Week 03: Electromechanical Actuators 2

Mahmut Selman Sakar

Institute of Mechanical Engineering, EPFL

Lecture Overview

- Dielectric Elastomers
- Electrostatic Actuators
- Ionic Electroactive Polymers

- Next week: Electromagnetic actuation

Second Assignment

- **2 Questions per Person**
- Direct entry of text

- Second deadline: March 8th, Friday at midnight

Cilia metasurfaces for electronically programmable microfluidic manipulation

Metric for Actuators

- **Output strain**: change in length upon excitation normalized to the initial length
- **Output stress**: Generated force upon excitation normalized to the initial cross-sectional area at rest or excited state
- **Power density**: Energy density normalized to actuation period
- **Lock-up state**: actuator holds its actuation state without consuming energy
- **Directionality**: Uni vs bidirectional, rotational
- **Cycle life**: number of cycles before failure
- **Efficiency**: output over input energy
- **Bandwidth**: Range of frequencies for continuous excitation
- **Magnitude** of the stimulus (e.g., voltage, heat, optical power)

Artificial Muscle

- Actuators actively contract and/or expand in length when excited by a stimulus
- Swimming (fish) 0.4 J/kg at 4 Hz, flight (locust) 6 J/kg at 25 Hz, running (rat) 40 J/kg at 7.5 Hz.
- Electromagnetic energy
- Thermal energy (phase change or thermal expansion)
- Electrochemical energy (Faradaic reaction or charge accumulation in the double layer)
- Fluid pressure (pneumatic or swelling pressure)
- Light (photothermal, phase change)

- History (1670s): Christian Huygens, Robert Hooke. Gunpowder forces a piston inside a cylinder. Energy density around 270 kJ/kg

Electricity and Actuators

- Electrostatic
- Electromechanical (solid state)
- Electrochemical (in liquid)
- Electromagnetic

Electroactive Materials

- **Electronic (or solid-state) Electroactive Materials**
  - Piezoelectric ceramics, electrostrictive and magnetostrictive alloys, ferroelectric polymers, dielectric elastomers.
  - Relatively high voltage, quick reaction (low hysteresis), strong mechanical forces

- **Ionic Electroactive Polymers**
  - Ionic polymer gels, conductive polymers
  - Working principle: wet electrochemistry– the mobility or diffusion of charged ions
  - Low voltage
  - Electrolysis

Dielectric Materials

- Dielectric: substances with no free charges

- **Polarization**: When the material is placed in an electric field, its negatively charged electrons separate slightly from the positively charged cores

- As a result, molecules acquire an electric dipole moment (p) in the direction of the electric field (E). Polarized molecules are attracted toward the electrodes

- Electric susceptibility (χ) relates the polarization (P) to the electric field

$$P = \chi E$$

Important Dielectric Parameters

- Electric dipole moment p
- Electric polarization (polarization density) P [coulomb/m^2]
- Electric displacement field (flux density) D [coulomb/m^2]
- Dielectric constant ε_r
- Electric susceptibility χ
- Vacuum permittivity (permittivity of free space) ε_0

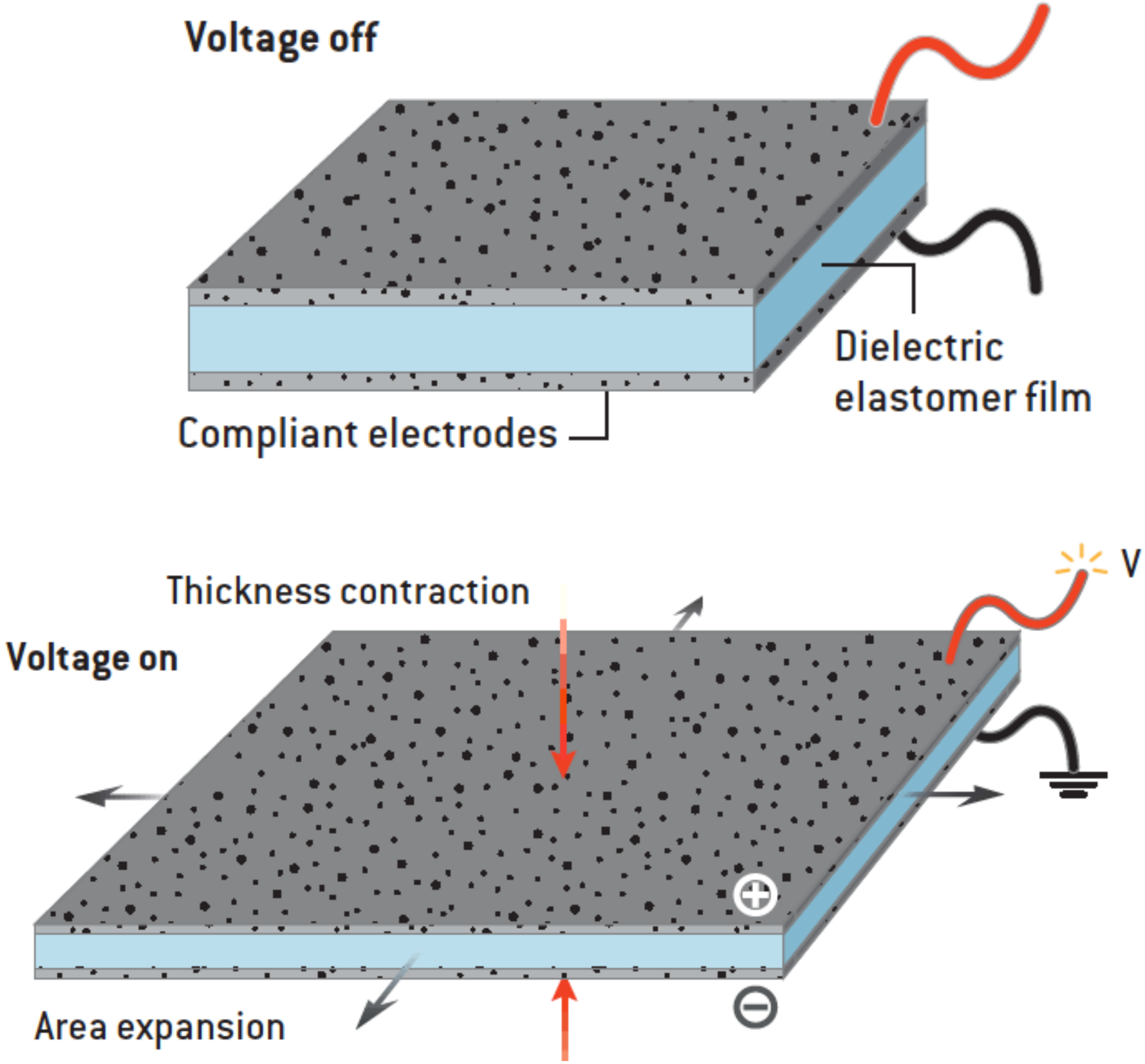
- Gauss's Law and Maxwell's equations

$$\varepsilon_r = 1 + \frac{\chi}{\varepsilon_0}$$

Strain and stress

- All dielectric solid-state materials when subjected to an external electric field undergo change in dimensions.
  - Why? Displacement of positive and negative charges.
  - Dielectric crystal lattice: cations and anions connected by springs (interionic chemical bonds)
  - Cations get displaced in the direction of the electric field and anions in the opposite direction
  - Amount of deformation depends on the crystal structure

Dielectric Elastomers (videos)



Dielectric Elastomers (DEA)

- DEA is a compliant capacitor (with variable capacitance) that converts electrical energy to mechanical work

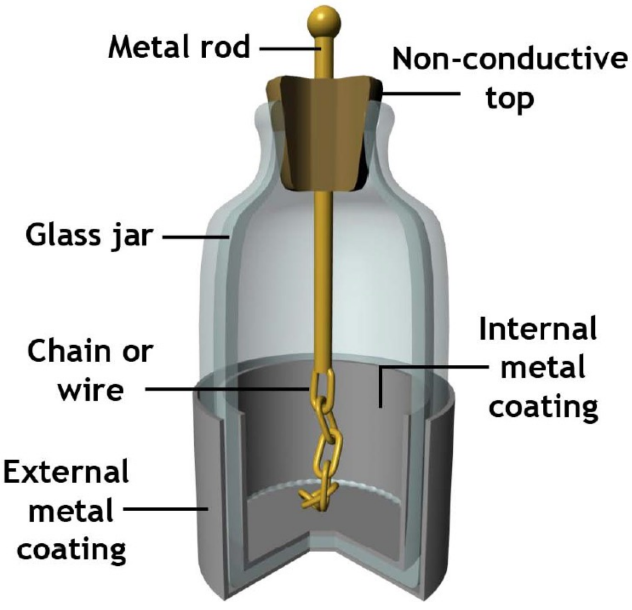
- Dielectric constant or relative permittivity
- Vacuum: 1, Glass: 4.7, Elastomer: 10, Ethanol: 24.3, Water: 78.4, Conjugated polymers: up to 100,000
- Dielectric strength or breakdown voltage (MV/m)
- The field strength at which breakdown occurs depends on
  - Geometry of the dielectric (insulator) and electrodes
  - Rate of increase of voltage
  - Thickness: thin films tend to exhibit greater strength than thick samples (defects)

Electric-field-actuated Polymers

- **Maxwell Stress**: When exposed to an electric field, all insulated plastics, such as polyurethane, contract in the direction of the field lines and expand perpendicular to them
- 1776: Alessandro Volta and Leyden jars (deformation of glass)

- Capacitors sandwiching a dielectric material (acrylics and elastomers): electrostatic forces
- Hyperelastic behavior of the membrane
- Compliant electrodes

- Polymers softer than polyurethane
  - Greater mechanical strain
  - Soft silicones



Electrostatic and electromechanical stress

$$p = \varepsilon_r \varepsilon_0 E^2 = \varepsilon_r \varepsilon_0 \, (V/t)^2$$

where p is the effective compressive stress, ε_r is the relative dielectric constant of the material, ε_0 is the permittivity of the free space, E is the electric field (V/m), V is the applied voltage, t is the film thickness.

- Effective compressive stress is twice the stress normally calculated for two rigid, charged capacitor plates.
  - In an elastomer, the planar stretching is coupled to the thickness of compression (constant volume)
  - Compressive stress has compressive and tensile components

- For small deformations (<20%) strain can be approximated as (linear)

$$s_z = -\frac{p}{Y} = -\varepsilon_r \varepsilon_0 E^2 / Y$$

→ Elastic modulus (Y)

High-speed, giant strain actuators

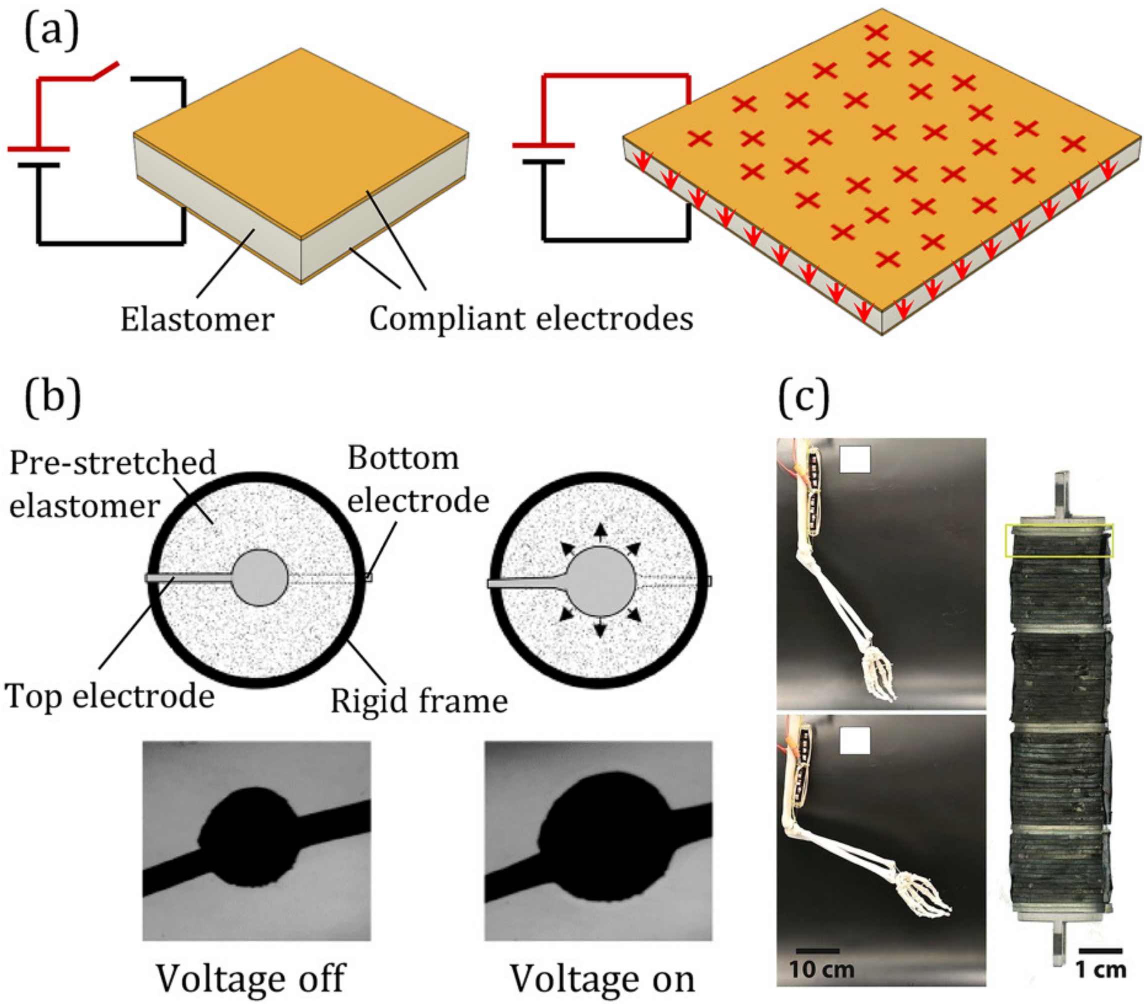
- Stanford Research International (SRI) published the paper in 2000.
- Artificial muscles (light weight, quiet operation, high strain and efficiency)
- Low elastic modulus (1 MPa) and high dielectric strength (>100 MV/m)
- Up to kHz range bandwidth
- Low viscoelastic losses and low electrical leakage
- Electromechanical coupling is 60-80% for acrylic, 90% for elastomer
- Up to 380% strain (typical 10-100%), up to 7.2 MPa stress, elastic energy density up to 3.4 J cm^{-3}
- On the order of 1 kV for electrode separation of 10 to 100 μm
- **Key innovation**: pre-strain

Architected DEAs

- Single-film dielectric elastomers are thin (to minimize actuation voltage) which leads to small force output (< 10mN)
- Solution: Stock multiple layers to reach Newtons of force

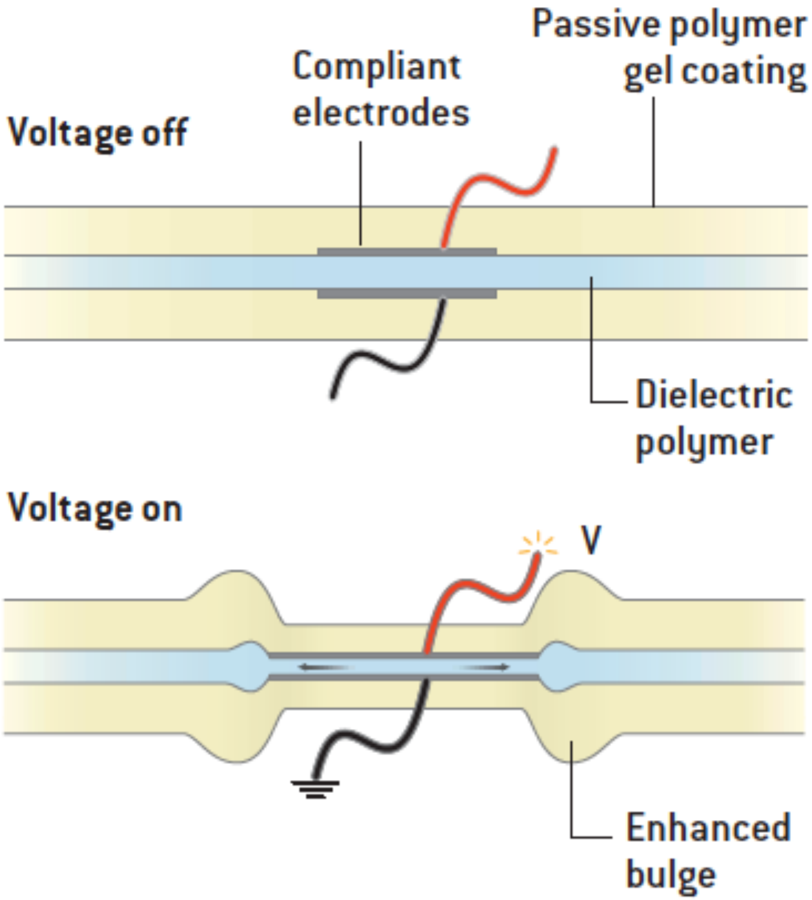
- Strain-stiffening elastomers in a multilayered configuration
  - No need for pre-stretch
  - NO need for a rigid frame

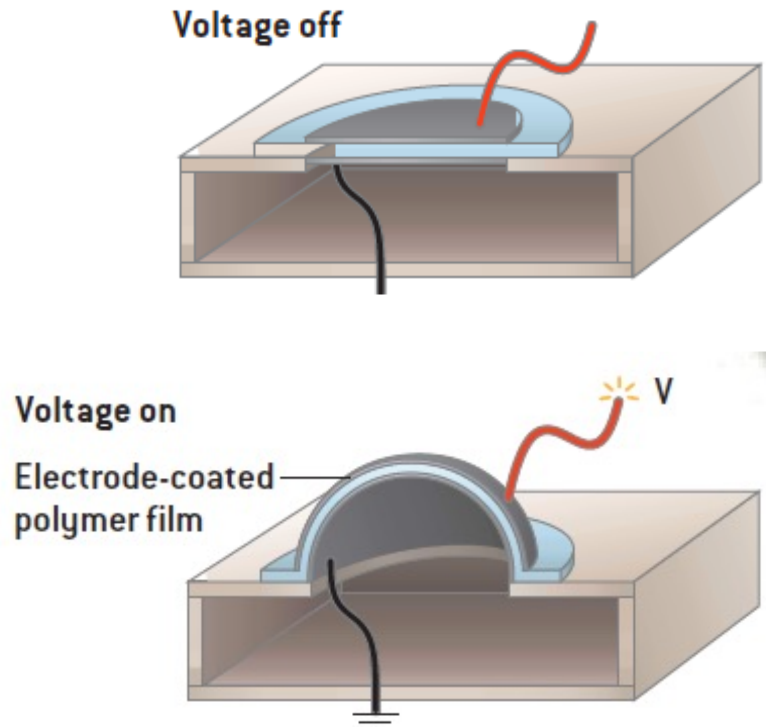
Configurations



Applications

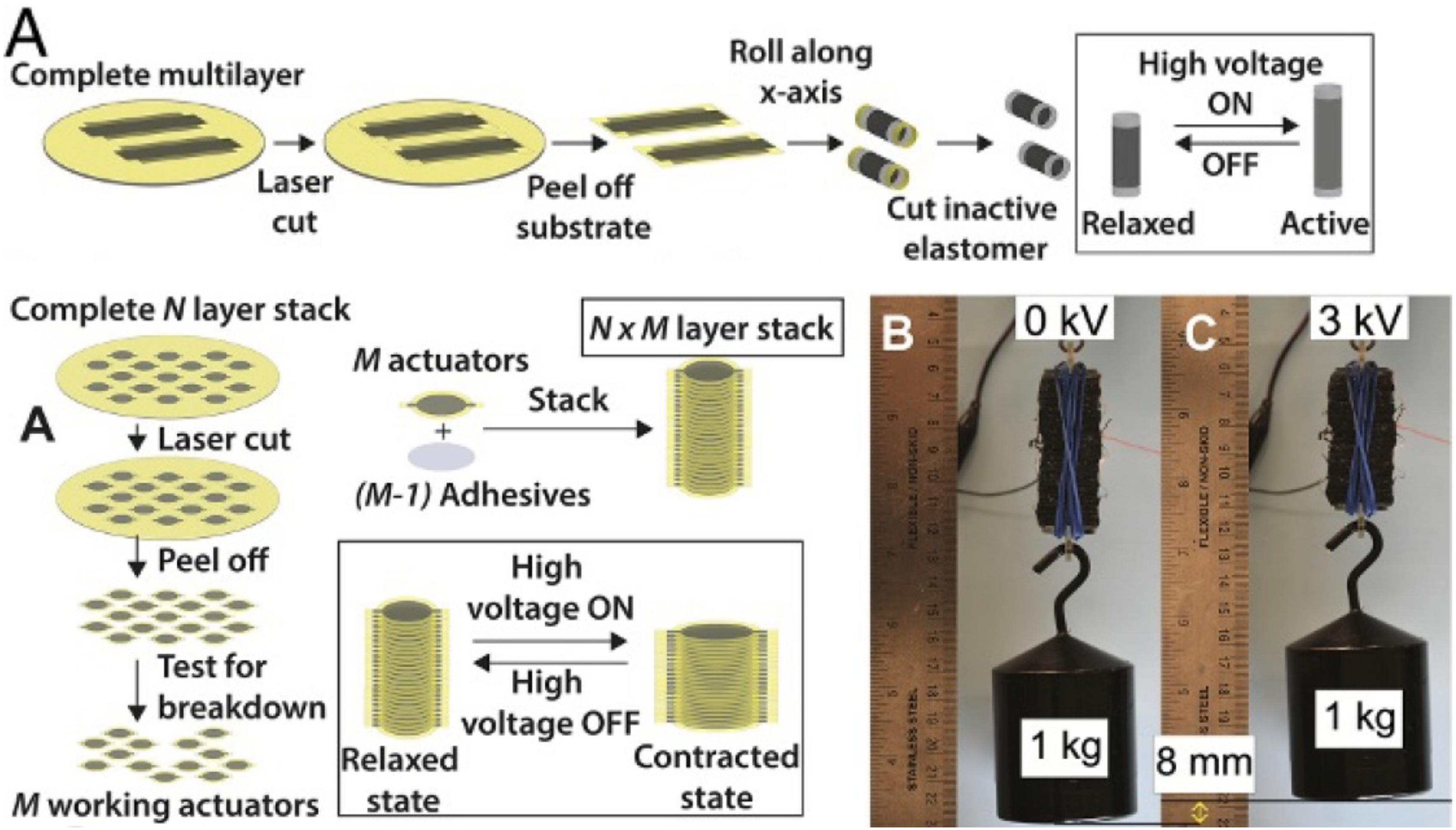
- Controllable texture, Diaphragm actuator (speaker, pump)



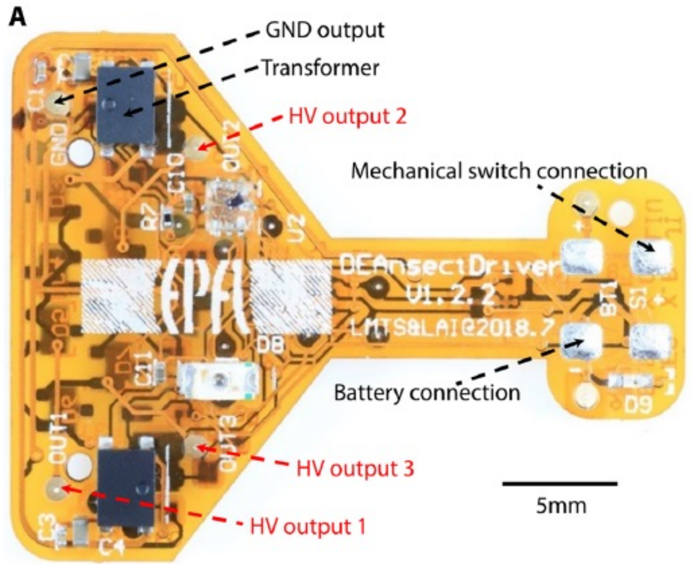


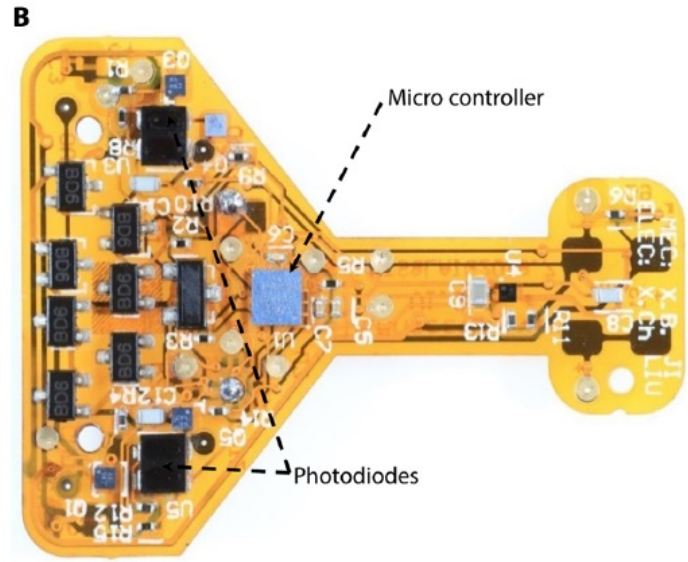
Applications (video)

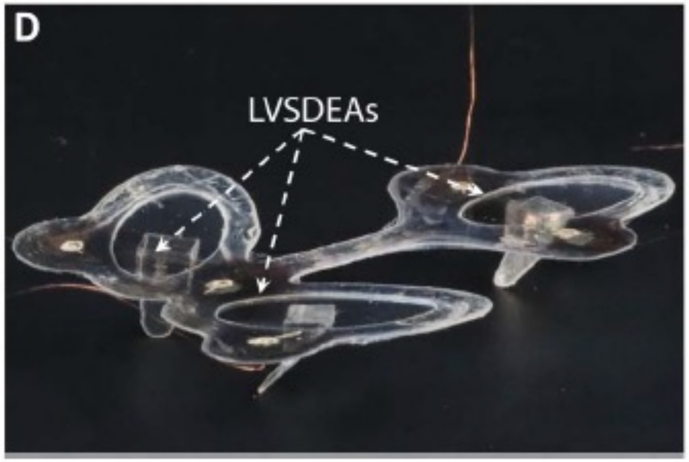
- Robotic actuators

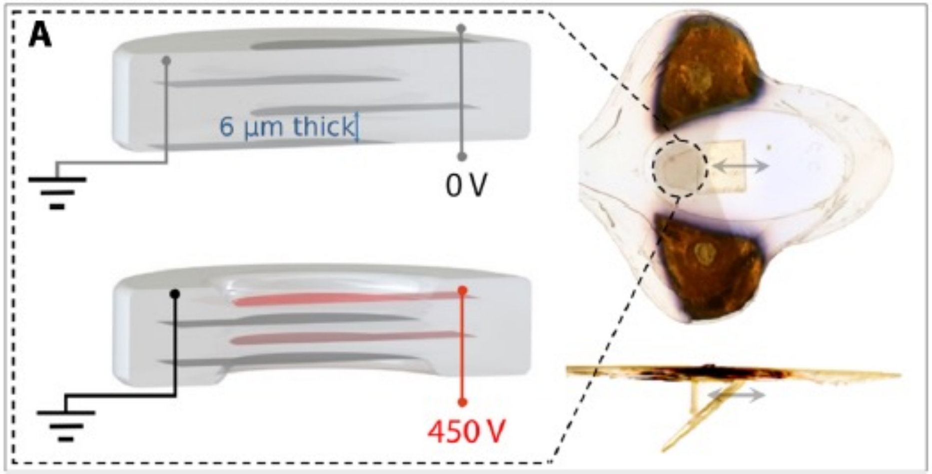


Soft robotic insect (video)







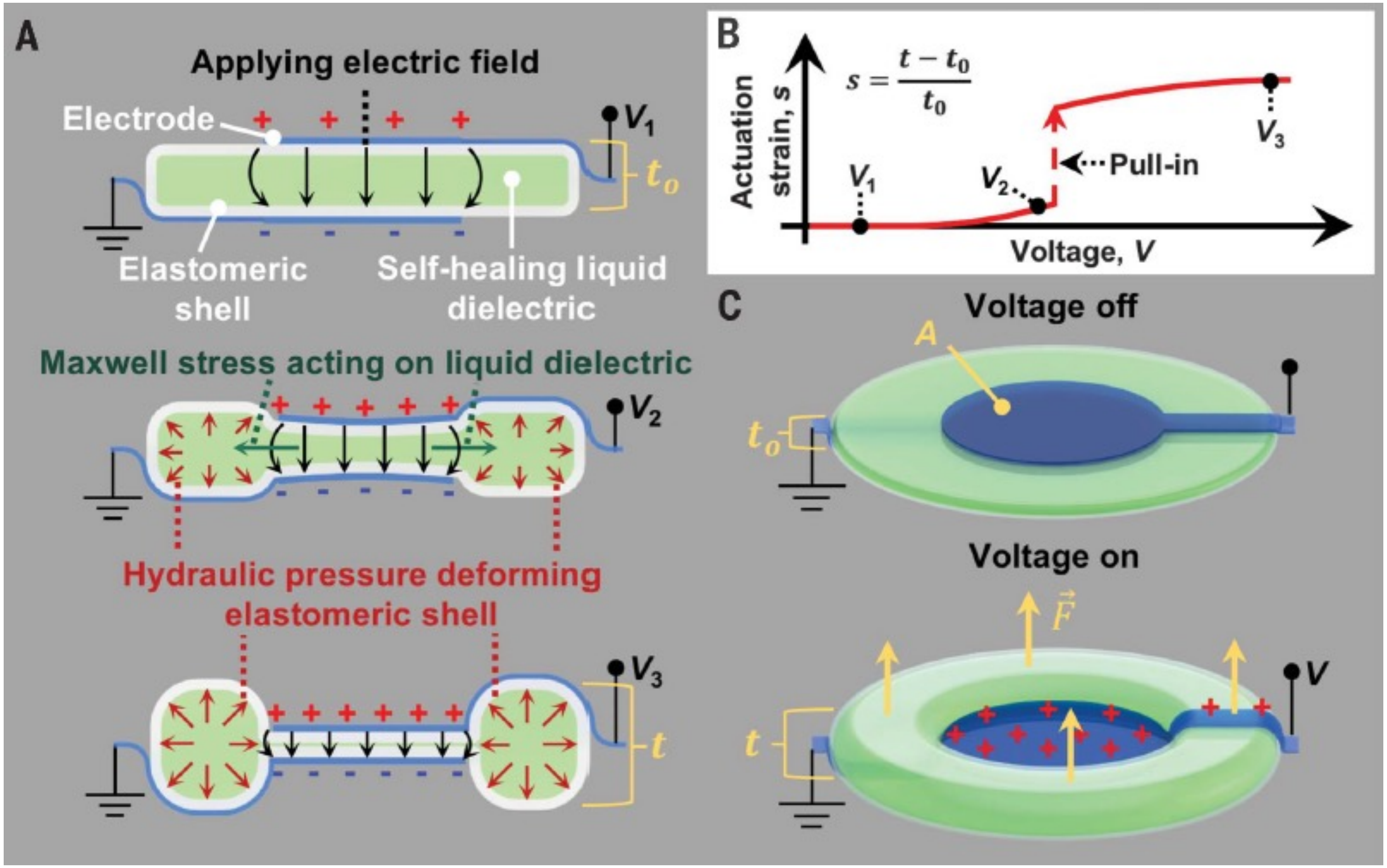


Increasing dielectric constant

- To increase strain and decrease actuation voltage
- Typical values around 10
- Assuming a 50% energy conversion efficiency, the field required is 67 $V{\cdot}\mu m^{-1}$ to generate 0.1 $J{\cdot}cm^{-3}$ (comparable to piezo)
- Composite approach: Add particles with high dielectric constant
  - Titanium dioxide (TiO_2) particles
  - Downside: Increase in stiffness of the polymer
- Organic composites: PVDF (poly-vinvylidene fluoride)

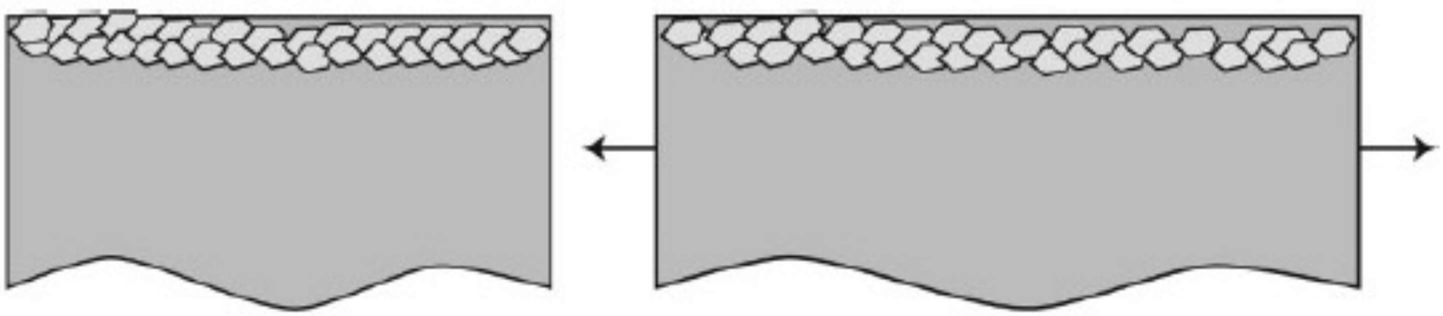
Electrohydraulic Actuators (video)

- Larger forces, higher breakdown voltage

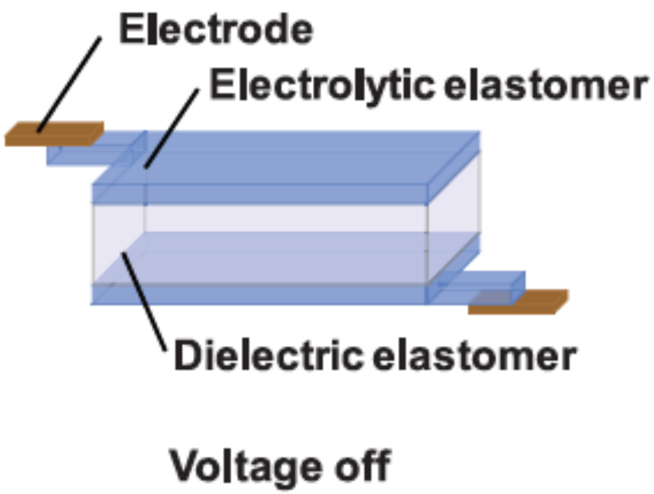


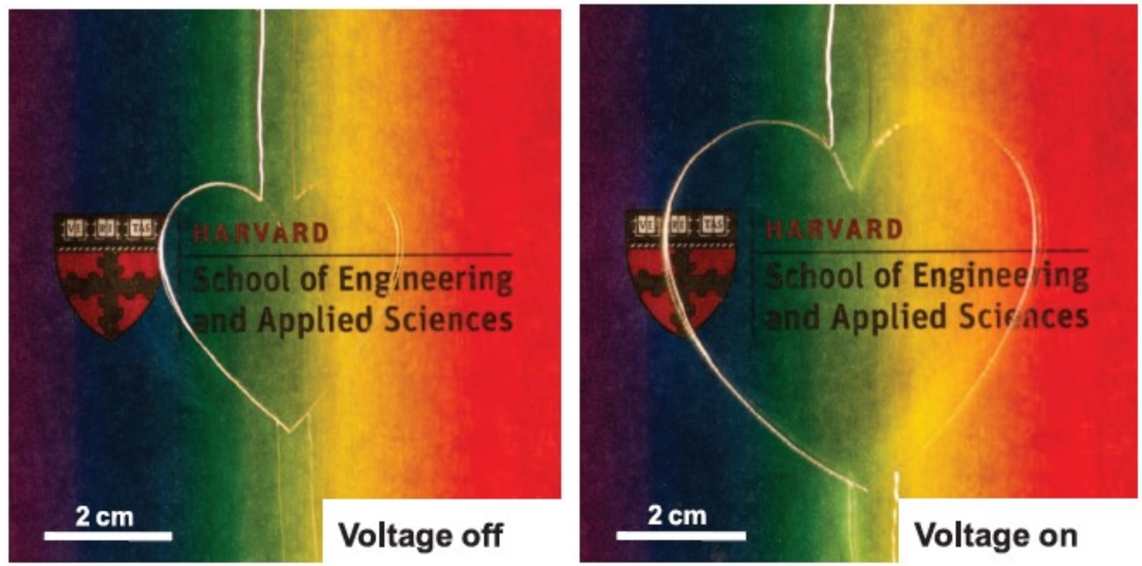
Compliant Electrodes

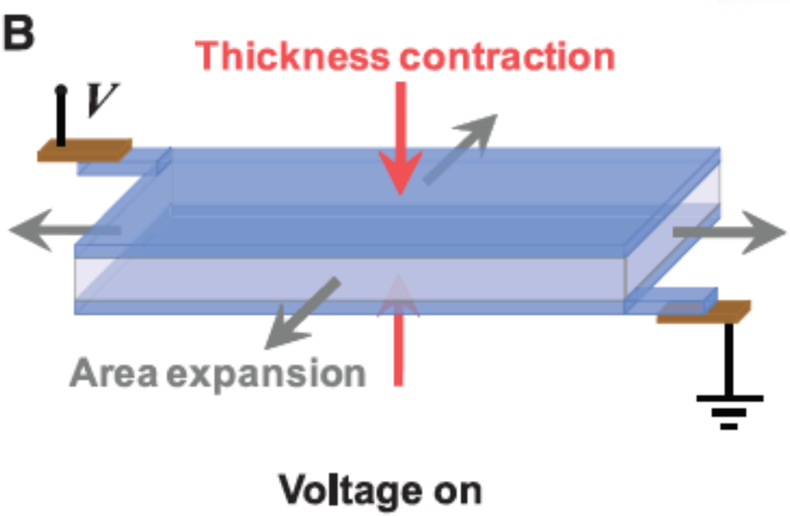
- Conductive paste (carbon-impregnated grease or silver paste)
- Spin-coated conductive rubber
- Sprayed graphite particles
- Carbon sheets
- Compliance with high conductivity

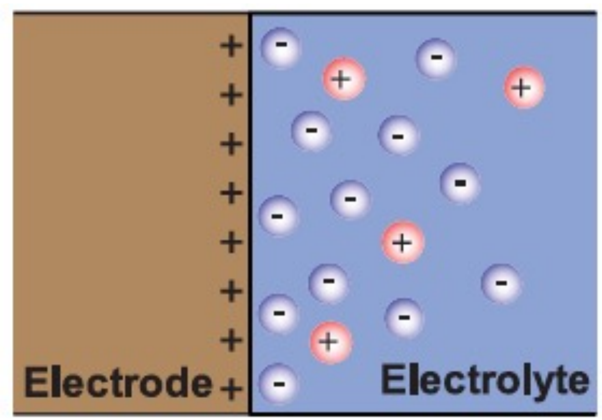


Hydrogel electrodes (ionic conductors)



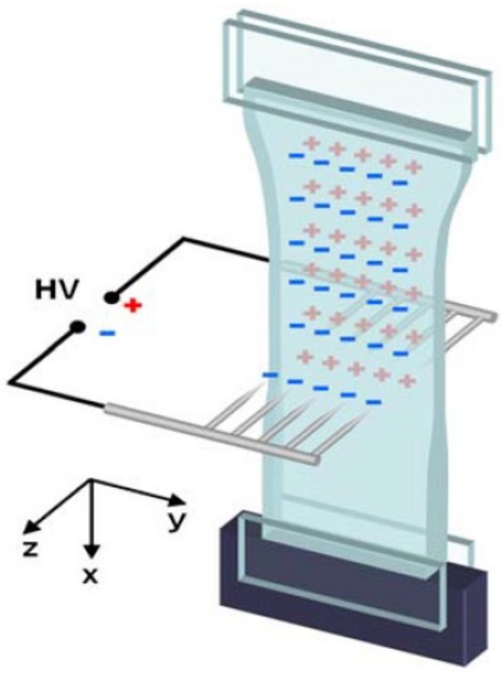


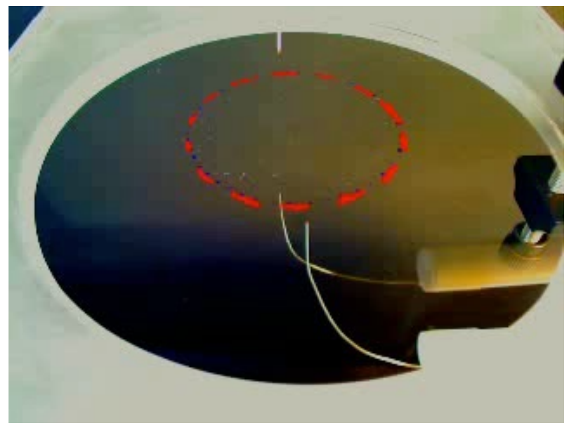




Electrode-free Actuators

- Driven by sprayed-on electrical charge (corona discharge) by needle combs (first studied by Rontgen in 1880)
- Preventing electromechanical instabilities (pull-in)
- Novel configurations





Performance

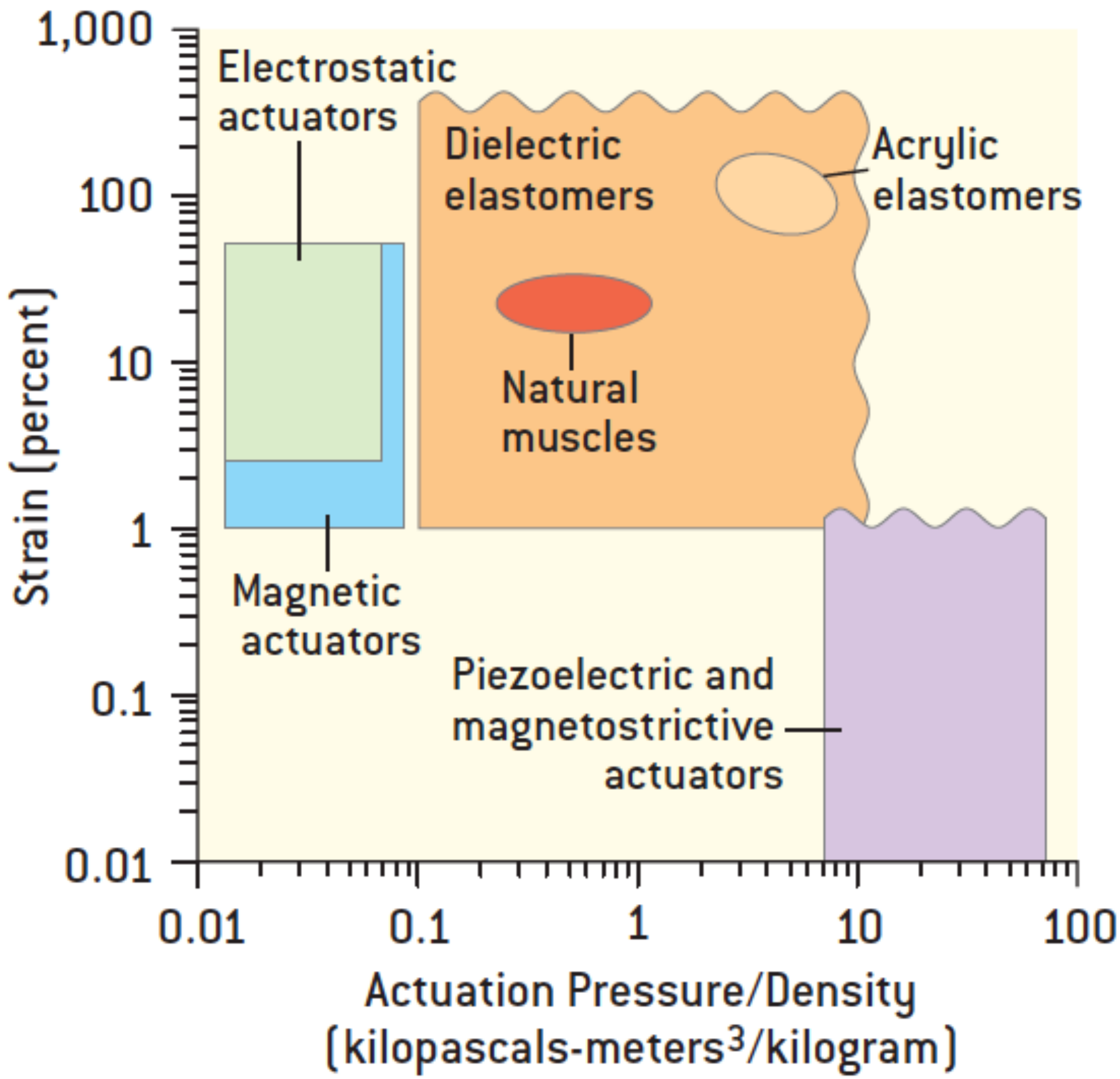
Property	Dielectric elastomers[154–157]
Stimulus	Voltage/electric field
Amplitude of stimulus	100–150 MV m^{-1} (breakdown <420 MV m^{-1})
Areal strain [%]	<380
Thickness strain [%]	<79
Stress [MPa]	<7.2
Work density [MJ m^{-3}]	<3.5
Tensile strength [MPa]	<7.2
Electromechanical coupling efficiency [%]	<90
Dielectric constant	2–10
Bandwidth	<1 kHz
Efficiency [%]	<90
Cycle life	$>10^6$

Performance

TABLE I. Comparison between EAP and widely used transducer actuators.

Property	EAP	SMA	EAC
Actuation strain	Over 300%	<8% (short fatigue life)	Typically 0.1%–0.3%
Force	0.1–25 MPa	200 MPa	30–40 MPa
Reaction speed	μ sec to min	millisecond to minute	microsecond to second
Drive voltage	1–2.5 g/cc	5–6 g/cc	6–8 g/cc
Consumed power	Ionic EAP: 1–7 V Electronic EAP: 10–150 V/μm	5 V	50–800 V
Fracture behavior	Resilient, elastic	Resilient, elastic	Fragile

Performance comparison



Electrostatic Actuation

- Electrostatic force between charged plates
- Electrostatic fields can exert great forces across very short distances
- High efficiency but low power density

Method	Efficiency	Speed	Power density
Electrostatic	Very high	Fast	Low
Electromagnetic	High	Fast	High
Piezoelectric	Very high	Fast	High
Thermomechanical	Very high	Medium	Medium
Phase change	Very high	Medium	High
Shape memory	Low	Medium	Very high
Magnetostrictive	Medium	Fast	Very high
Electrorheological	Medium	Medium	Medium
Electrohydrodynamic	Medium	Medium	Low
Diamagnetism	High	Fast	High

Electrostatic Force

- Energy stored in an electric field (in Joule)

$$W = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 abV^2}{d} = \frac{\varepsilon AV^2}{2d}$$

Where a is the length, b is the height of the width and d is the gap between plates.

- Micron-sized air gap: E ≤ 10^8 V/m → W = 44 kJ/m^3

- Electrostatic Attractive Force (perpendicular to the plates)

$$F = \frac{\partial W}{\partial d} = \frac{\varepsilon AV^2}{2d^2}$$

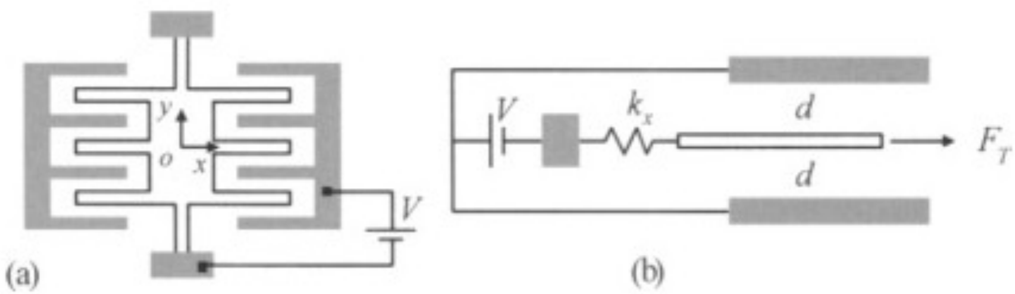
Scaling Analysis

- Assuming that all dimensions scale linearly proportional to L
- Volume scales with L^3
  - Inertia, weight, heat capacity, and body forces
- Surface area scales with L^2
  - Friction, heat transfer, surface forces

- Assuming that the voltage and d is constant, F scales as $\sim L^2$
- If we scale the gap as well then F remains the same

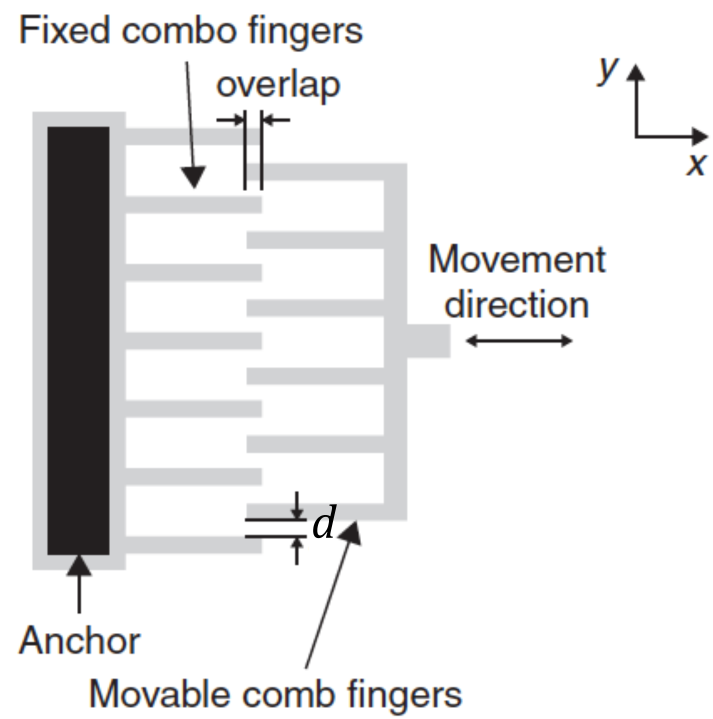
Comb Drive

- Make use of tangential forces for driving
- The stationary electrodes are arranged symmetrically on both sides of each moving finger so that normal forces cancel out



$$F_N = \frac{\varepsilon A V^2}{2d^2} \qquad F_T = \frac{\varepsilon b V^2}{2d}$$

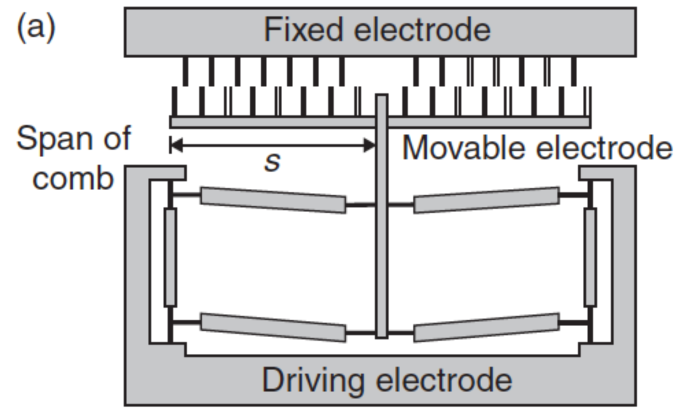
where b is the height of the finger.



Comb Drive

- For a set of n capacitors the total driving force is given by

$$F_T = n\varepsilon \frac{bV^2}{d}$$



- The restoring force is

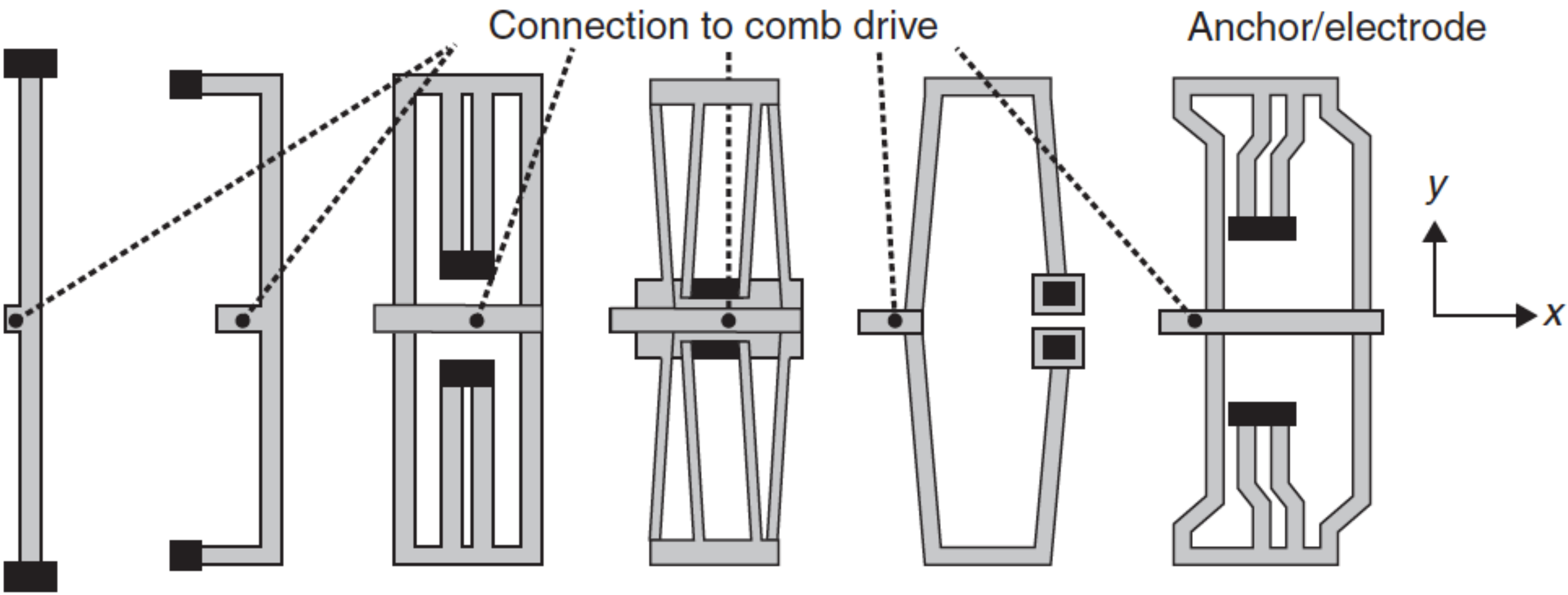
$$F_R = kx = 4\frac{Ebw^3}{l^3}x$$

where w is the width and l is the length of the flexure

- The equation of motion

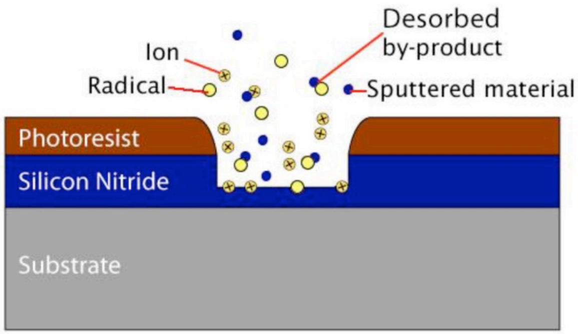
$$F_T - F_R = n\varepsilon \frac{bV^2}{d} - 4\frac{Ebw^3}{l^3}x = 0$$

Beam suspension configurations



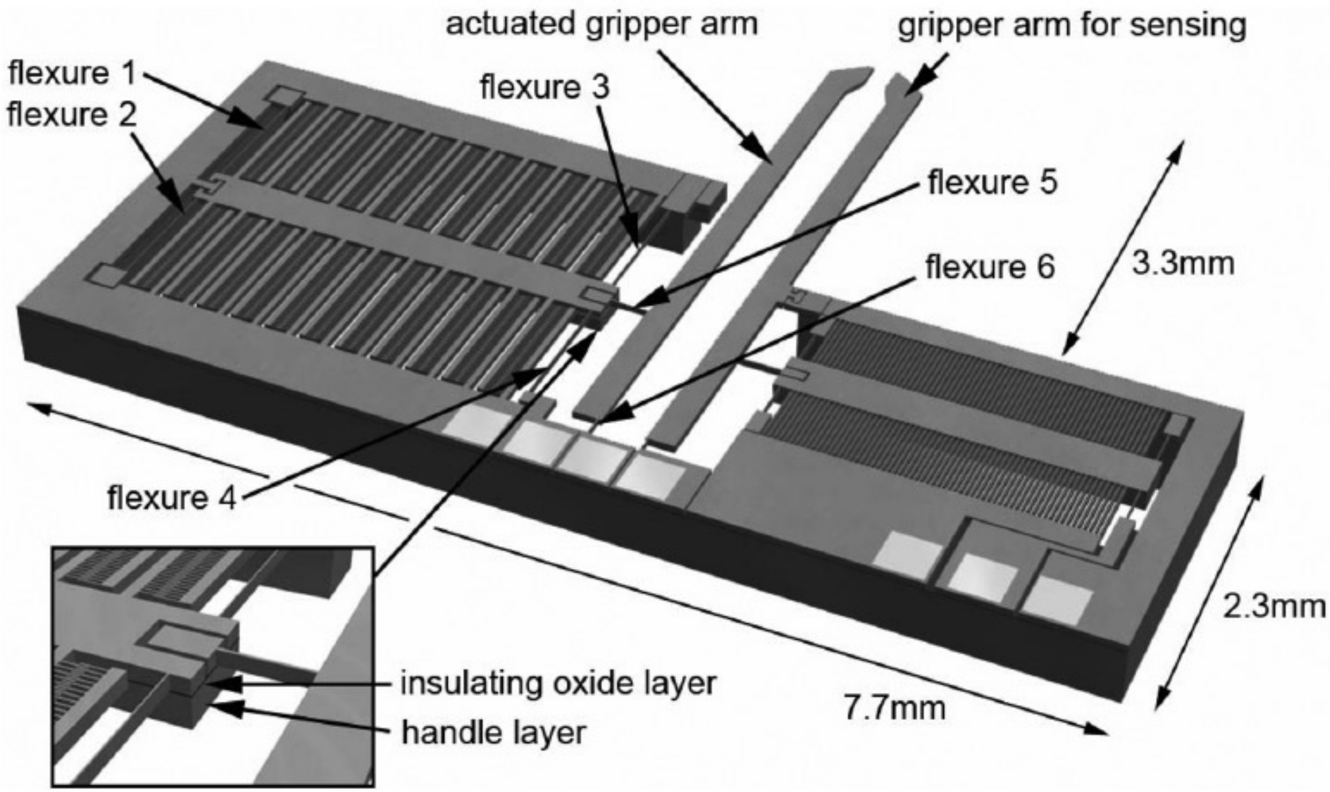
Microfabrication

- Etching
  - Wet etching: Material is removed through a chemical reaction with liquid etchant (HF)
  - Dry etching: Gaseous etchant suspended in RF-energized plasma

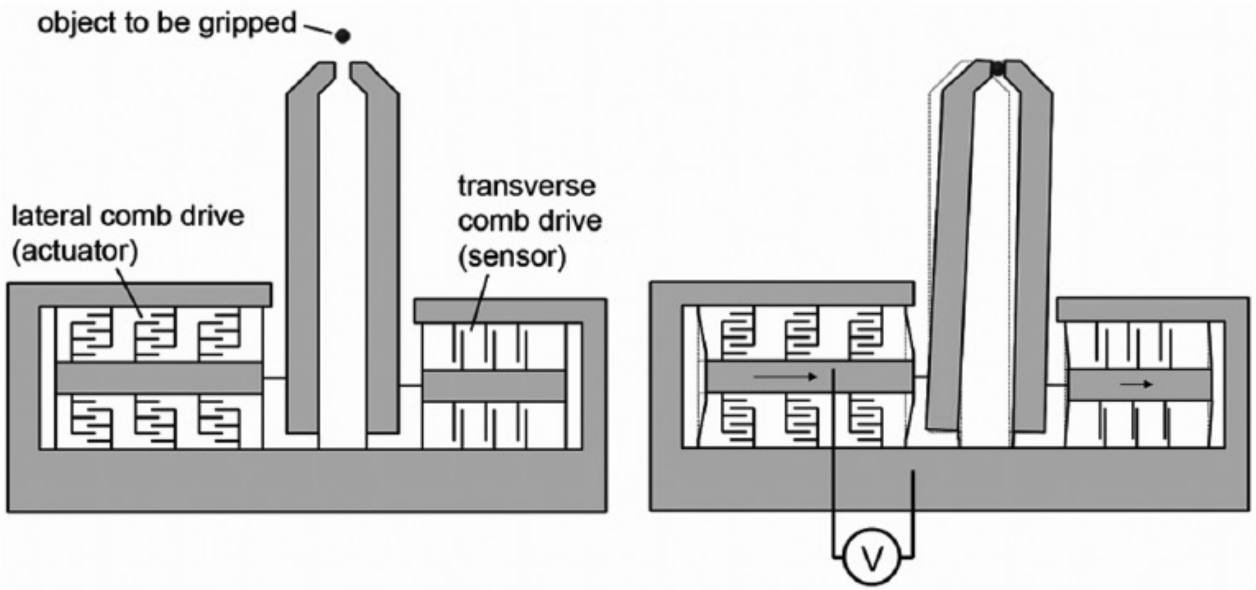


- Reactive Ion Etching
  - Two regimes: physical and chemical (both dry)
  - Ions from plasma are accelerated to the sample
  - Highly energetic impact causes the material to sputter away
  - Selectivity: material hardness
  - Free radicals from plasma are absorbed and a chemical reaction occurs
  - The products are removed from the substrate
  - Selectivity: chemical reactivity

Capacitive Force Sensors and Grippers



Capacitive Force Sensors and Grippers



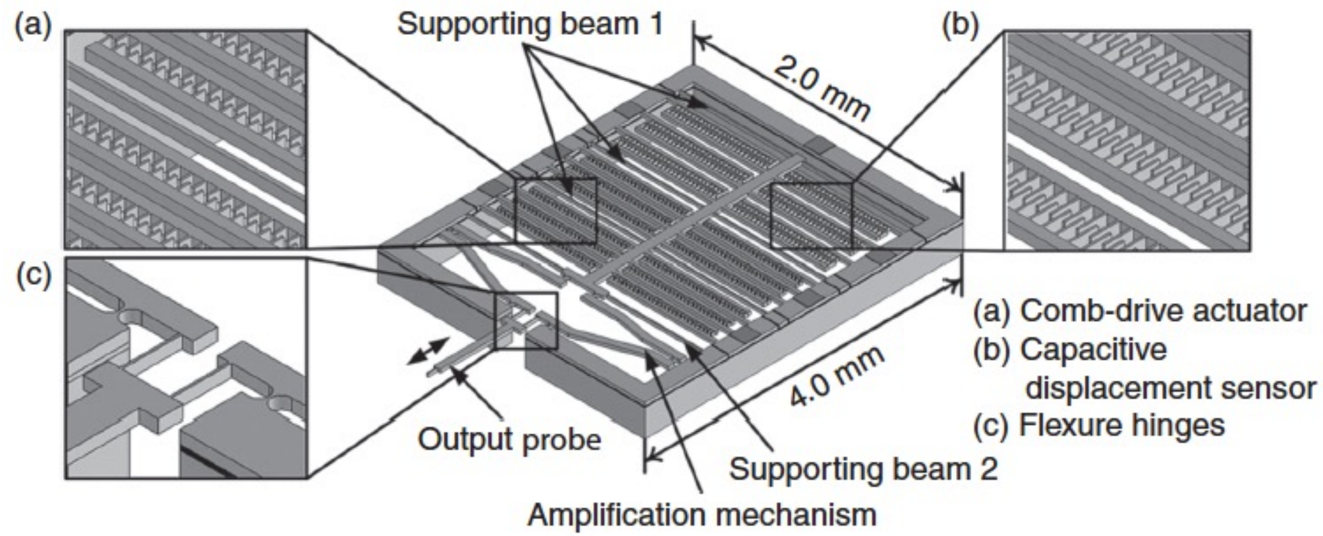
	50μm opening	100μm opening	200μm opening
actuation voltage	0-110V	0-150V	0-150V
gripper opening range	0-50μm	0-100μm	100μm-200μm
flexure dimensions	900μm x 10μm x 50μm		
electrode dimensions	100μm x 5μm x 50μm		
gap spacing between electrodes	5 μm		

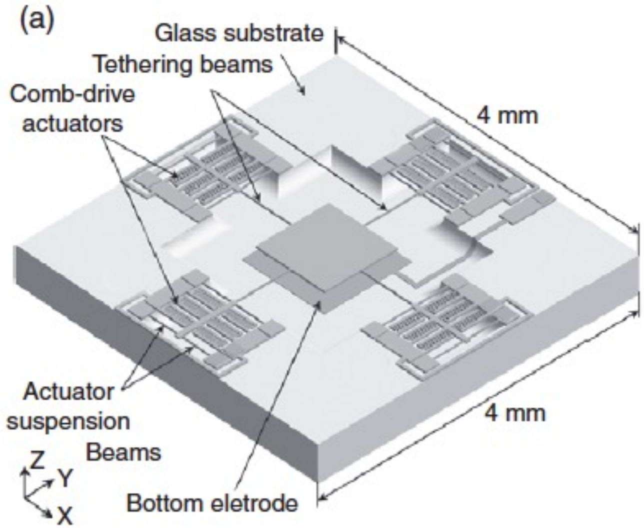
Capacitive Force Sensors and Grippers

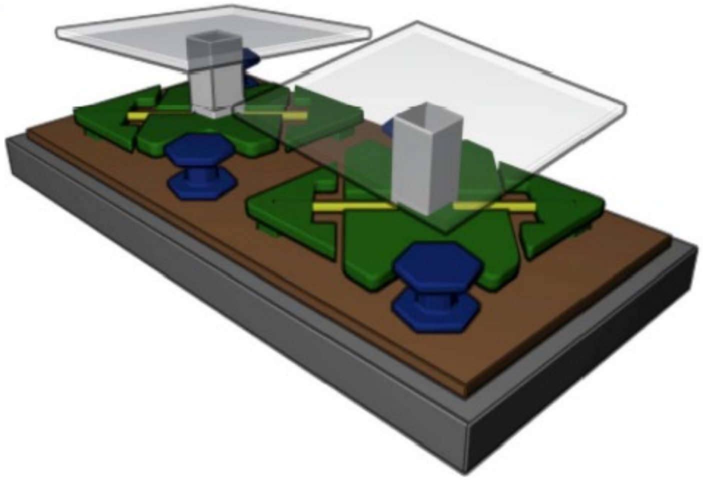
	150µm flexure	300µm flexure
linear range	± 2800µN	± 360µN
sensitivity*	0.55mV/µN	4.41mV/µN
resolution	520nN	70nN

[illegible]	[illegible]	[illegible]	[illegible]
gripper opening range	0-50µm	0-100µm	100µm-200µm
flexure dimensions	900µm x 10µm x 50µm		
electrode dimensions	100µm x 5µm x 50µm		
gap spacing between electrodes	5 µm		

Nanopositioning Stages and Digital Mirror Device (video)

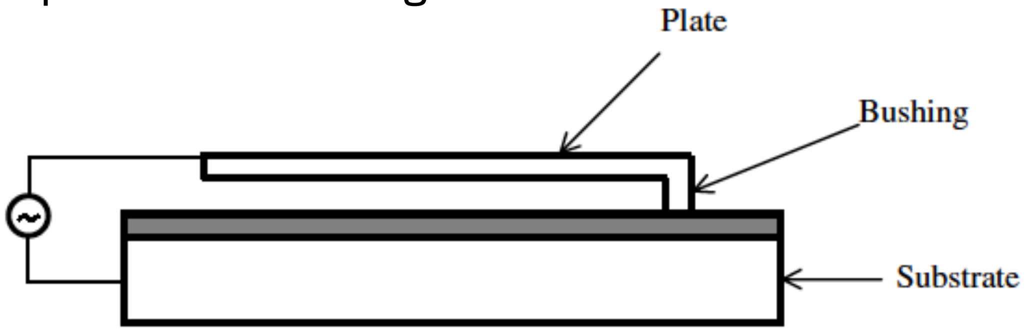






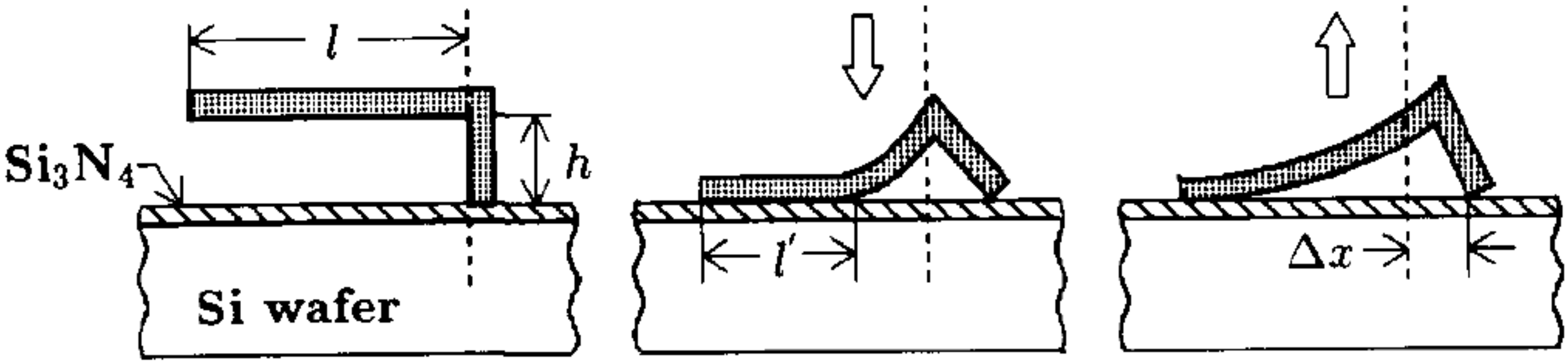
Scratch Drive Actuator

- Deformation of a plate and sliding motion



- Capacitor like structure.
  - The plate experiences an electrostatic force that pulls it down.
  - Warping of the plate causes the bushing to shift, and slide towards the edge in contact with the substrate.
  - When voltage is removed, the plate and bushing snap back to original position, but translated forwards a small distance

Scratch Drive Actuator

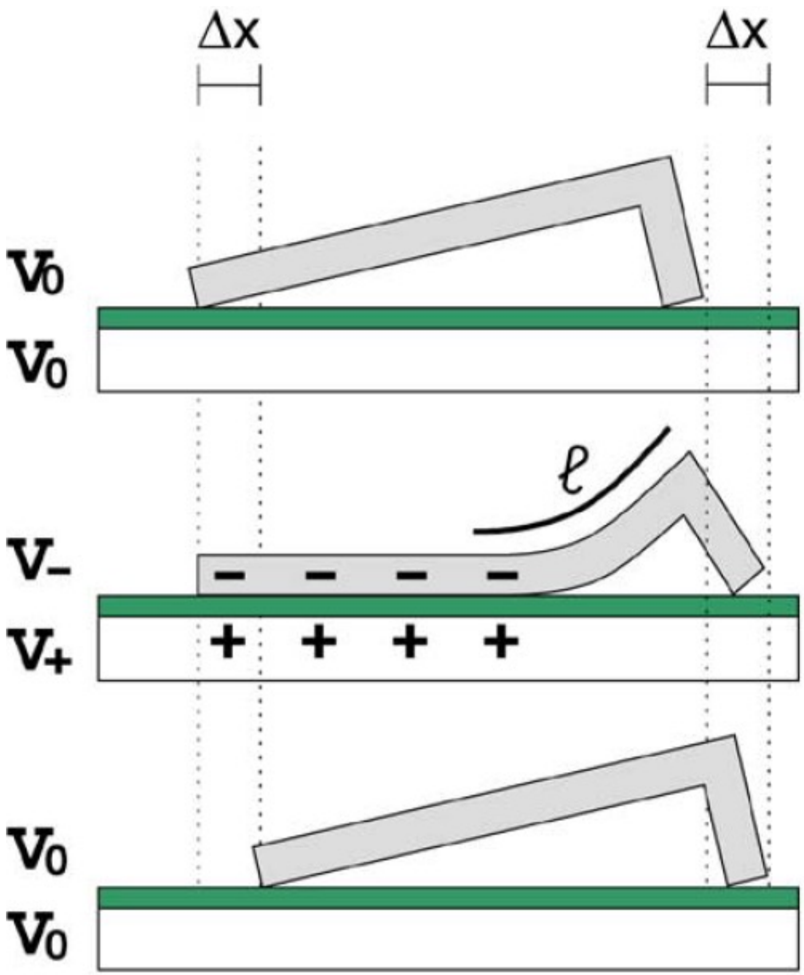


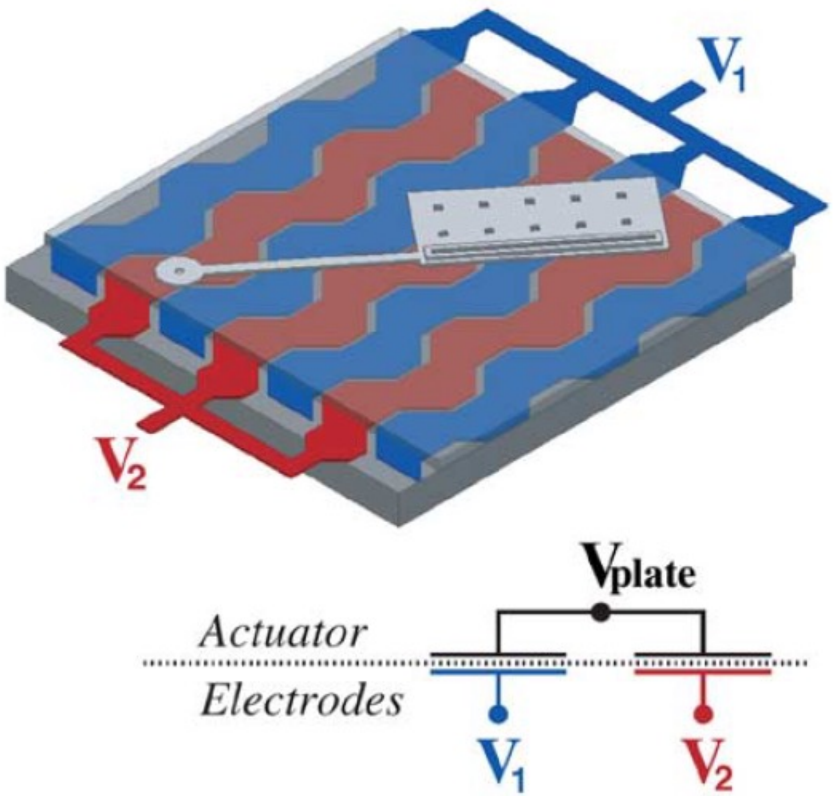
$$\Delta x = \frac{h^2}{2(l - l')}$$

$$v = \Delta x \cdot f$$

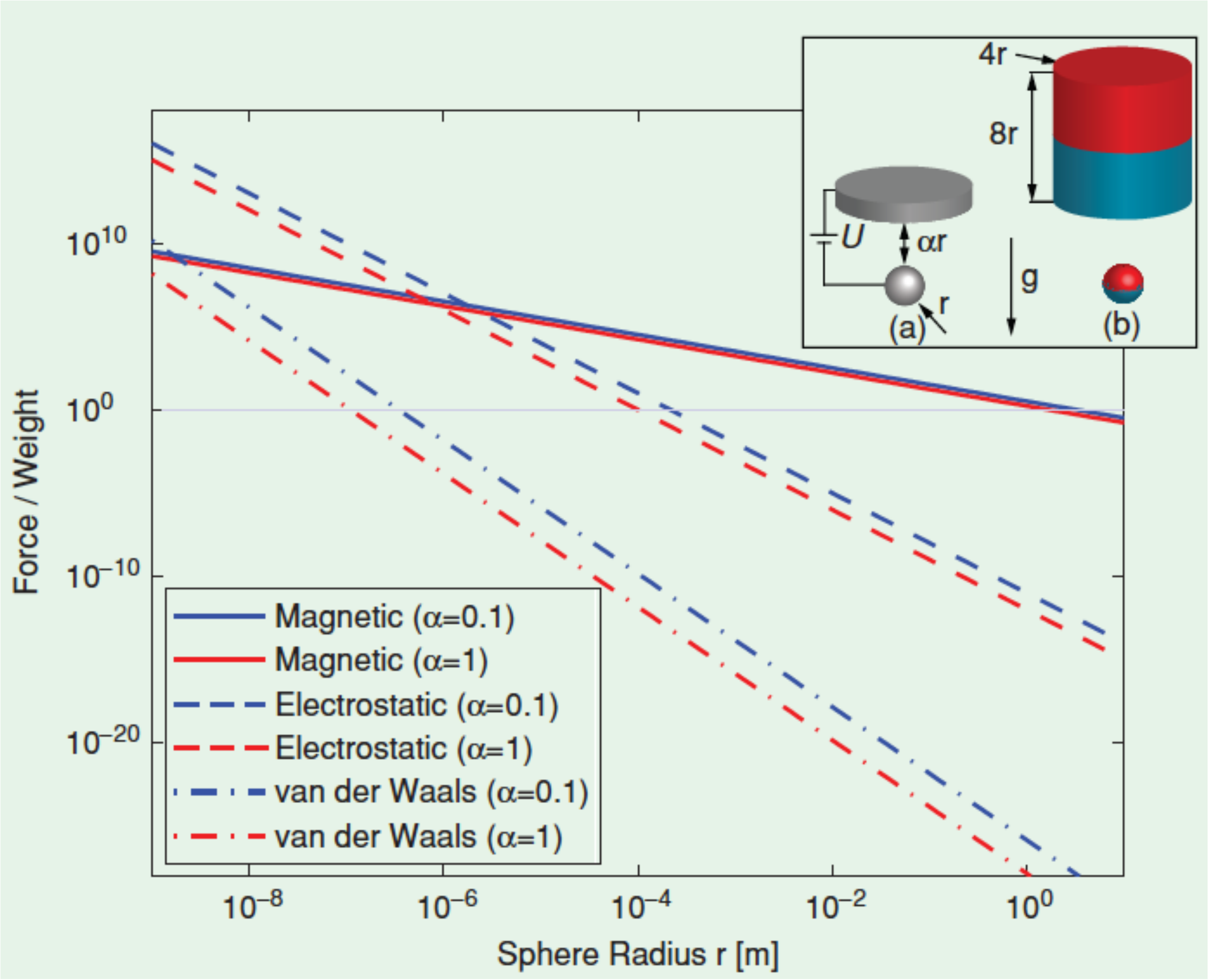
- Velocity and step size determined by the frequency and amplitude of the driving signal
- Linear motion, potentially large range of travel with relatively high force, and very fine control (step size on the order of 10-30 nm for 1 um bushing height)

Untethered Scratch Drive Actuator (video)





Scaling of Attractive Forces

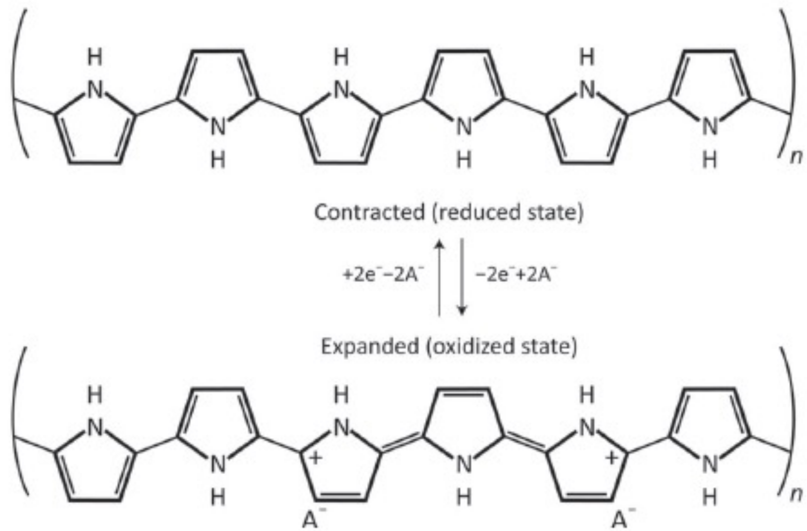


Ionic Electroactive Polymers

- Conjugated Polymers
  - Doping to convert semiconductor to conductor
- Rely on ion or solvent transport to control volume change
  - Electrochemical oxidation or reduction in an electrolyte
- Require low voltage
- Work in liquid electrolytes including bodily fluids
- Polypyrroles (PPys)

$$(\mathrm{M})_n - me^- + m\mathrm{A}^- \leftrightarrow (\mathrm{M})_n^{m+}(\mathrm{A}^-)_m$$

Contracted (reduced state) ↔ Expanded (oxidized state)



Mechanism

- Conducting polymers under a tensile load (F): Hooke's law

$$\varepsilon_f = \varepsilon_0 + F\left(\frac{1}{K'} - \frac{1}{K}\right) = \varepsilon_0 + \sigma_E\left(\frac{1}{Y'} - \frac{1}{Y}\right)$$

Generated tensile strain (ε_f) is the sum of tensile strain under no load (ε_0) and the strain due the change in stiffness.

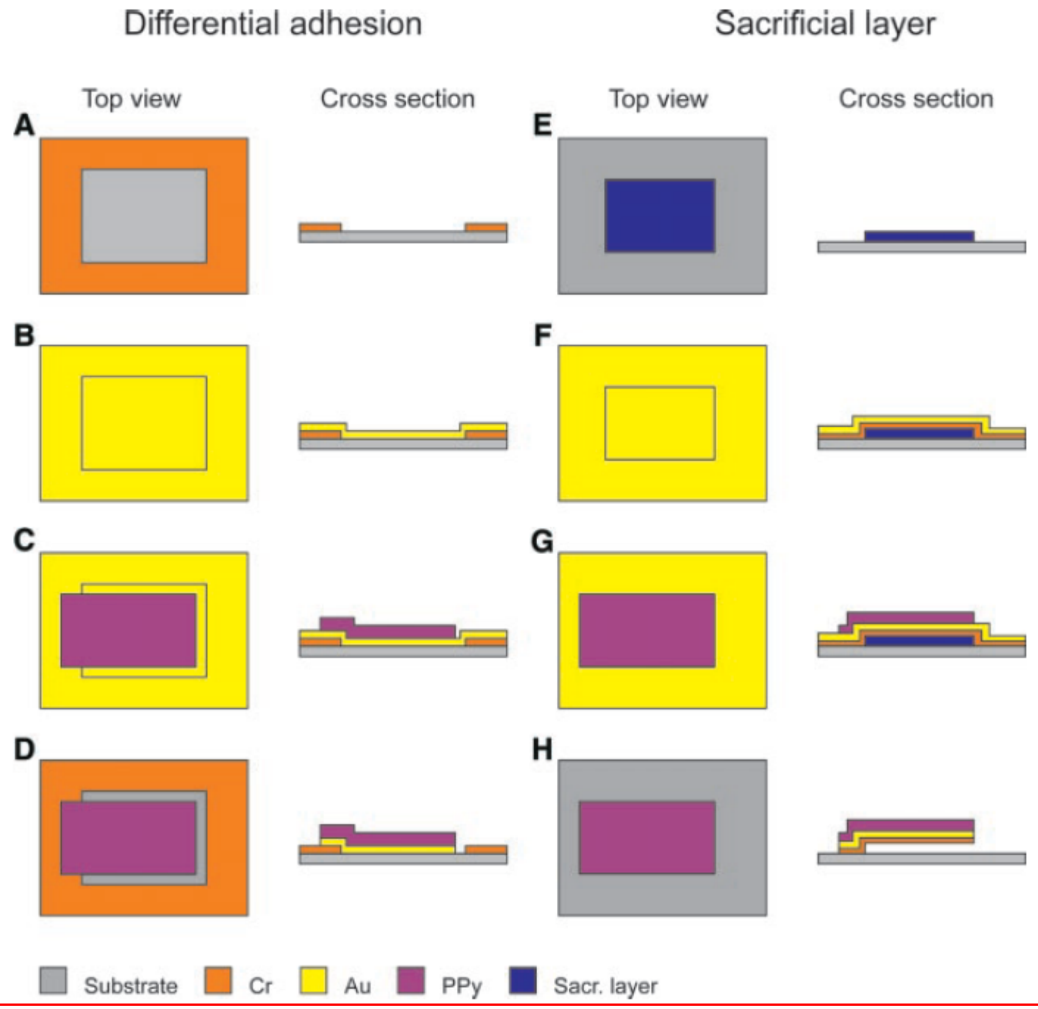
- Charge injection is a diffusion process: thickness determines the actuation time (bandwidth). Lowering thickness decreases force.
- Slow response and low force
- Hydrolysis and low efficiency
- Delamination of the polymer from the electrode

Performance

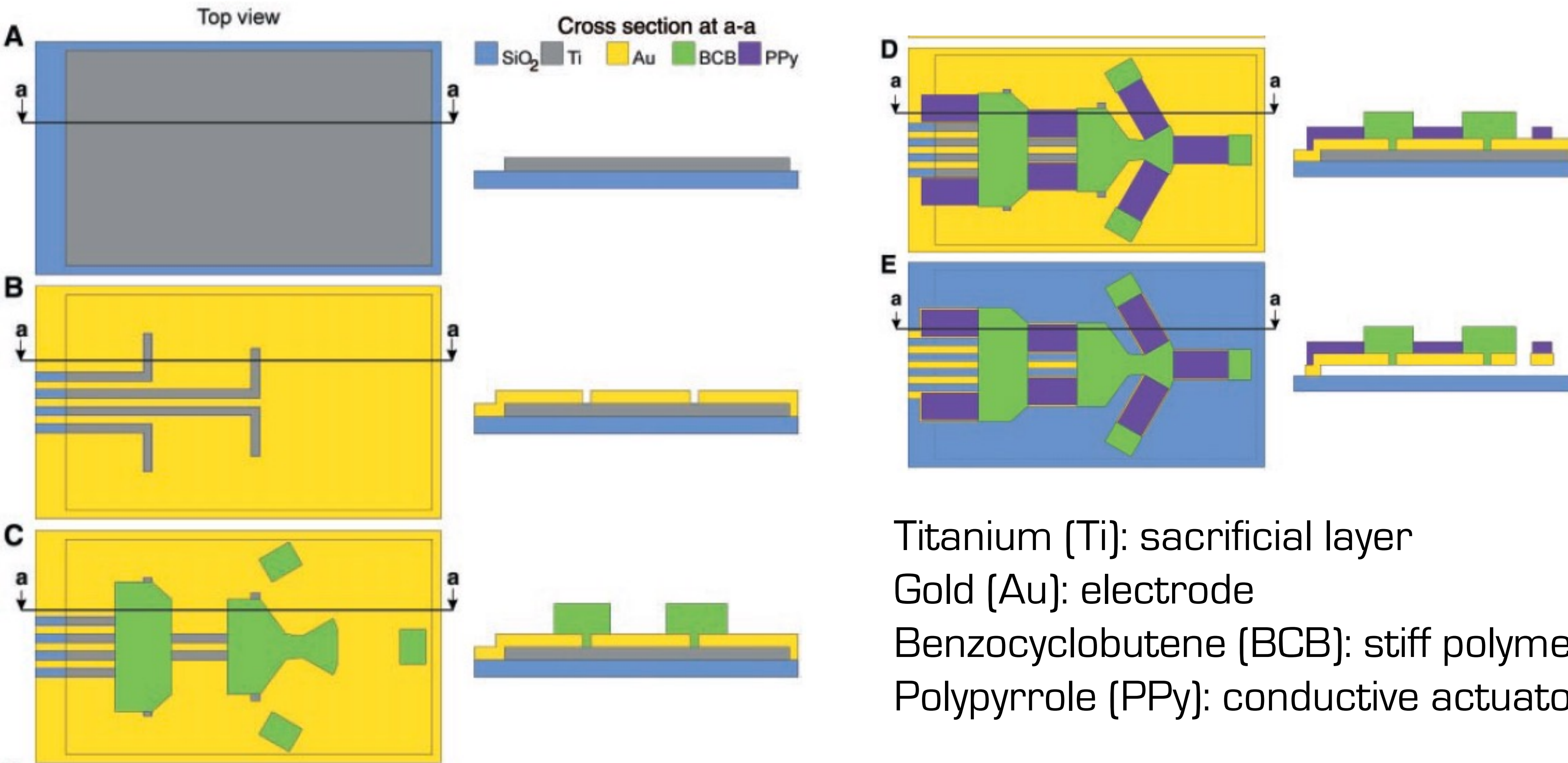
Property	Conducting polymers[a)]
Stimulus	Voltage (charge injection in the structure)
Amplitude of stimulus	2–10 V[162] (<40 V as an electrode)[193]
Strain [%]	2–10[158] (<40)[194,195]
Stress [MPa]	<34[158]
Strain rate [% s^{-1}]	<12[191]
Work density [MJ m^{-3}]	<100[196]
Tensile strength [MPa]	≈100[197]
Bandwidth [Hz]	<1000[198]
Efficiency [%]	<18[199]
Cycle life	<500 000[200]
Conductivity [MS m^{-1}]	>1[201]

Conjugated Polymer Actuators

- Electrodeposition of Ppy layer



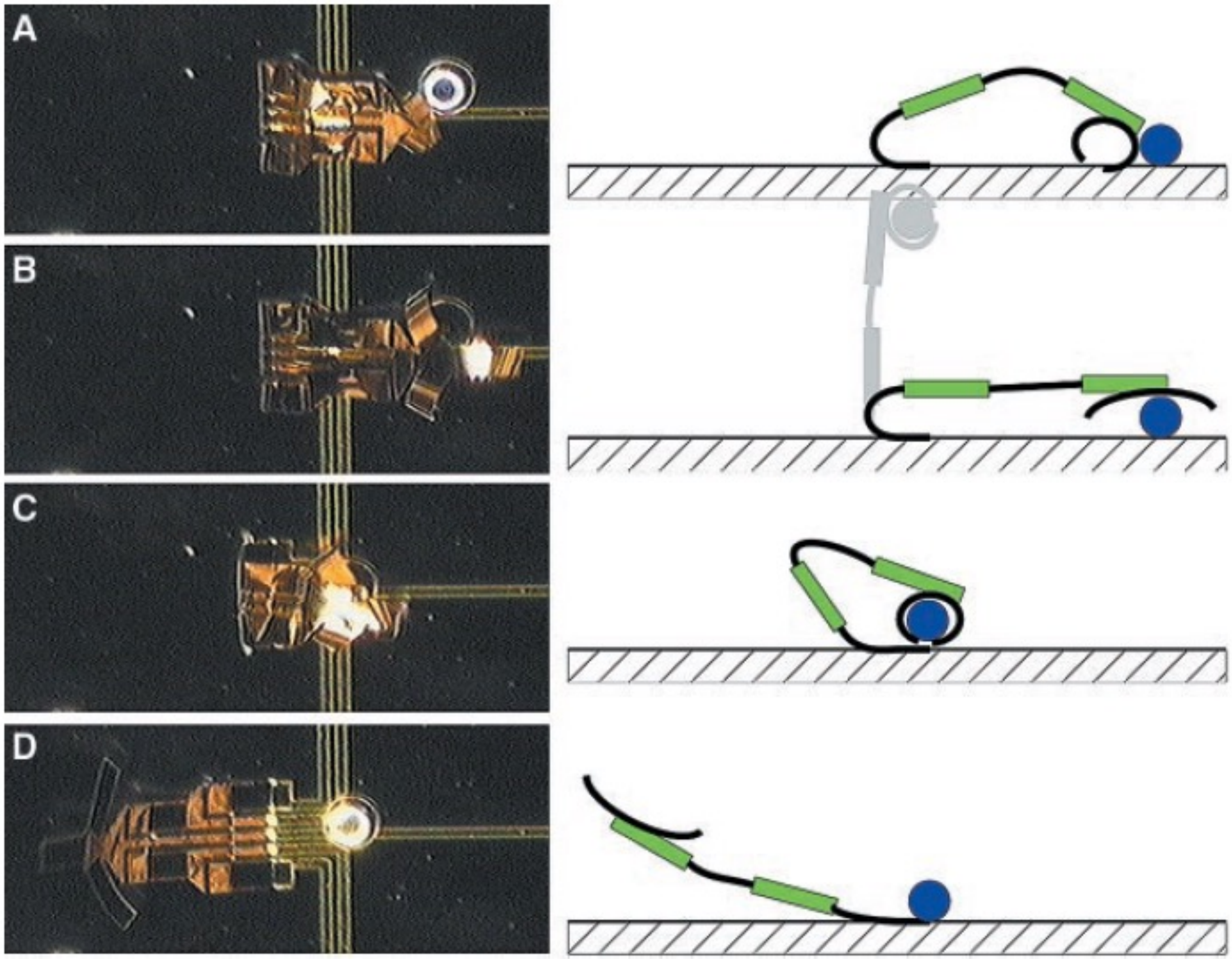
Micromanipulation



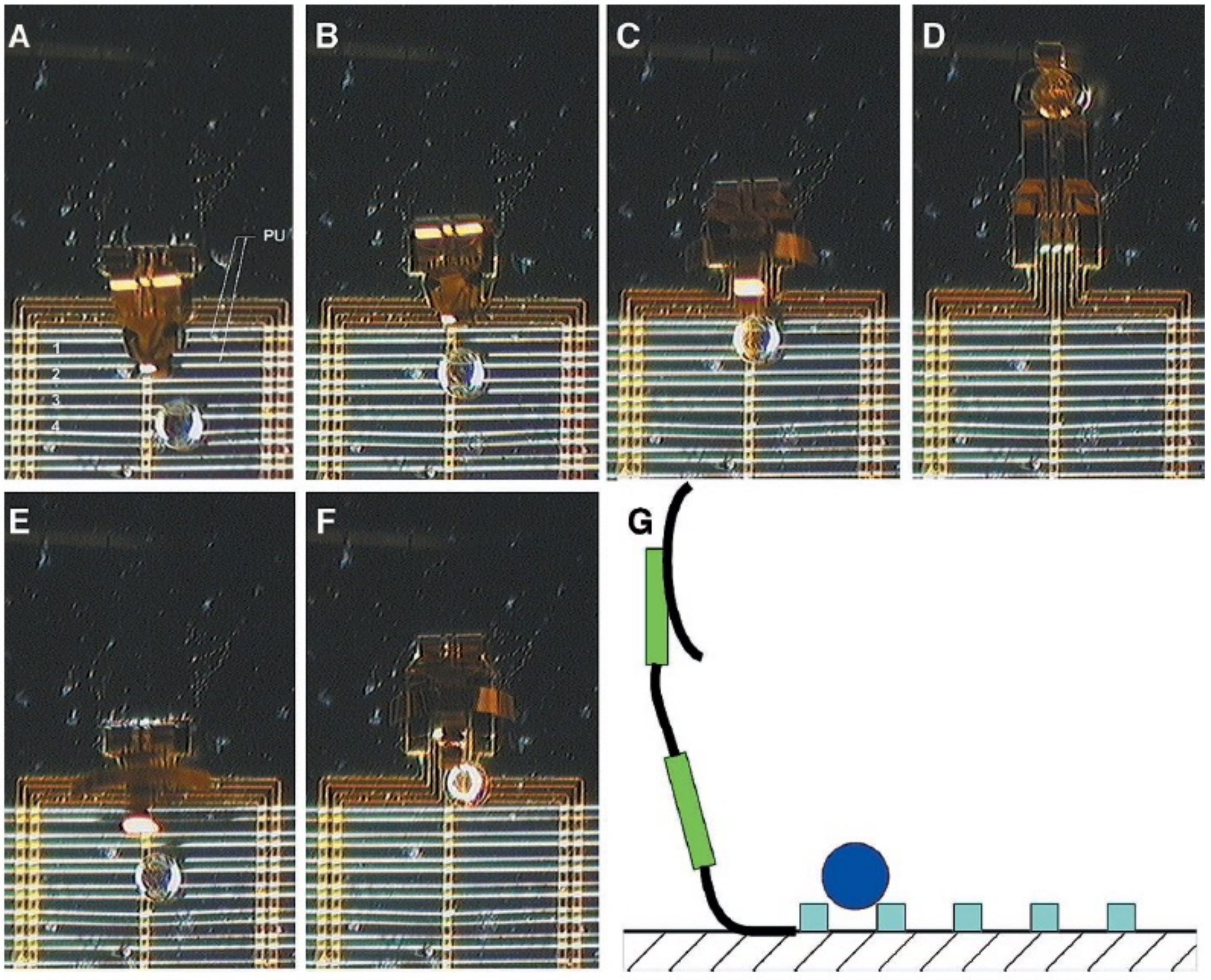
Titanium (Ti): sacrificial layer
Gold (Au): electrode
Benzocyclobutene (BCB): stiff polymer
Polypyrrole (PPy): conductive actuator

BCB as rigid passive layer
Gold-PPy bilayer bending actuator

Micromanipulation

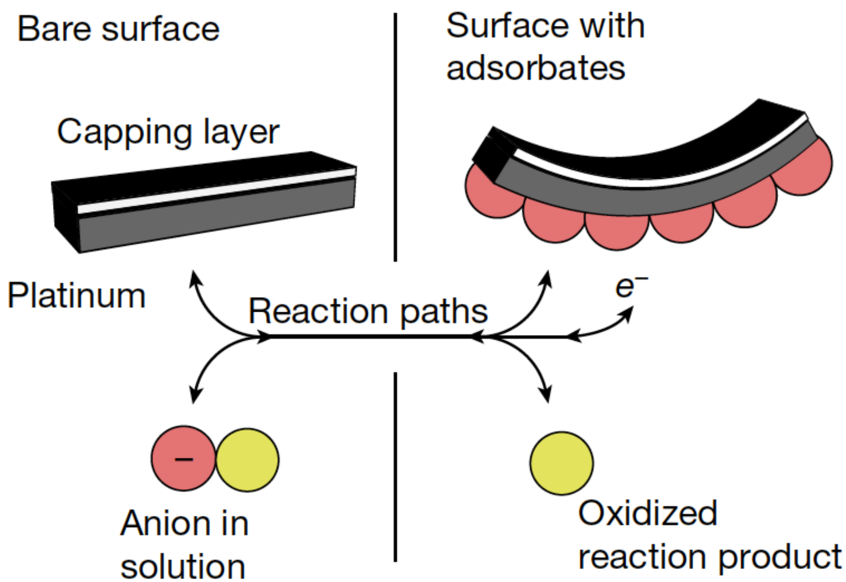


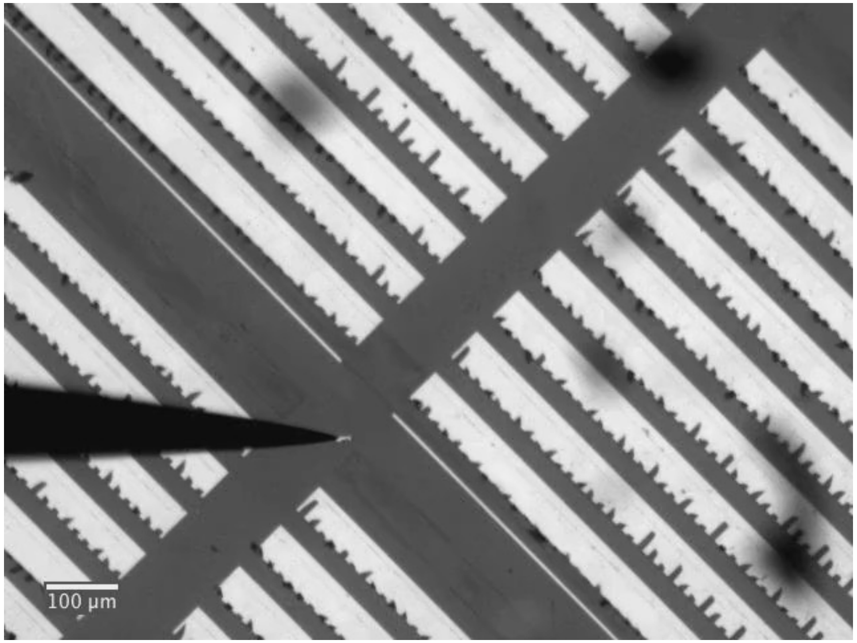
Micromanipulation



Platinum-based surface electrochemical actuators

- 7-nm thick layers of platinum
- Ions absorb/desorb from the platinum surface, changing surface stress
- Low voltage (200 μV), low power (10 nW) and compatible with semiconductor technology





Platinum-based surface electrochemical actuators