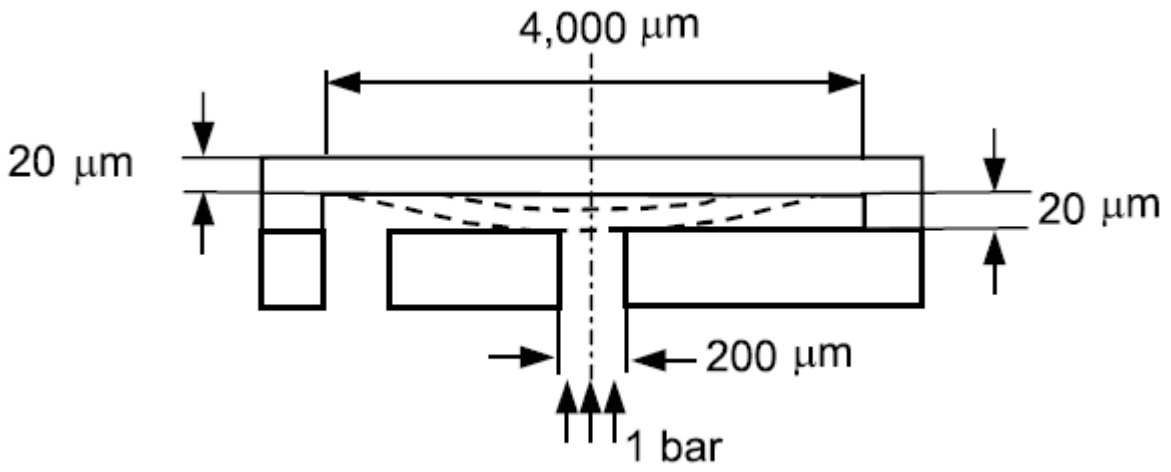


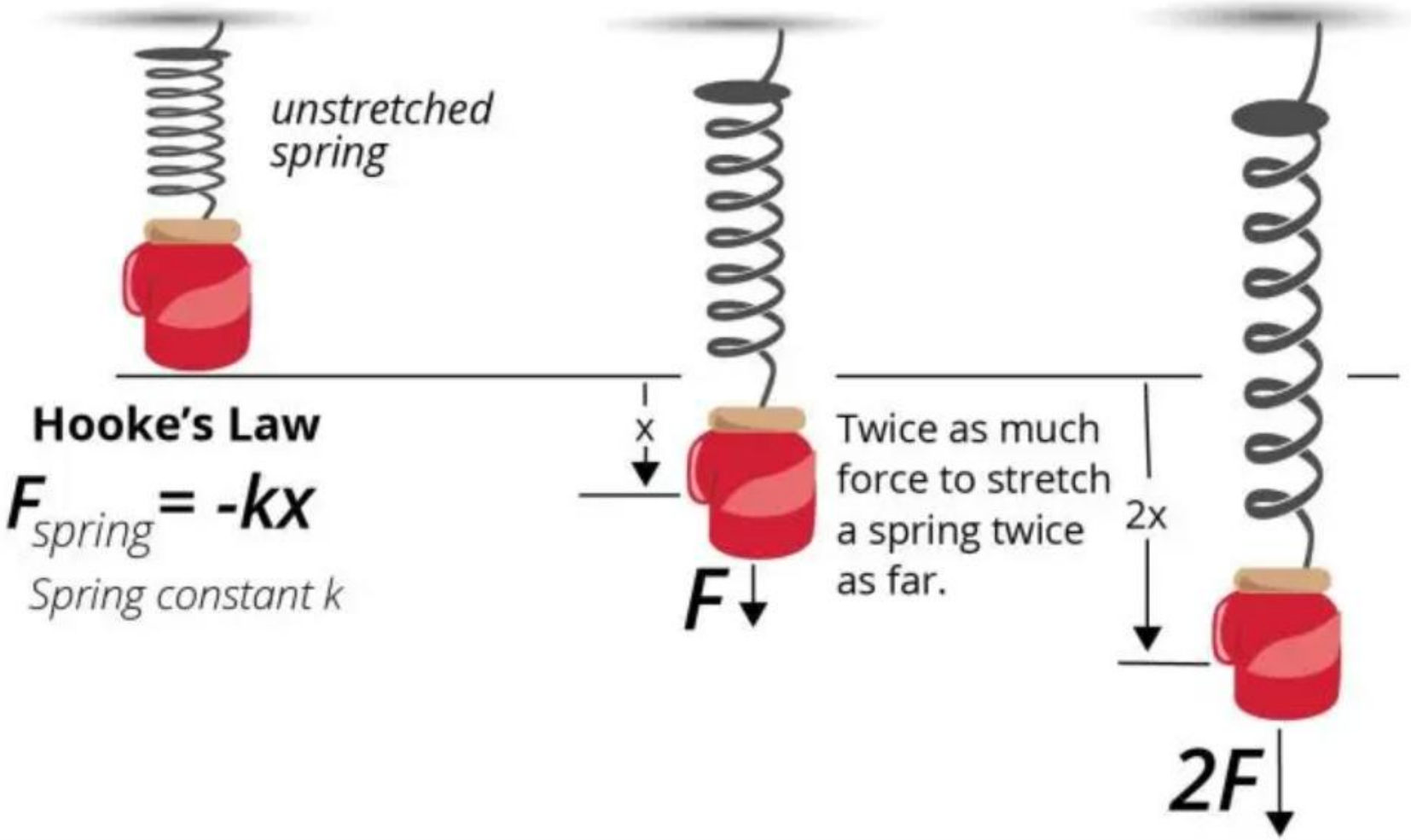
Figure 6.5 Basic actuation concepts for an active microvalve: (a) pneumatic; (b) thermopneumatic; (c) thermomechanic; (d) piezoelectric; (e) piezoelectric; (f) electrostatic; (g) electromagnetic; (h) electrochemical; and (i) chemical.

Example: Designing a Pneumatic Microvalve

A pneumatic microvalve has a circular silicon membrane as the valve seat. The membrane is 20 μm thick and has a diameter of 4 mm. The valve is normally open with a gap of 20 μm between the membrane and the valve inlet. Determine the pressure required for closing the valve at an inlet pressure of $p_{\text{in}} = 1$ bar. The opening diameter is 200 μm.



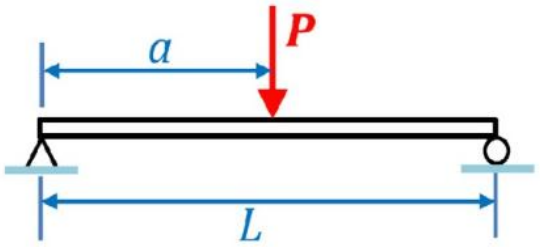
Spring constant



Spring constant

2. Find the spring constant k of

a) A simply supported beam



b) A cantilever beam

c) A fixed-end beam

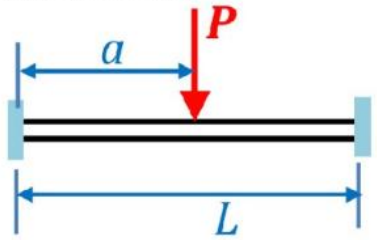
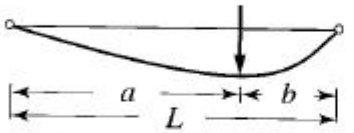
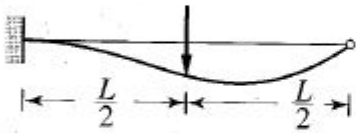
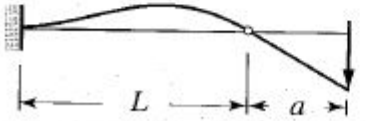
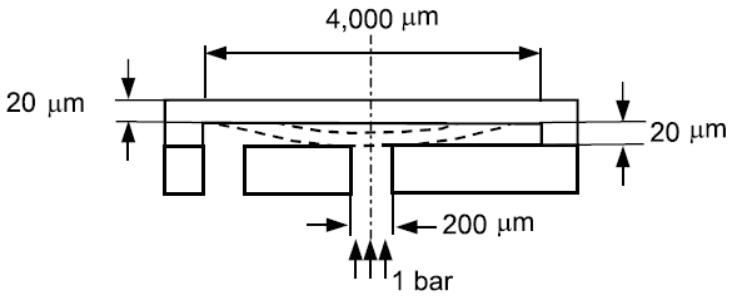


Table 1.2 - Equivalent Spring Constants (continued)

Component Sketch and Description	k_{eq}
 Pinned-pinned beam with a force at midspan	$\frac{48EI}{L^3}$
 Clamped-clamped beam with a force at midspan	$\frac{192EI}{L^3}$
 Pinned-pinned beam with an off-center force	$\frac{3EIL}{a^2b^2}$
 Clamped-pinned beam with a force at midspan	$\frac{768EI}{7L^3}$
 Clamped-clamped beam with one end sagging under a force	$\frac{12EI}{L^3}$
 Pinned-pinned beam with an overhang and a force at the tip	$\frac{3EI}{a^2(L+a)}$
 Clamped-pinned beam with an overhang and a force at the tip	$\frac{12EI}{a^2(3L+4a)}$

E = modulus of elasticity
I = cross-sectional area moment of inertia
A = cross-sectional area
G = shear modulus
J = cross-sectional area polar moment of inertia



Solution. Assume a distributed load on the valve membrane, a Poisson's ratio of 0.25, and a bulk Young's modulus of silicon of 170 GPa. For a small deflection, the spring constant of the valve membrane is estimated as (see Appendix D):

$$k = \frac{16\pi E t^3}{3r^2(1-\nu^2)} = \frac{16\pi \times 170 \times 10^9 \times (2 - \times 10^{-6})^3}{3 \times (2 \times 10^{-3})^2 (1 - 0.25^2)} = 6.08 \times 10^3 \text{ N/m}$$

If the microvalve is closed at p_{act}, the force balance on the membrane is:

$$p_{\text{act}} A_{\text{m}} = p_{\text{in}} A_{\text{m}} + F_{\text{spring}}$$

Thus:

$$p_{\text{act}} = p_{\text{in}} + \frac{F_{\text{spring}}}{A_{\text{m}}} = p_{\text{in}} + \frac{kg}{\pi r_{\text{m}}^2}$$

$$p_{\text{act}} = 10^5 + \frac{6.08 \times 10^3 \times 20 \times 10^{-6}}{\pi \times (2 \times 10^{-3})^2} = 100,000 + 9,677 = 109,677 \text{ Pa}$$

The reader can calculate the pressure required for keeping the valve closed and compare it with the above result.

Check valve

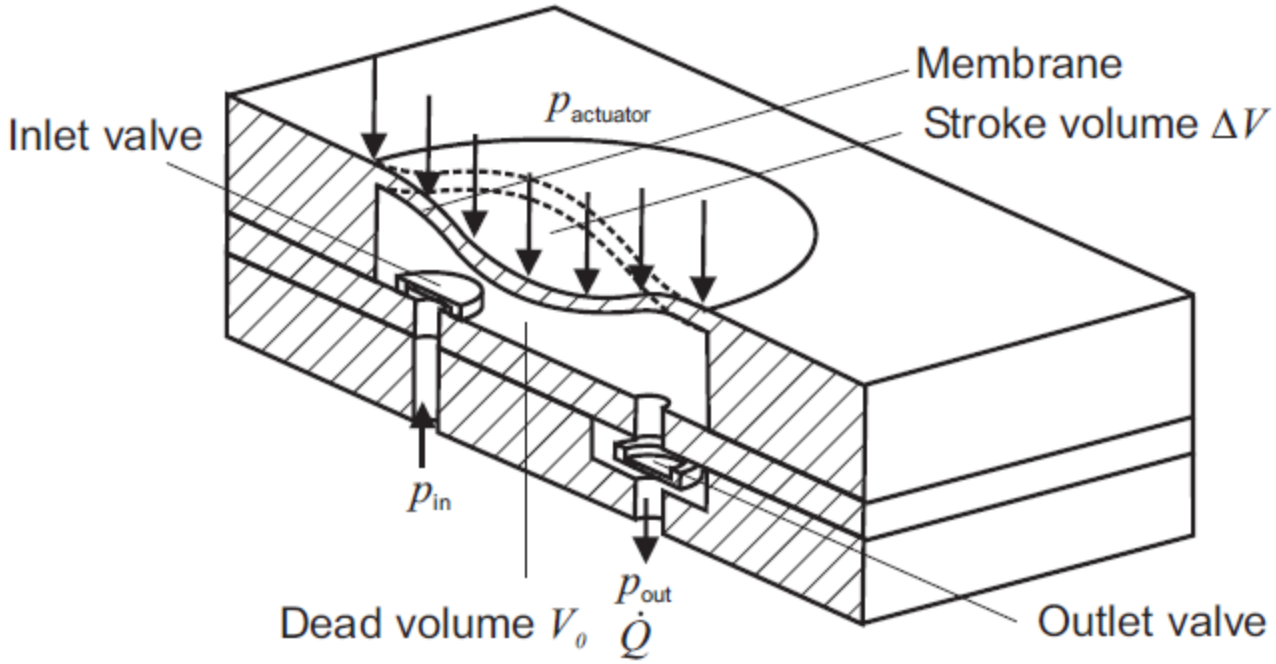


Figure 7.4 General structure of a check-valve pump.

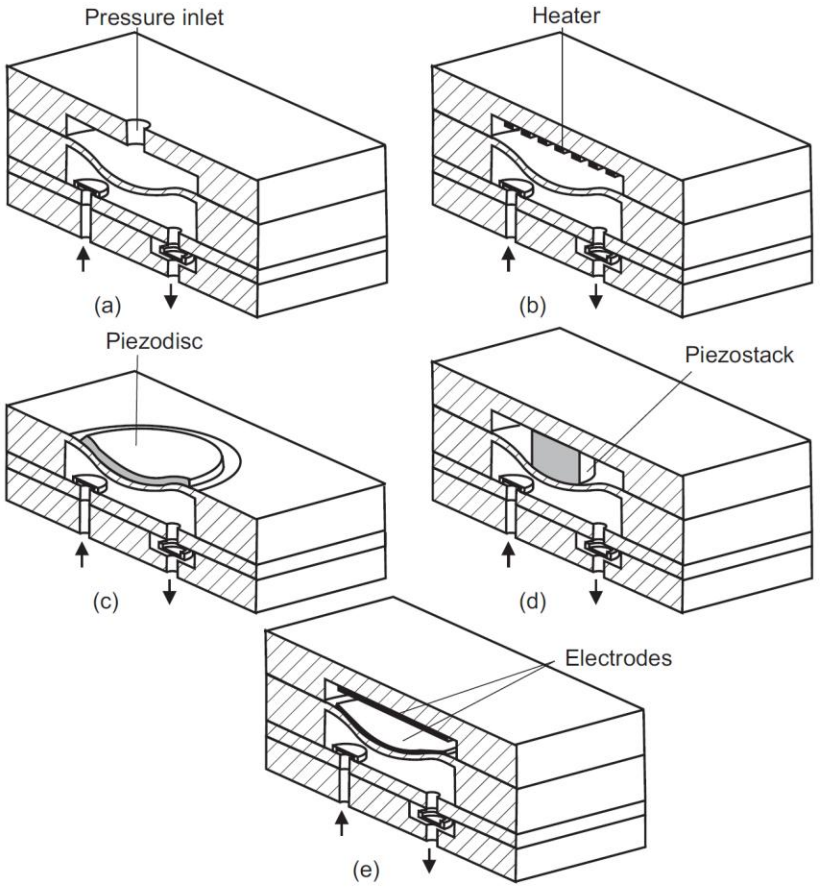
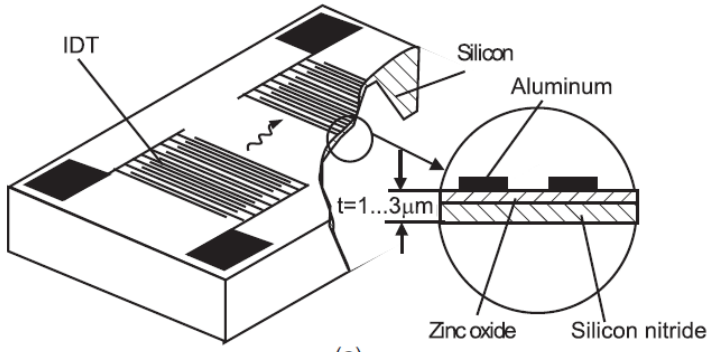


Figure 7.2 Actuation schemes for check-valve micropumps: (a) pneumatic; (b) thermopneumatic; (c) piezoelectric disc; (d) piezoelectric stack; and (e) electrostatic.

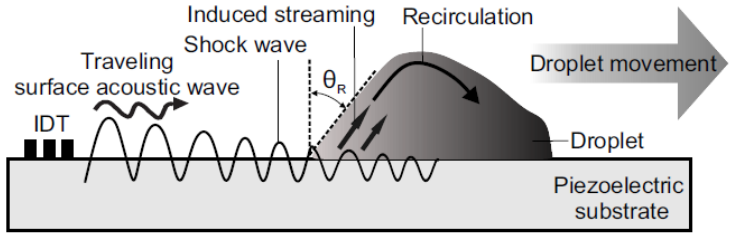
Surface acoustic wave

Introduction to Acoustofluidics

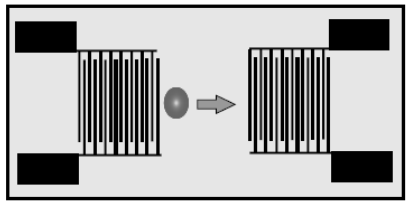
- *Acoustics Meets Microfluidics*
- Microacoustofluidics: using acoustic waves to manipulate fluids & particles at microscale.
- Relies on **surface acoustic waves (SAWs)** traveling along a solid substrate.
- Two main types:
  - **Traveling SAWs (TSAWs)**
  - **Standing SAWs (SSAWs)**
- Generated using **interdigital transducers (IDTs)** on a piezoelectric layer.
- SAWs have amplitudes of only a few nanometers, but can exert strong forces on droplets.


IDT
Silicon
Aluminum
t=1...3μm
Zinc oxide
Silicon nitride

(a)


Induced streaming
Recirculation
Shock wave
Traveling
surface acoustic wave
θ_R
Droplet movement
IDT
Droplet
Piezoelectric
substrate

(b)



(c)

How SAWs Manipulate Fluids

- Mechanisms of Acoustic Control

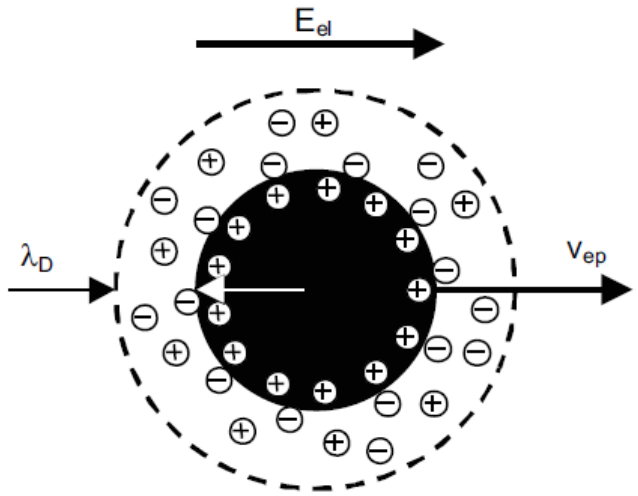
- SAWs travel slower than bulk sound → energy trapped near surface.
- Can:
  - Push and move droplets on hydrophobic substrates.
  - Propel liquid plugs through enclosed microchannels.
  - Induce internal circulation inside droplets (acoustic streaming).
- Typical vibration speeds: ~1 m/s, but accelerations up to $10^8\, m/s^2$.
- Enables **on-chip pumping, mixing, and microcentrifugation**.

Advanced Phenomena: Jetting & Atomization

- *Harnessing High-Power Acoustics*
- At high power, TSAWs can overcome capillary stress → **jetting**.
  - Droplet surface deforms → thin liquid jet extruded.
- Even higher power: **atomization.**
  - Droplet breaks into aerosol droplets (~1 μm size).
  - Requires power ~1 W.
- Applications:
  - Controlled droplet generation.
  - Aerosol creation for drug delivery.
  - Novel mixing and spraying methods.

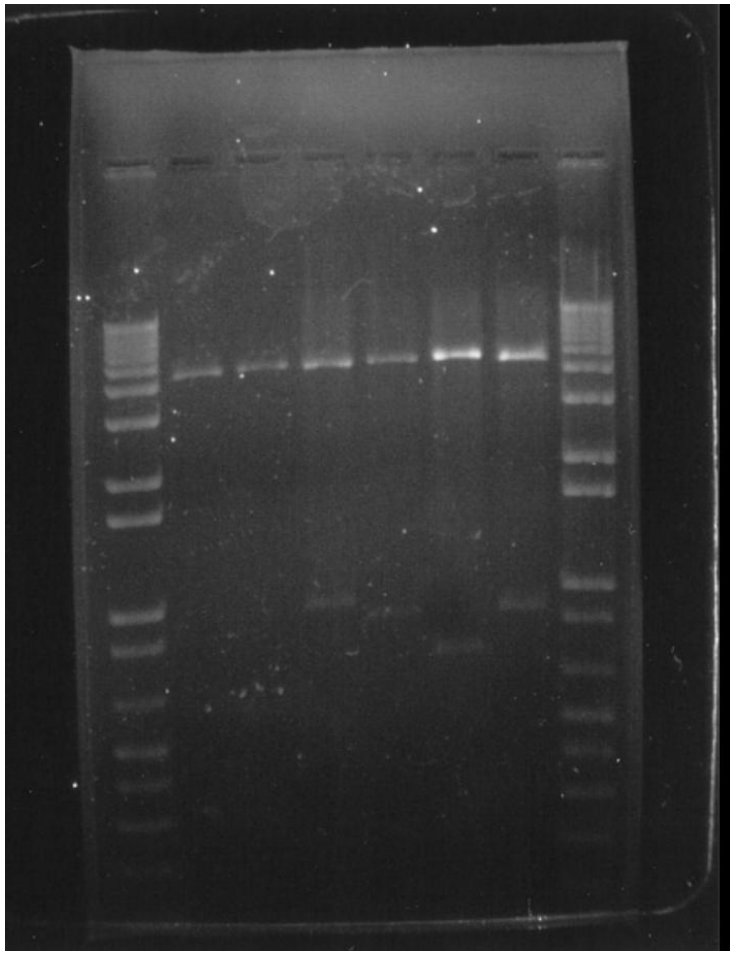
Electrophoresis

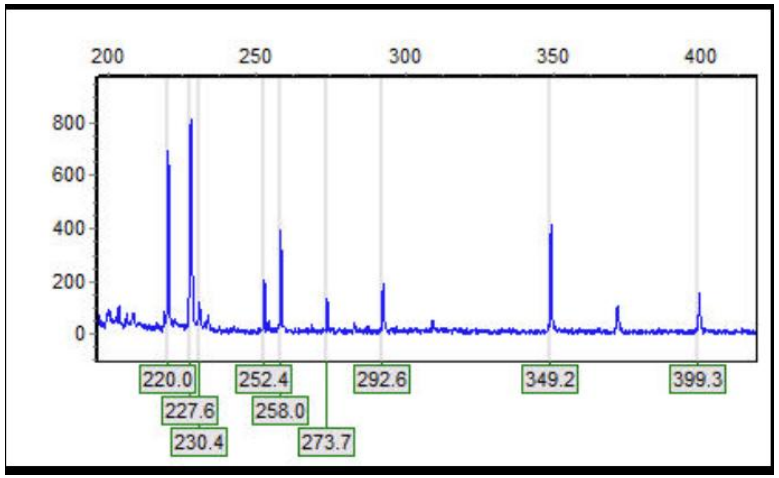
- **Definition**: Motion of charged particles in a fluid under the influence of a uniform electric field.
- **Mechanism**: Charged particles experience a Coulomb force and migrate towards the electrode of opposite polarity.
- **Key Parameters**:
  - Particle charge
  - Electric field strength
  - Fluid viscosity
- **Applications in Microfluidics**:
  - DNA/protein separation (lab-on-a-chip devices)
  - Manipulation of charged nanoparticles and biomolecules



$$q_s E_{el} = 6\pi\eta u_{ep} r_0$$

$$u_{ep} = \frac{q_s E_{el}}{6\pi\eta r_0}$$





Limitations of Electrophoresis

- Only works for **charged particles**
- Efficiency depends strongly on **ionic strength of the medium**
- Challenges in high-throughput microfluidic integration due to **Joule heating** and **buffer limitations**

Dielectrophoresis

- **Definition**: Motion of **polarizable (charged or neutral) particles** in a **non-uniform electric field.**
- **Mechanism**: Particles experience induced dipole moments, leading to forces in regions of high or low field intensity.
- **Types**:
  - **Positive DEP**: Particles attracted to high-field regions
  - **Negative DEP**: Particles repelled from high-field regions

$$\bar{\mathbf{F}}_{\mathrm{DEP}} = \frac{1}{2}\Re\left[\left(\bar{\mathbf{m}}(\omega) \bullet \nabla \bar{E}^{*}_{\mathrm{el}}\right)\right]$$

$$\bar{\mathbf{m}}(\omega) = 4\pi\varepsilon_{\mathrm{m}} r_0^3 K(\omega)\bar{E}$$

$\bar{\mathbf{m}}(\omega)$ is the dipole moment

$$K(\omega) = \frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_m}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_m}$$

Table 2.7

Positive and Negative DEP Force Classifications and Particle Behavior

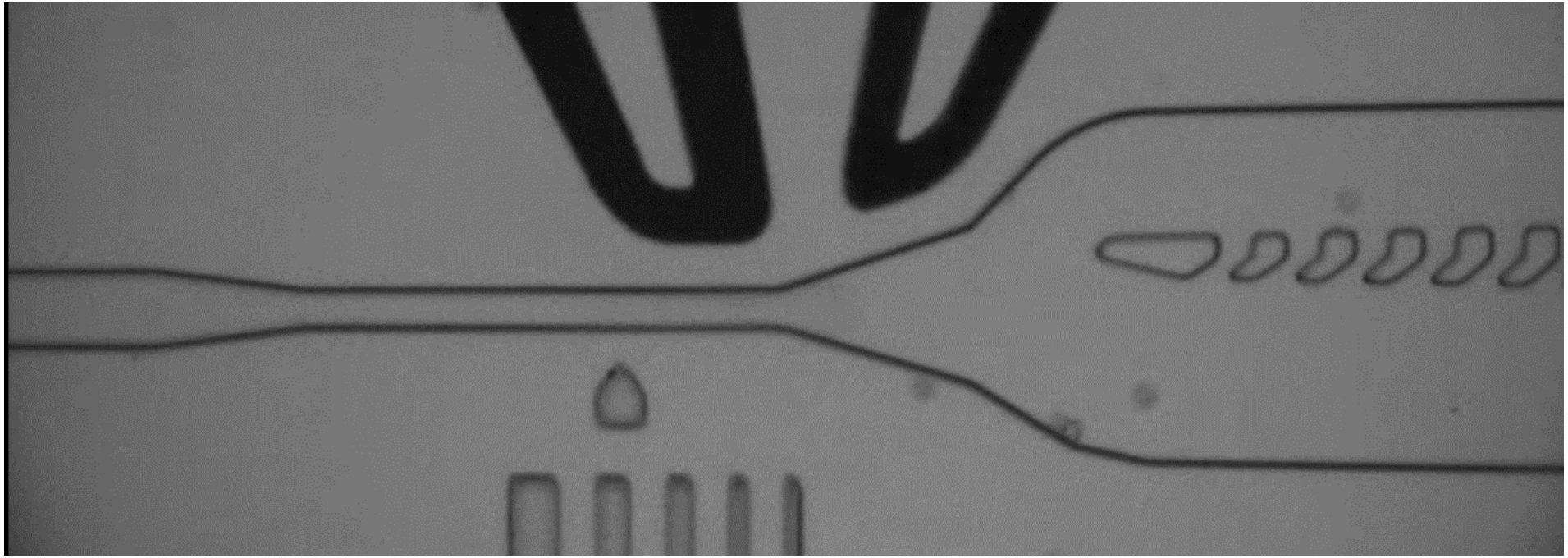
Positive DEP $\Re[K(\omega)] > 0$	DEP force is toward higher electrical fields	Particles collect at electrode edges
Negative DEP $\Re[K(\omega)] < 0$	DEP force is toward lower electrical fields	Particles are repelled from electrode edges

DEP in Microfluidics

- **Why DEP is powerful**:
  - Works on neutral as well as charged particles
  - Selective based on particle **size, shape, and dielectric properties**
- **Integration in microfluidics**:
  - Electrodes patterned inside microchannels create localized field gradients
  - Enables precise, label-free manipulation of cells, bacteria, nanoparticles, and biomolecules

- **Cell sorting & enrichment**
- **Pathogen detection** (bacteria/viruses captured in microchannels)
- **Nanoparticle assembly** (directed positioning of colloids or nanomaterials)
- **Point-of-care diagnostics** (rapid, portable analysis without labeling)

Applications of DEP in Microfluidics



Comparison

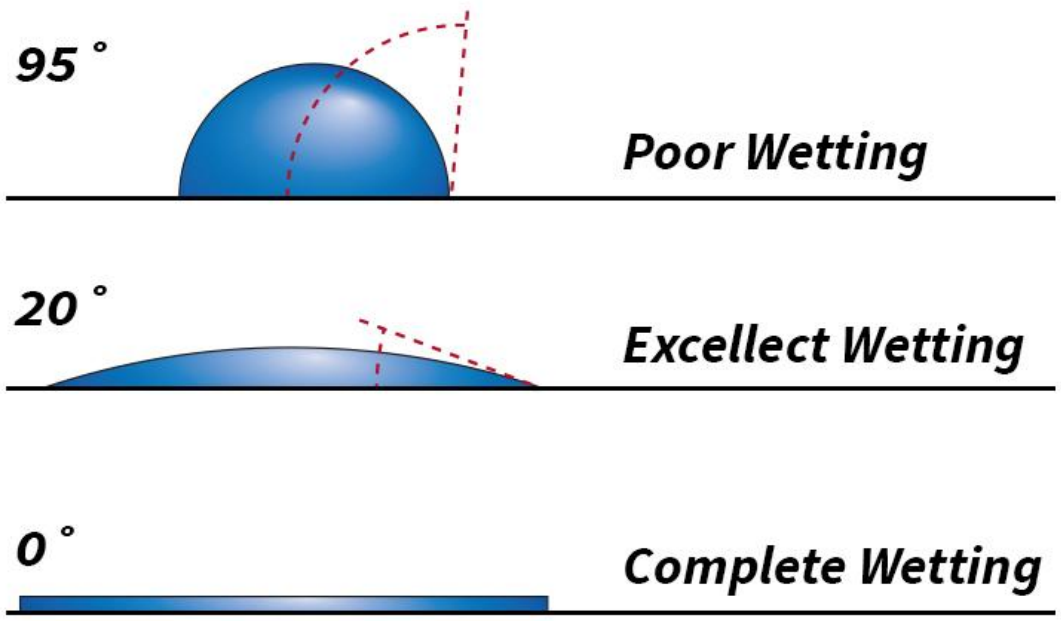
- **Electrophoresis**: Motion of charged particles in uniform fields → useful but limited.
- **Dielectrophoresis**: Motion of polarizable particles in non-uniform fields → versatile and widely used in microfluidics.
- DEP expands the toolbox for **lab-on-a-chip systems** by enabling **label-free, selective, and precise manipulation**.

Electric Field Requirements

Feature	**Electrophoresis**	**Dielectrophoresis (DEP)**
Electric field type	**Uniform field** (constant strength and direction across space)	**Non-uniform field** (field strength varies spatially)
Force origin	Direct Coulomb force on charged particles	Induced dipole interacting with field gradient
Particles affected	Only **charged** particles	**Charged or neutral polarizable** particles
Field generation	Simple parallel electrodes	Patterned or microfabricated electrodes (e.g., interdigitated)
Illustration	→ Straight, equally spaced field lines	→ Curved, denser lines near electrodes (field gradient)

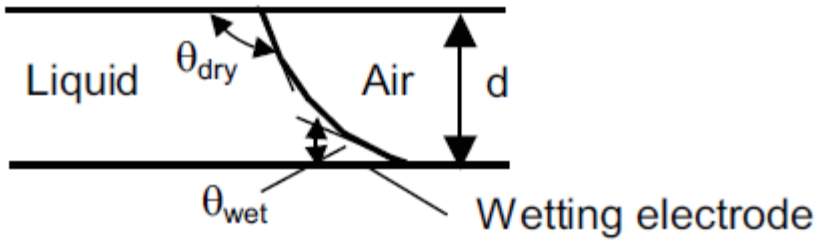
Wetting

- **Definition**: Interaction of a liquid with a solid surface, determined by the **contact angle (θ).**
- **Key concept**:
  - **Hydrophilic surface** → small θ (<90°), liquid spreads.
  - **Hydrophobic surface** → large θ (>90°), liquid beads up.
- **Governing law**: **Young's equation** balances surface tensions (solid–liquid, solid–vapor, liquid–vapor).
- **Applications**: Coatings, self-cleaning surfaces, microfluidic droplet control.



Electrowetting

- **Definition**: Modification of a liquid droplet's contact angle on a solid surface using an **applied electric field**.
- **Mechanism**: Voltage reduces effective solid–liquid interfacial tension, making the droplet spread more (contact angle decreases).
- **Key relation**: **Young–Lippmann equation** links contact angle with applied voltage.
- **Applications**:
  - Tunable lenses
  - Display technologies
  - Microfluidic droplet actuation



Direct electrowetting

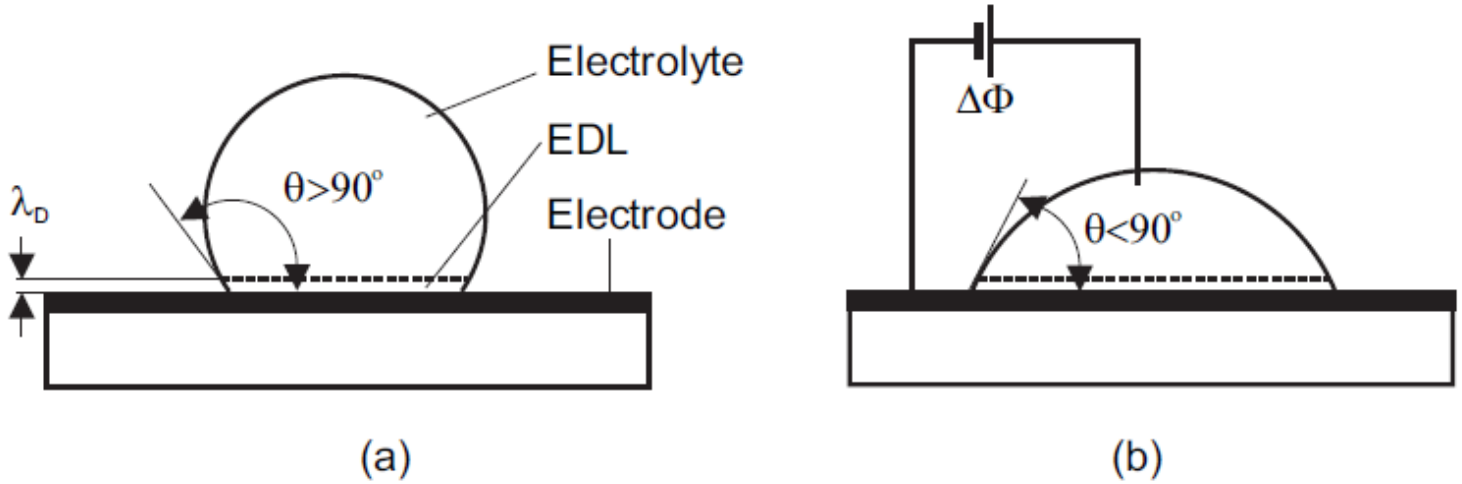


Figure 7.23 Direct electrowetting: (a) formation of an electric double layer at the interface; and (b) an applied voltage changes the contact angle.

Electrowetting on Dielectric (EWOD)

- **Definition**: Electrowetting performed on a **hydrophobic dielectric layer** coated above a conducting electrode.
- **Why EWOD?**
  - Prevents electrolysis (no direct droplet–electrode contact).
  - Enables **reversible and reliable actuation.**
- **Working principle**:
  - Droplet sits on a dielectric + hydrophobic layer.
  - Applying voltage reduces contact angle → droplet spreads or moves.
- **Microfluidics context**:
  - Droplet transport, merging, and splitting on lab-on-a-chip devices.
  - Digital microfluidics (DMF) platforms for biomedical assays.

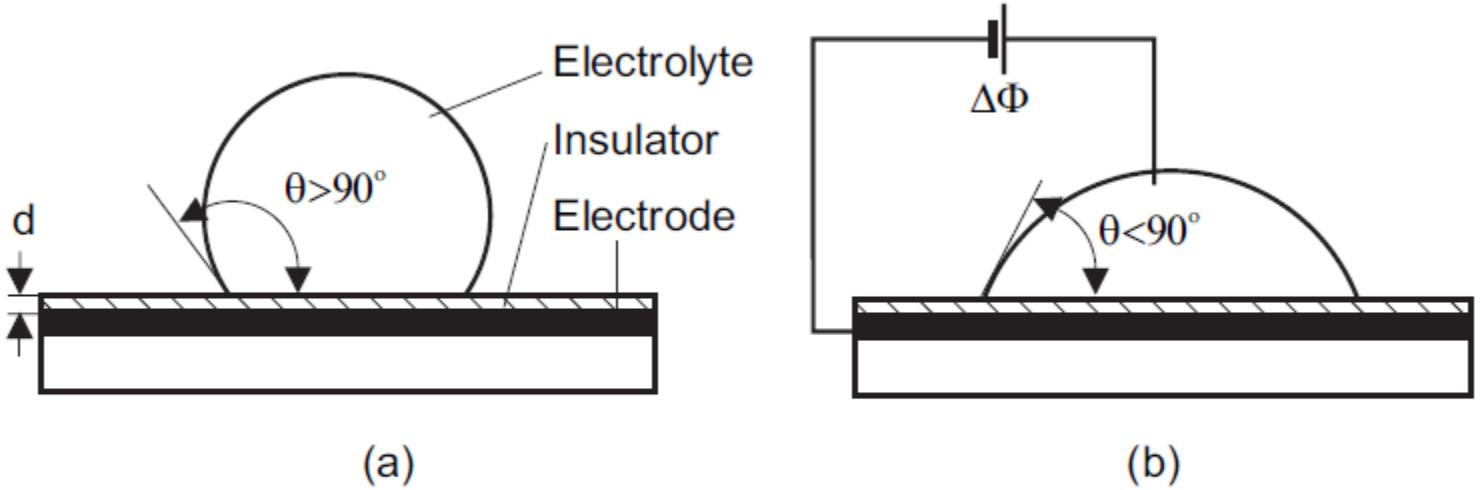
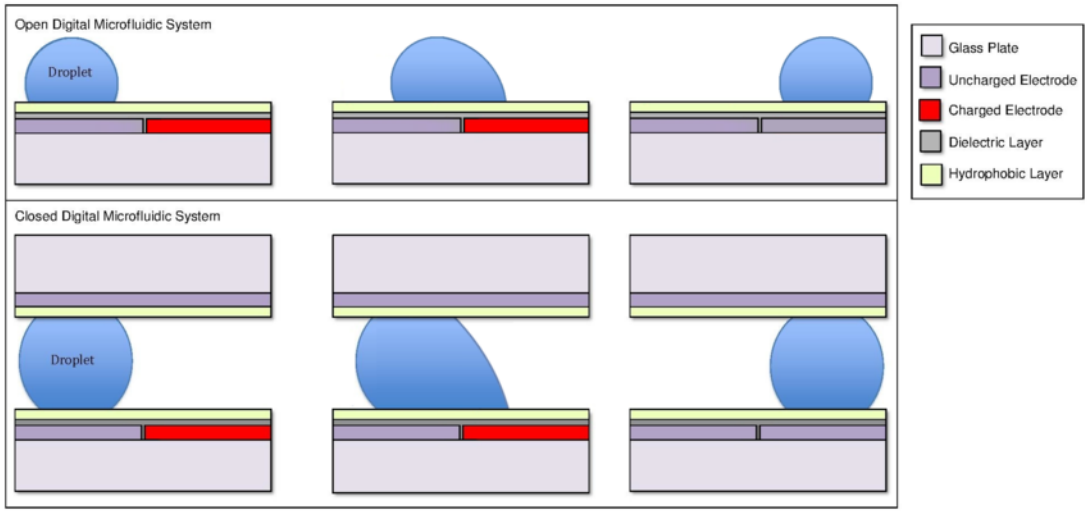
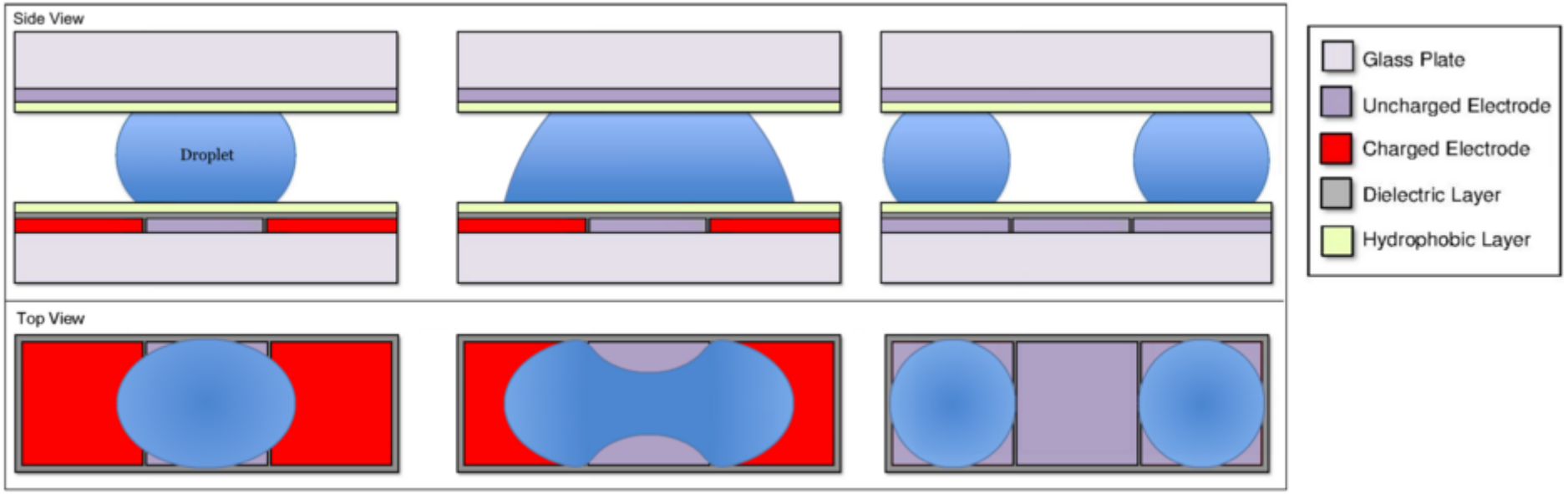


Figure 7.24 Electrowetting on dielectric: (a) the hydrophobic dielectric layer acts as a capacitor; and (b) an applied voltage changes the contact angle.

Digital microfluidics



Droplet splitting



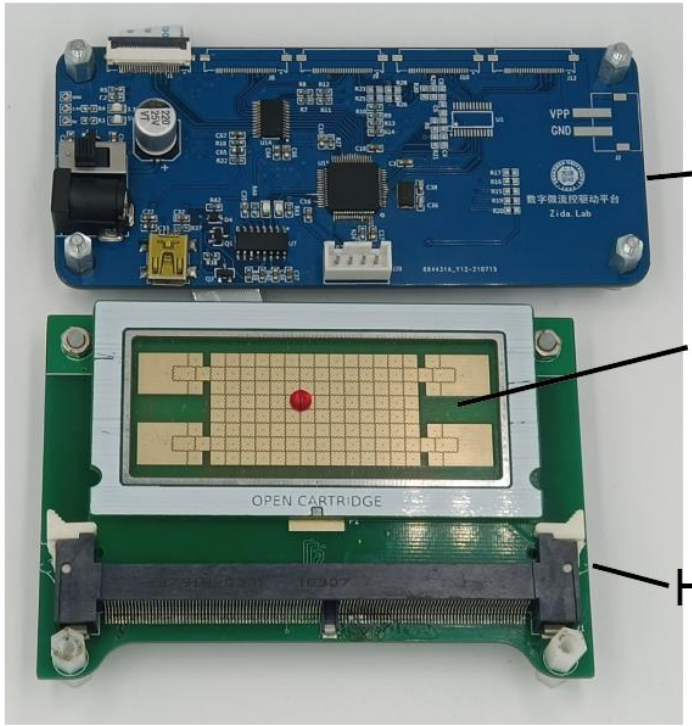
Fabrication

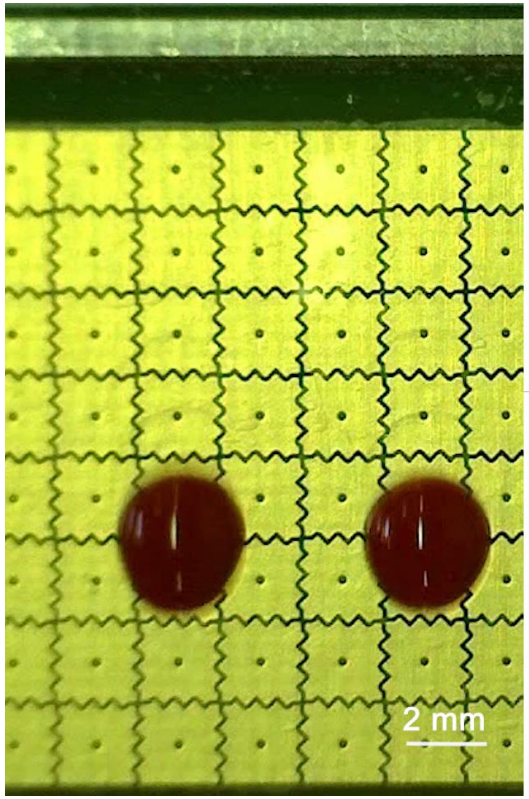
- Simplest form: printed circuit board
- https://www.bilibili.com/video/BV1et4y1471M

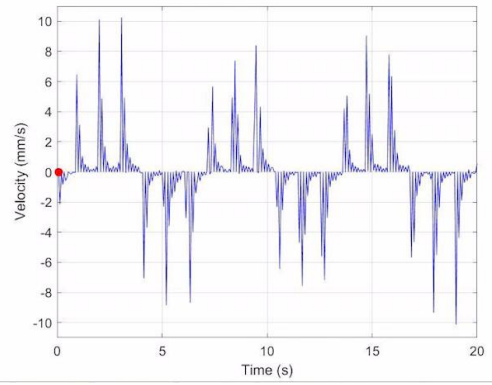
Fabrication

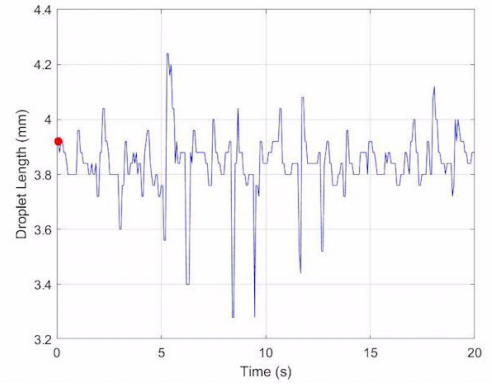
- https://www.bilibili.com/video/BV1wf4y1f7aJ

Digital microfluidics



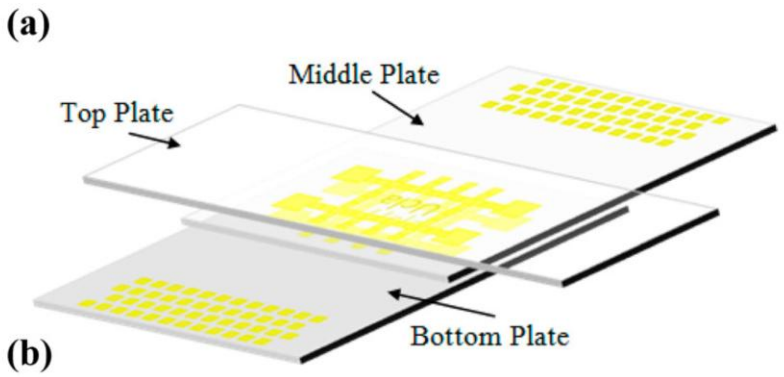


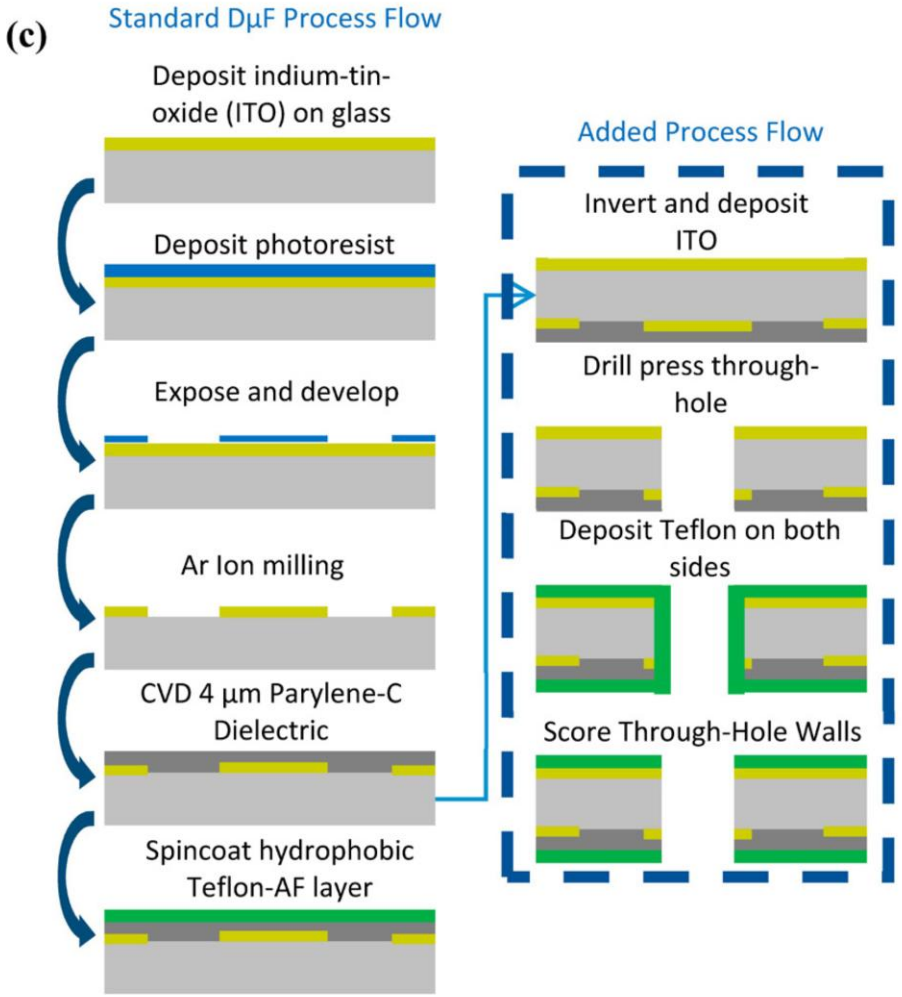




On glass

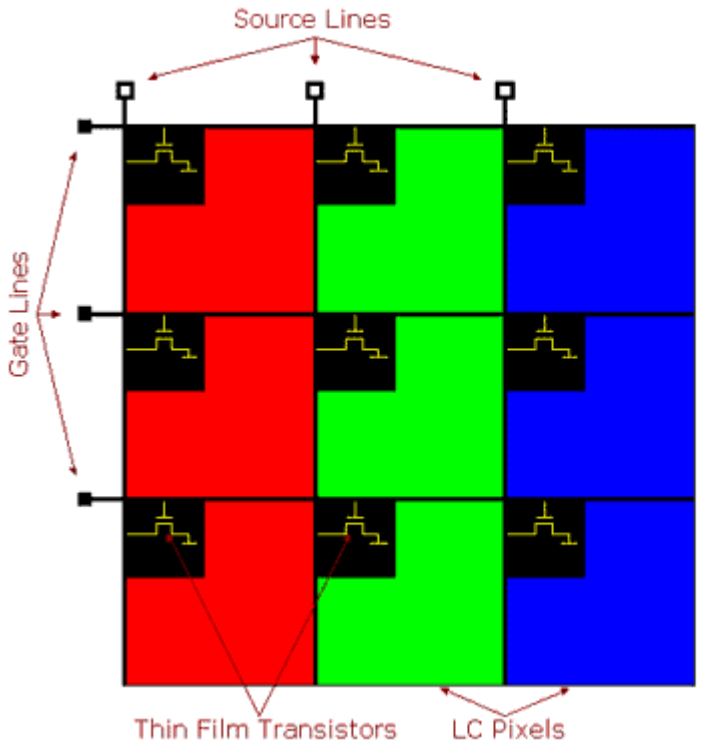
- https://www.bilibili.com/video/BV1oM4y1J7hA/


(a)
Middle Plate
Top Plate
Bottom Plate
(b)
Multi-pin connector for computer-aided actuation of bottom plate
Ground connections
Spacer
Manual actuation of middle plate


(c)
Standard DμF Process Flow
Deposit indium-tin-oxide (ITO) on glass
Deposit photoresist
Expose and develop
Ar Ion milling
CVD 4 μm Parylene-C Dielectric
Spincoat hydrophobic Teflon-AF layer
Added Process Flow
Invert and deposit ITO
Drill press through-hole
Deposit Teflon on both sides
Score Through-Hole Walls

Active matrix

- https://www.bilibili.com/video/BV1dW4y1A7UG



In an active matrix display, thin film transistors, used to switch power to the lower electrode, are mounted on the bottom substrate and triggered by the source and gate lines running between the pixel rows and columns. The transistors occupy part of the cell area, so cutting out a proportion of the light.

The electrodes on the top substrate are the width of each pixel and transparent, as are both top and bottom electrodes in passive matrix displays.

Applications of digital microfluidics

Application Area	What is done
Nucleic acid tests (NAAT / molecular diagnostics)	Full workflows like sample prep, amplification, detection on a DMF chip. Reducing human intervention, reagent volumes, time. (Nature)
Immunoassays / Biomarker detection	On-chip ELISA-like assays, homogeneous and heterogeneous immunoassays. Multiplexed antigen/antibody detection. (MDPI)
Point-of-Care (POC) / Portable diagnostics	Devices that are portable / battery powered, with minimal external equipment, aimed at use outside central labs. (CSU Strata)
Lab automation (especially library prep, sequencing, etc.)	Automating steps like normalization, quantification, droplet handling to support high-throughput workflows. Companies like Illumina are incorporating DMF for parts of their fluid handling. (Illumina)
Chemical / Radiochemical synthesis	Using EWOD / DMF chips for small-scale chemical reactions or radiochemistry (e.g. PET tracers) to allow precise reagent use and controlled reaction conditions. (Van Dam Lab)
Single cell / Droplet encapsulation	High-throughput droplet-based single cell sequencing (or similar analyses) where each cell is isolated in a droplet. DMF helps with precise droplet control. (Wikipedia)

Application

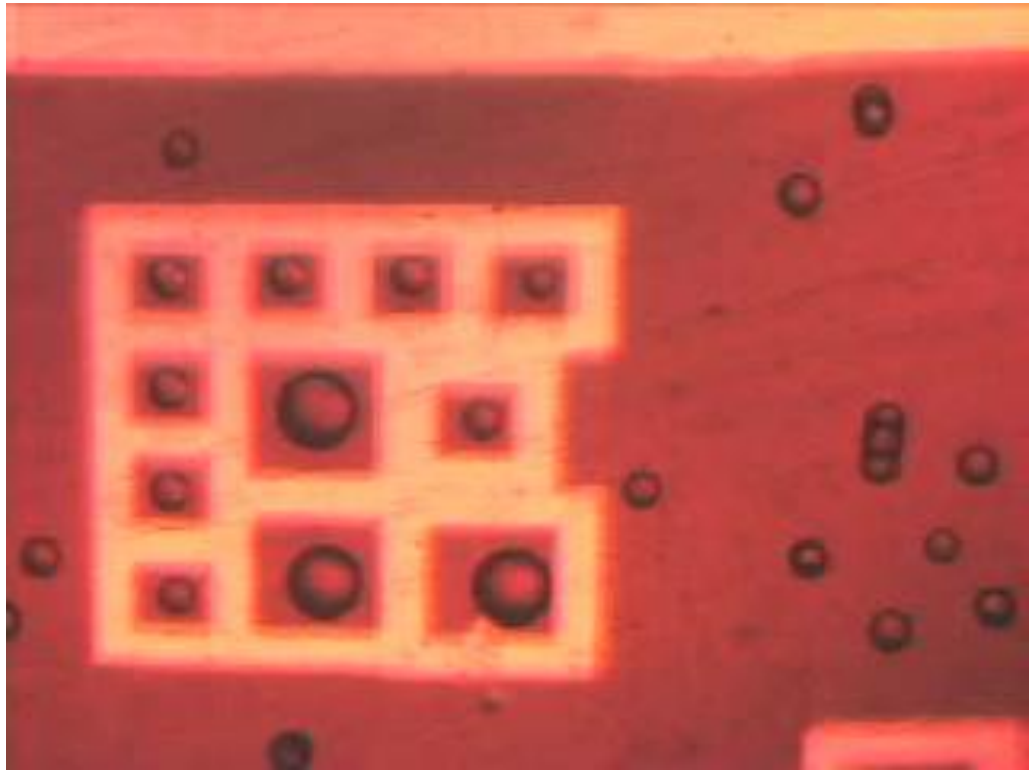
- https://baebies.com/tests/finder-g6pd/

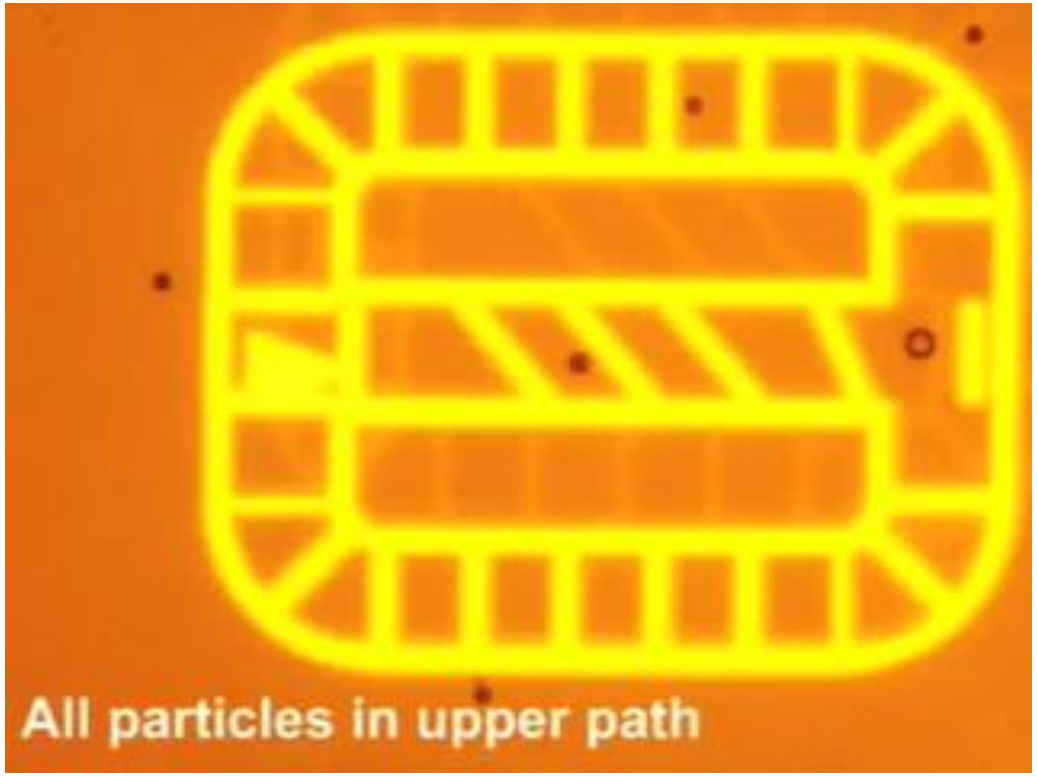
Trends, Opportunities & Challenges

- **Trends / Opportunities**
  - **Miniaturization & integration**: Packaging multiple steps (sample prep, mixing, reaction, detection) on a single DMF chip toward “sample-to-answer” devices.
  - **Low cost / alternative materials**: Use of flexible substrates (PCB, plastics, films), substrates other than glass or silicon, to lower fabrication cost.
  - **Battery-powered or portable devices**: Moving away from lab bench reliance.
  - **Multiplexing / multiplexed detection**: Multiple assays on same chip; multiple analytes automatically.
- **Challenges**
  - **Droplet control issues**: Splitting, merging, transporting, evaporative loss, and contamination especially in open architectures.
  - **Fabrication complexity / cost**: Especially for high numbers of electrodes, using durable dielectric and hydrophobic coatings, aligning multiple layers, etc.
  - **Integration of detection**: Getting reliable readout (optical, fluorescence, electrochemical) integrated on-chip or in small portable systems; assay sensitivity.
  - **Regulatory, validation, robustness**: For real-world diagnostic use, devices must be thoroughly validated; durability in different settings; reproducibility.

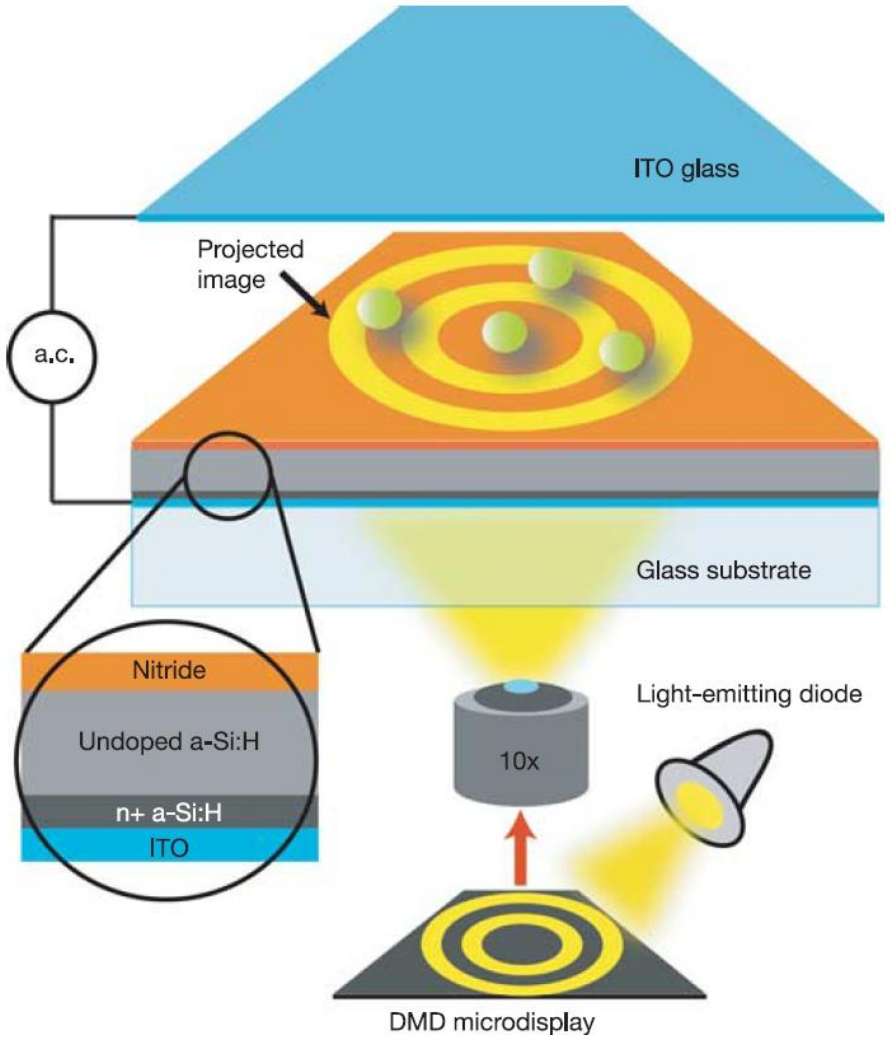
Opto-Electrical Positioning (OEP)

- **Definition**: OEP combines **electrical fields** with **light patterns** to manipulate particles or cells inside a microfluidic environment.
- **Mechanism**:
  - Photoconductive surface beneath the fluid chamber.
  - When illuminated, local conductivity changes → creates a non-uniform electric field.
  - This exerts **dielectrophoretic (DEP) forces** on cells, enabling movement.
- **Key Feature**: **Cells are moved with "light cages"**, making positioning precise, flexible, and contact-free.




All particles in upper path

X



Why This Layered Structure?

The **n^+ a-Si:H / intrinsic a-Si:H / nitride** structure is very similar to what's used in **thin-film solar cells and photodiodes** — because it provides:

1.Transparent front electrode (ITO) for optical access.

2.n^+ a-Si:H for good ohmic contact with ITO and efficient carrier transport.

3.Intrinsic a-Si:H for the photoconductive response.

4.Si_3N_4 dielectric to make the system robust in a fluidic environment.

3. Nitride (Si_3N_4)

2. Undoped a-Si:H (intrinsic layer)

1. n^+ a-Si:H (n-type hydrogenated amorphous silicon)

Fabrication

1. Substrate & Bottom Electrode

- **Material**: Borosilicate glass substrate.
- **Deposition**: **Indium Tin Oxide (ITO)** by **RF magnetron sputtering**.
- **Patterning**: If needed, **photolithography + wet etching** defines electrode areas (though the paper notes "featureless layers" → patterning was minimal).

2. n^+ a-Si:H Layer (~50 nm)

- **Deposition**: **Plasma-Enhanced Chemical Vapor Deposition (PECVD)**.
- **Precursors**: Silane (**SiH_4**) + Phosphine (**PH_3**) in hydrogen plasma.
- **Purpose**: Create a thin, heavily doped (n^+) hydrogenated amorphous silicon layer for ohmic contact between ITO and the intrinsic layer.

3. Intrinsic a-Si:H Layer (~1 µm)

- **Deposition**: **PECVD**.
- **Precursors**: Pure silane (**SiH_4**) + hydrogen.
- **Hydrogenation**: Incorporated to passivate dangling bonds, reducing trap states.
- **Role**: This is the **active photoconductor** whose conductivity changes under light exposure.

4. Silicon Nitride (Si_3N_4) Layer (~20 nm)

- **Deposition**: **PECVD** at low temperature (~250–350 °C, compatible with glass).
- **Precursors**: Silane (**SiH_4**) + ammonia (**NH_3**) or nitrogen (**N_2**).
- **Role**:
  - Dielectric / passivation layer.
  - Protects the a-Si:H from liquid exposure.
  - Prevents charge leakage into the fluid.