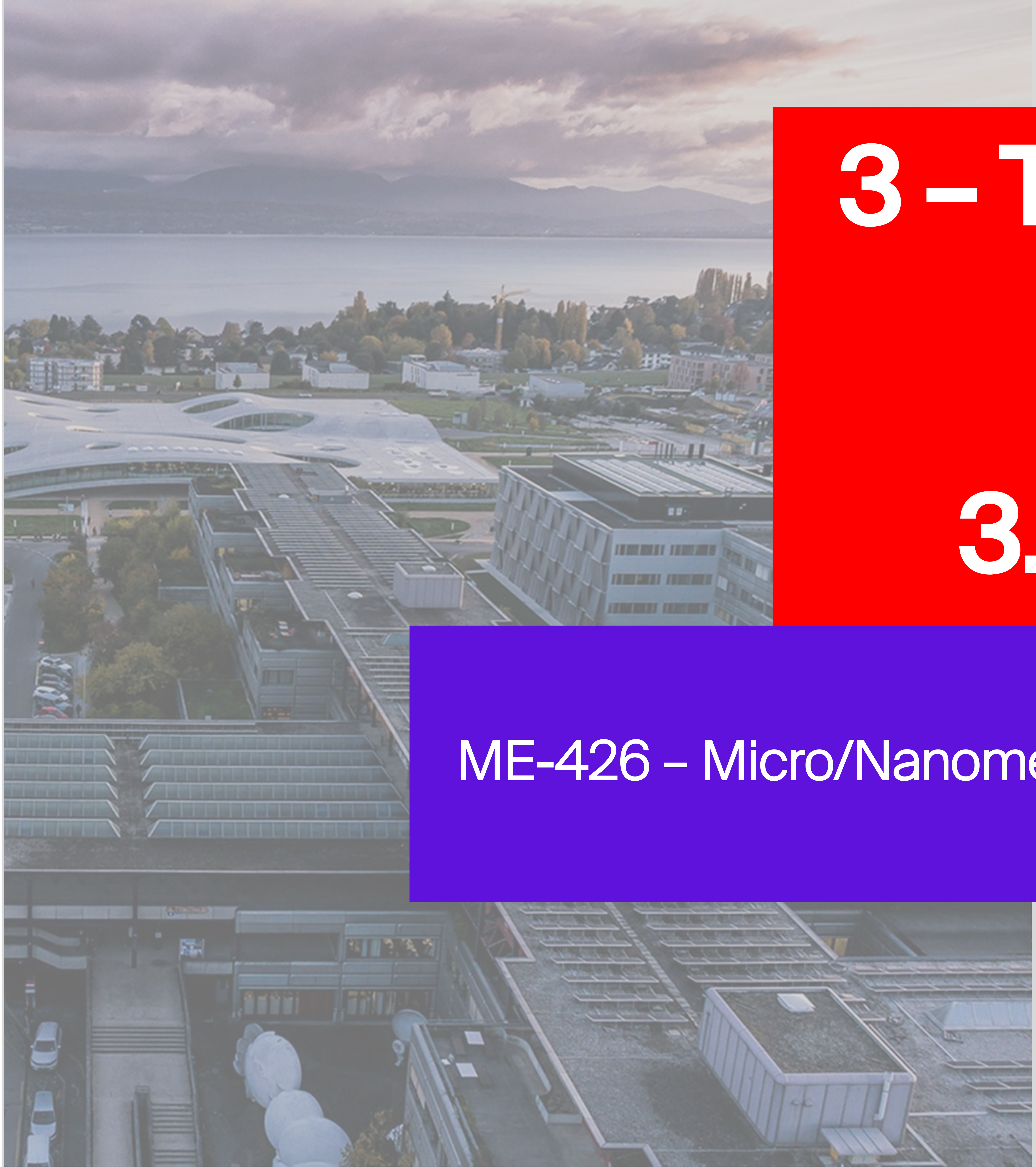


EPFL

3 – Transduction of the motion

3.1 - Actuation

ME-426 – Micro/Nanomechanical Devices

Prof. Guillermo Villanueva

École polytechnique fédérale de Lausanne

Introduction

- Transduction
- Actuation
- Shaped Memory Polymer
- Force-based
- Deformation-based

Transduction

Definition of a transducer in N/MEMS

A transducer is a device, usually electrical, electronic, or electro-mechanical, that converts one type of energy to another for the purpose of measurement or information transfer. Most transducers are either sensors or actuators. In a broader sense, a transducer is sometimes defined as any device that senses or converts a signal from one form to another.

(www.Wikipedia.com)

Transduction of the motion

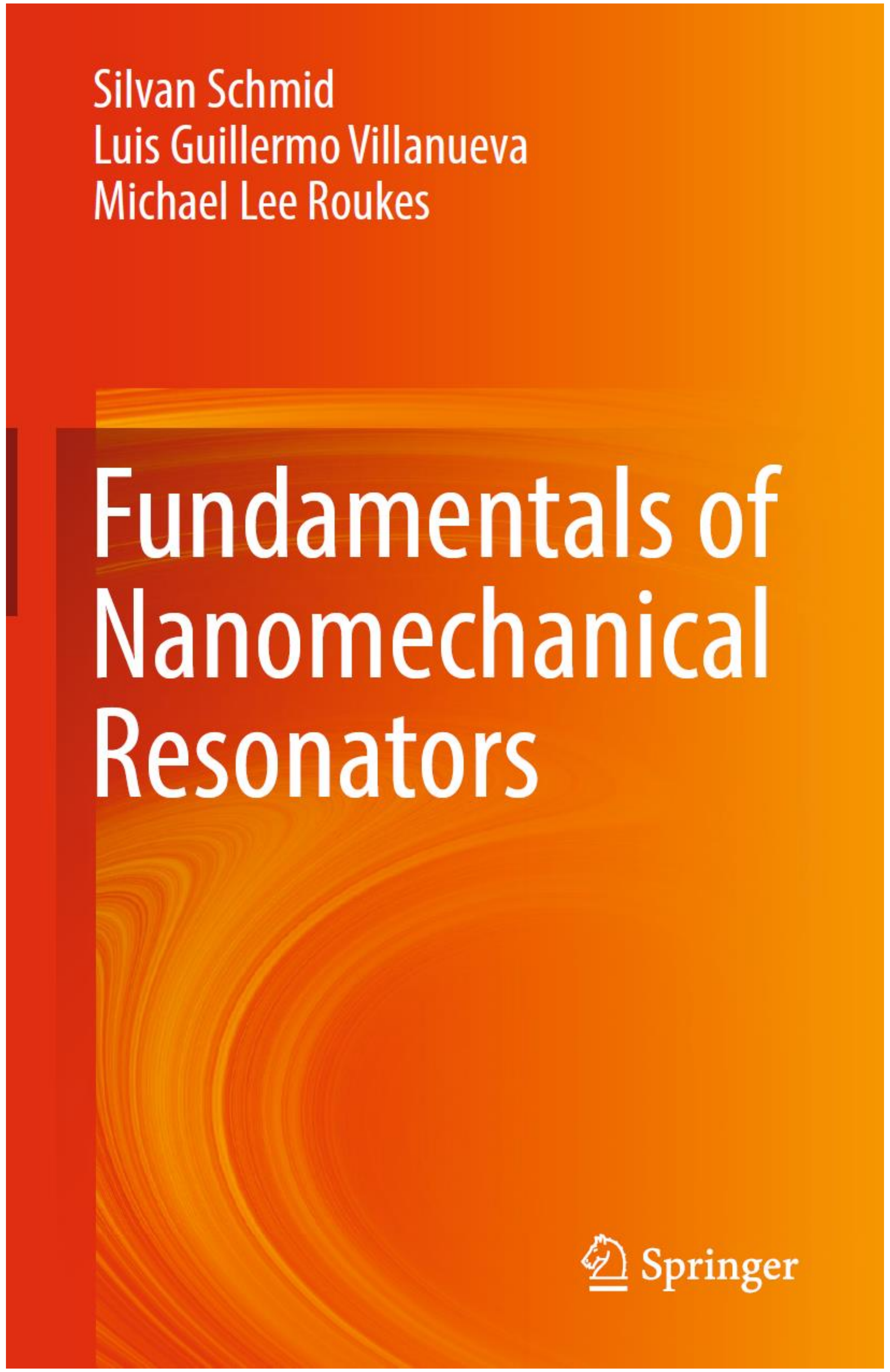
- MEMS are, above all, mechanical devices
  - Some have electronics, some have optical or magnetical elements
  - But all are mechanical

- Mechanical devices either serve as supports OR they MOVE

- Question (1) – take anything around you (e.g. a pen) and move it
  - How have you moved it?
- Question (2)
  - How do you know it has moved?

Transduction in the microscale

- Chapter 4: Transduction
- Available at EPFL [for free]



Transduction in the microscale

Actuation

- Pressure
  - Shape Memory Polymers
- Force
  - Magnetic force
  - Electrostatic force
- Expansion
  - Piezoelectric
  - Thermal
    - Electro-thermal
    - Opto-thermal

Detection

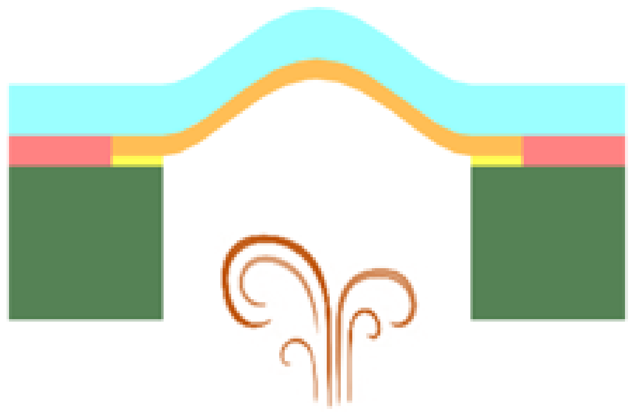
- “Seeing”
  - Optical lever
  - Interferometers
- Associated with a Force
  - Magnetomotive
  - Capacitive
- Associated with deformation
  - Piezoelectric
  - Change in resistance
    - Piezo-metallic (metal gauges)
    - Piezoresistive

Actuation

Shape Memory Polymer

Shape Memory Polymer

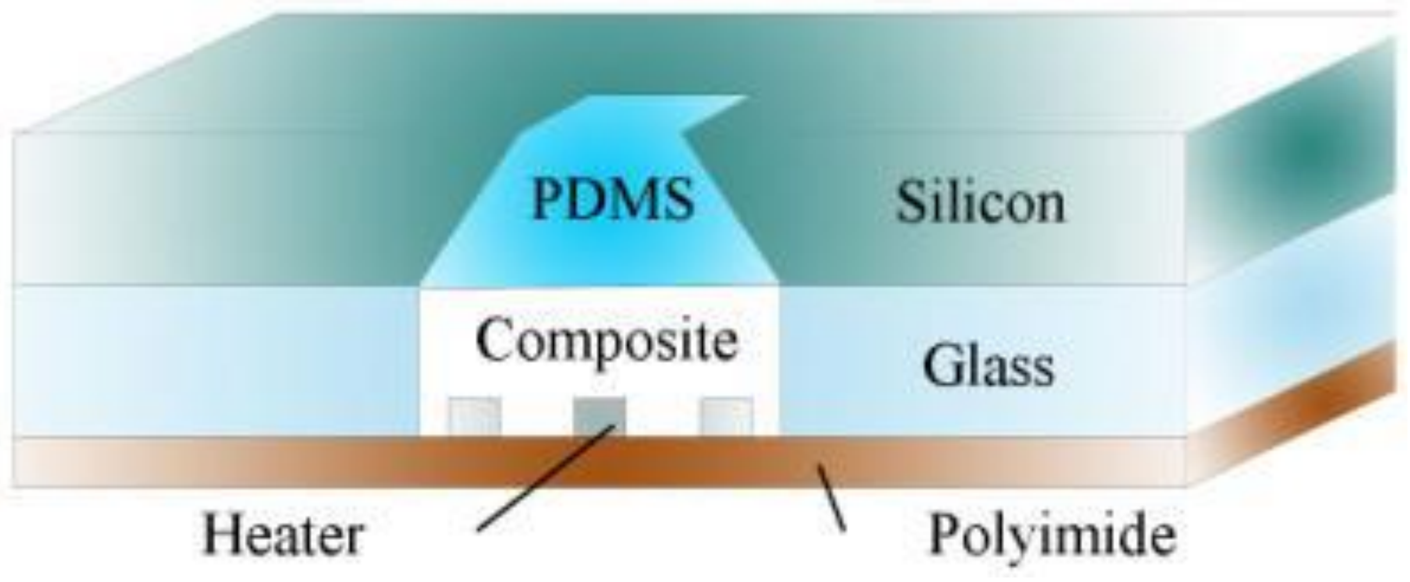
- Pressure deforms
- To maximize deformation
  - Softer polymer
- To keep force
  - Phase change!

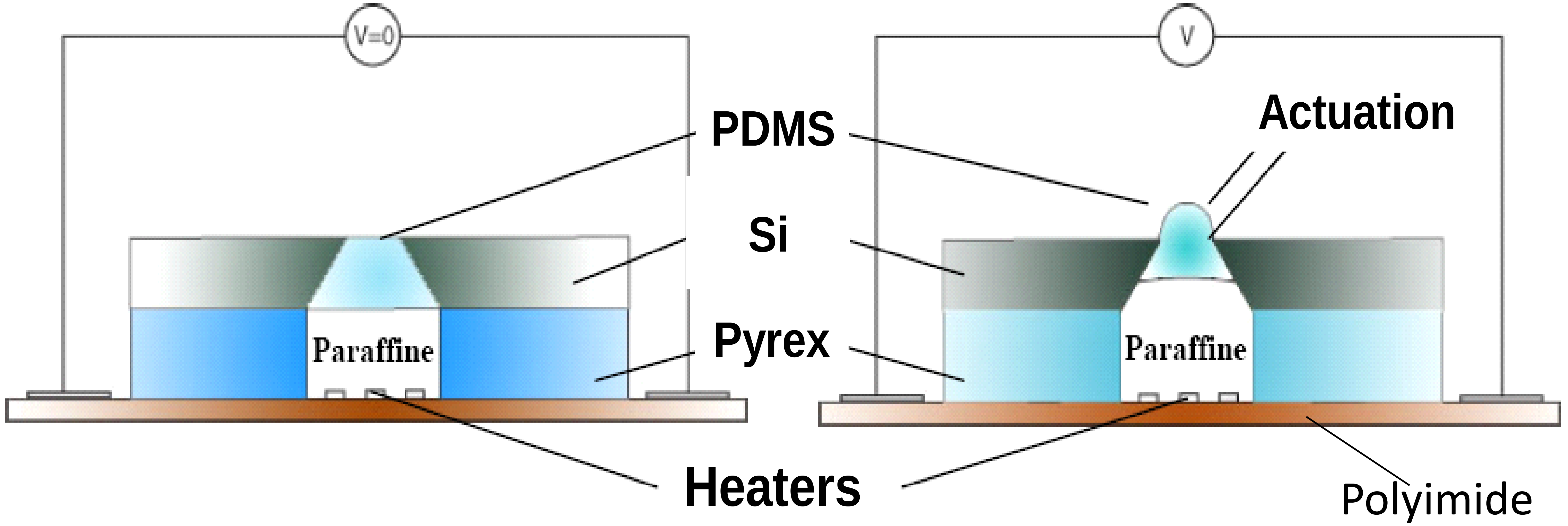


Pneumatic actuation
(positive pressure)

Phase change actuators

- Paraffin from solid to liquid phase
  - Response time of few seconds
  - Issue with the reversibility





From EPFL-SAMLAB

Transduction in the microscale

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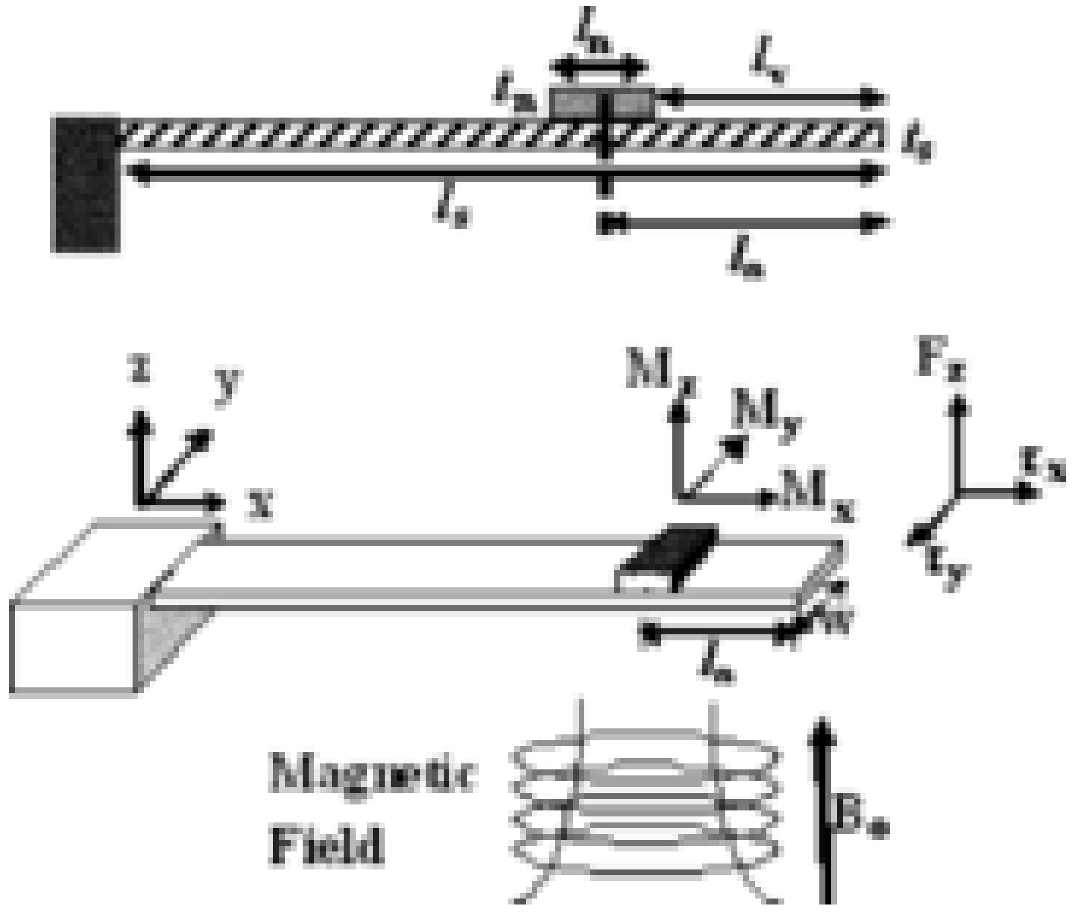
Actuation

Force-based Actuation

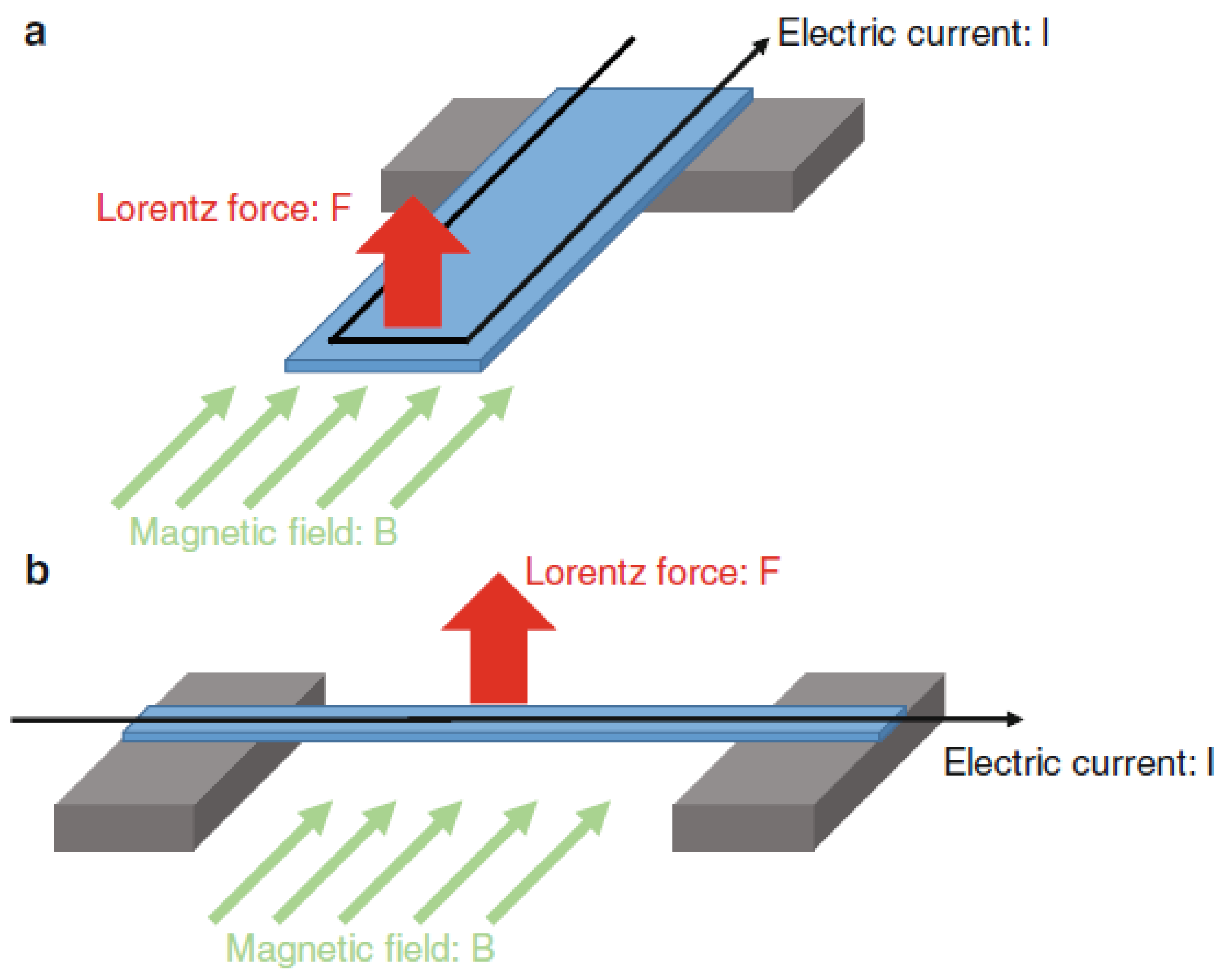
Magnetic Actuation (1)

- Magnetic material on MEMS
  - Magnetic force on dipoles
  - $\vec{F} = \nabla(\vec{m} \cdot \vec{B})$
  - Ferromagnetic material on MEMS
  - External magnetic field causes force on system
  - Almost no heating, purely reactive actuation
  - Tough to get ferromagnetic materials at the µ-scale



Magnetic Actuation (2)

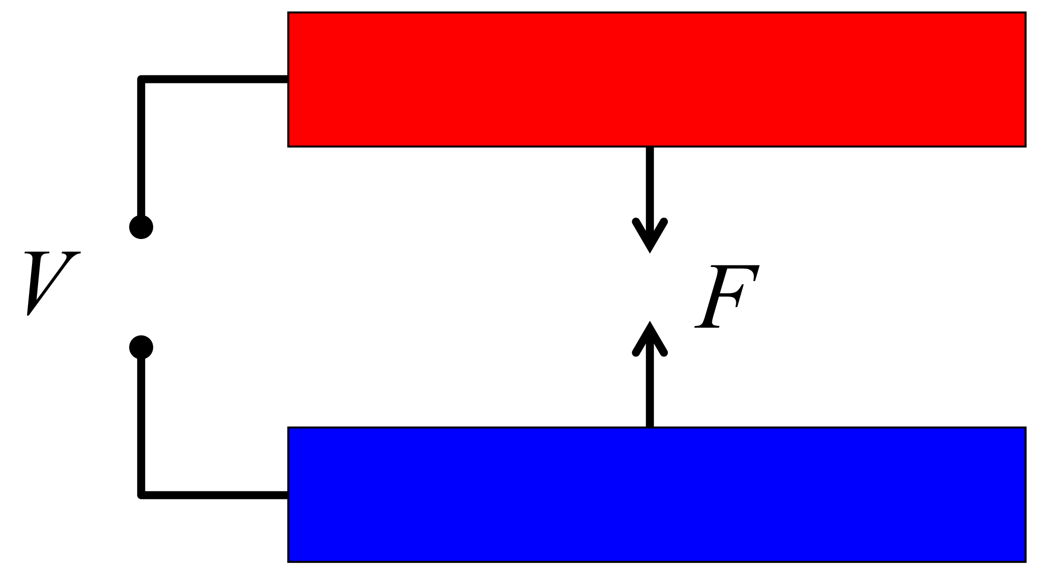
- Metal lines on MEMS
  - Lorentz force
  - $\vec{F} = q\,\vec{v} \times \vec{B} = l \cdot \vec{I} \times \vec{B}$
  - External magnetic field is typically constant
  - Current on the MEMS and Force is generated
  - Very simple fabrication
  - Difficult to integrate
  - Heating of MEMS

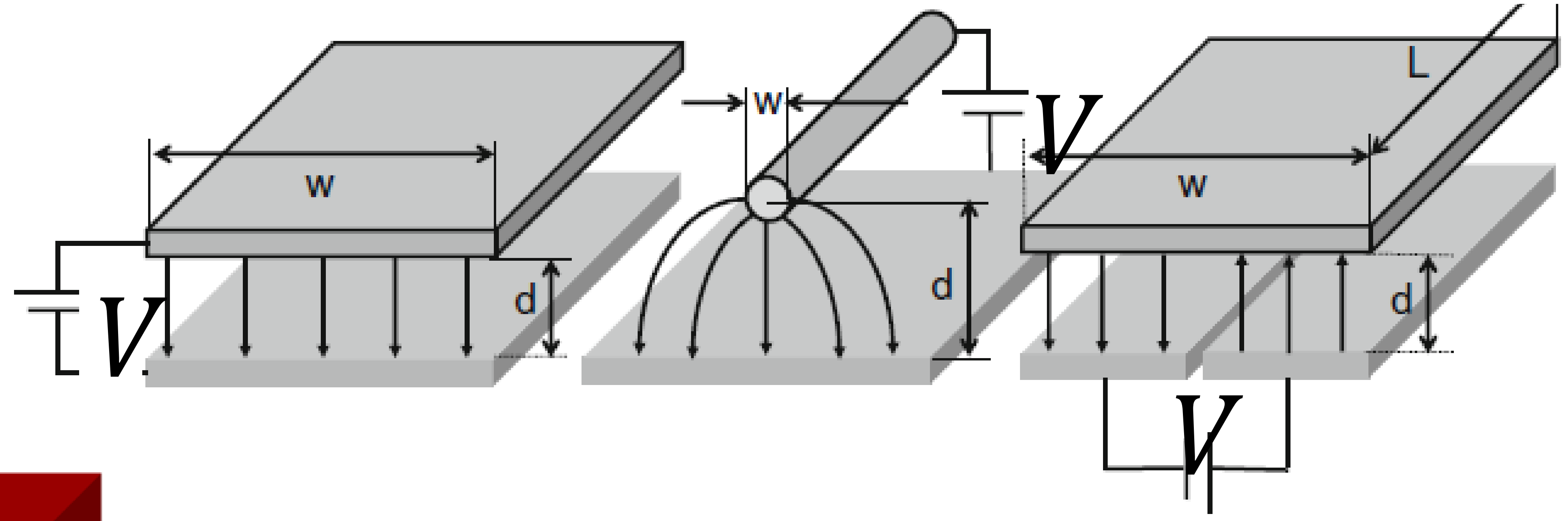


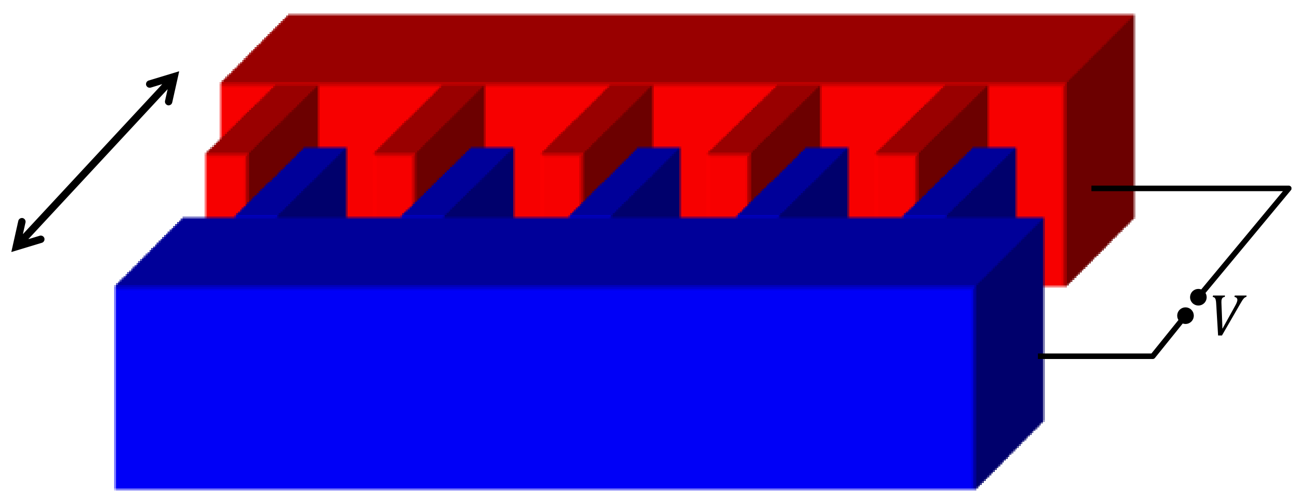
Electrostatic Actuation (1)

- Voltage applied between two conductive surfaces
- Capacitor
  - $F = \frac{1}{2}\frac{\partial C}{\partial \xi} V^2$

  - Very fast, speed tuned via Voltage
  - Purely reactive coupling
  - Very low power consumption
  - Possible to do comb-drive
  - Nonlinear
  - Pull-in voltage
  - Only attractive

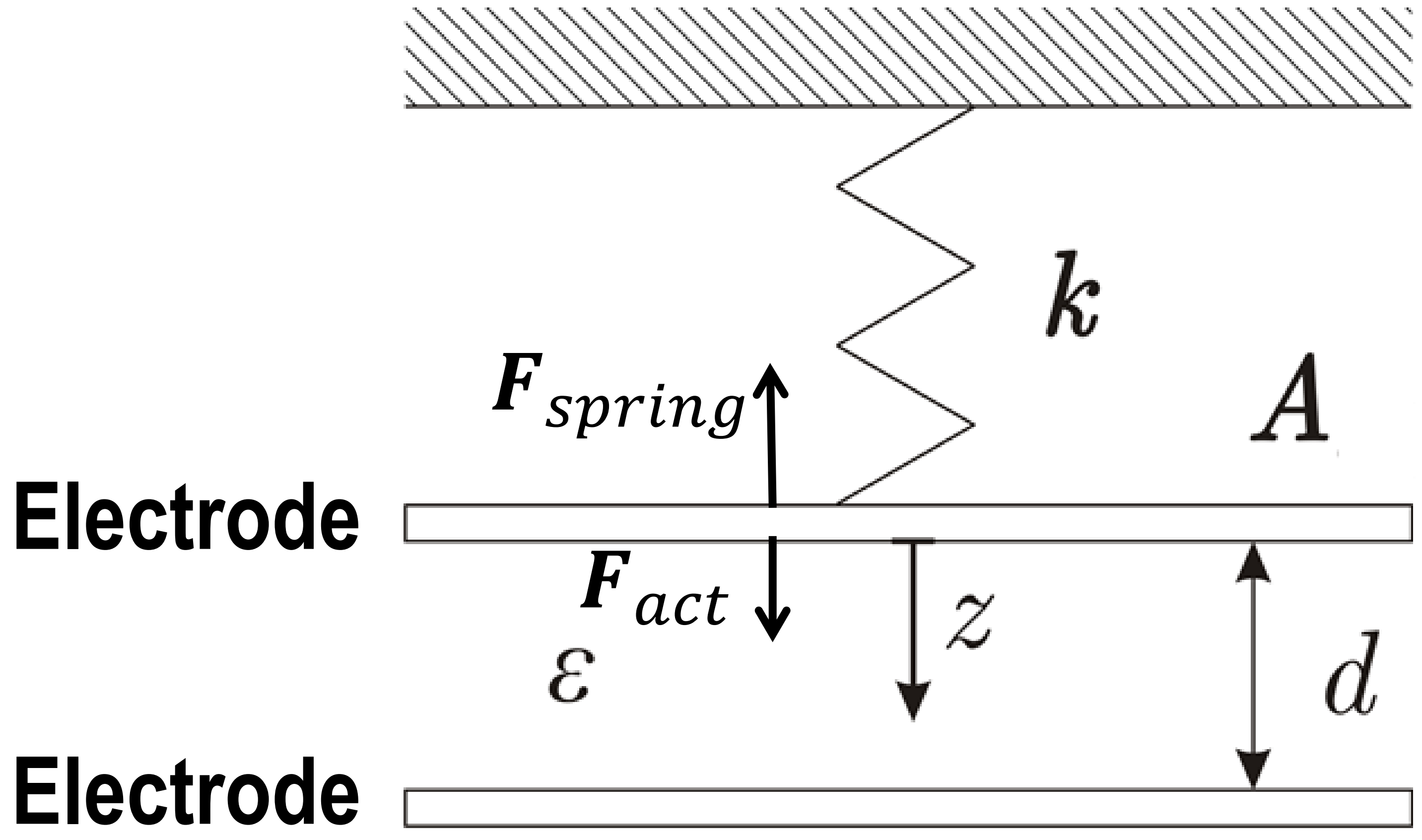




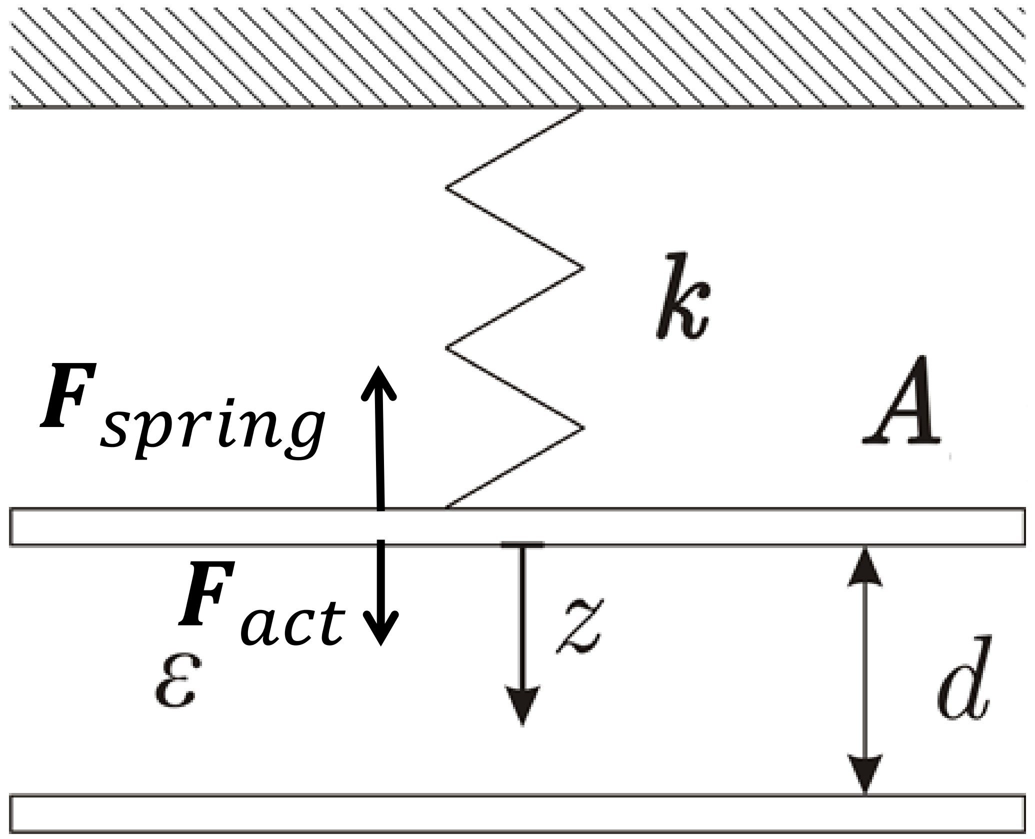


Electrostatic Actuation (2) – Parallel-Plate actuator

- Voltage applied between two conductive surfaces
- Capacitor $C = \frac{\varepsilon_r \varepsilon_0 A}{d-z}$
  - $F_{act} = \frac{1}{2}\frac{\partial C}{\partial z}V^2 = \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 A}{(d-z)^2}V^2$
  - $F_{spring} = kz$
- Equilibrium:
  - $\frac{1}{2}\frac{\varepsilon A}{(d-z)^2}V^2 = kz$
- Pull-in – system becomes unstable if $\frac{\partial(F_{act}-F_{spring})}{\partial z} > 0$
  - $\frac{\partial(F_{act}-F_{spring})}{\partial z} = 0 \rightarrow k = \frac{\varepsilon A}{(d-z_{crit})^3}V^2 \rightarrow z_{crit} = \frac{d}{3} \rightarrow V_{crit} = \sqrt{\frac{8kd^3}{27\varepsilon A}}$
  - That critical point is called *pull-in*



Electrostatic Actuation (3) – Parallel-Plate actuator

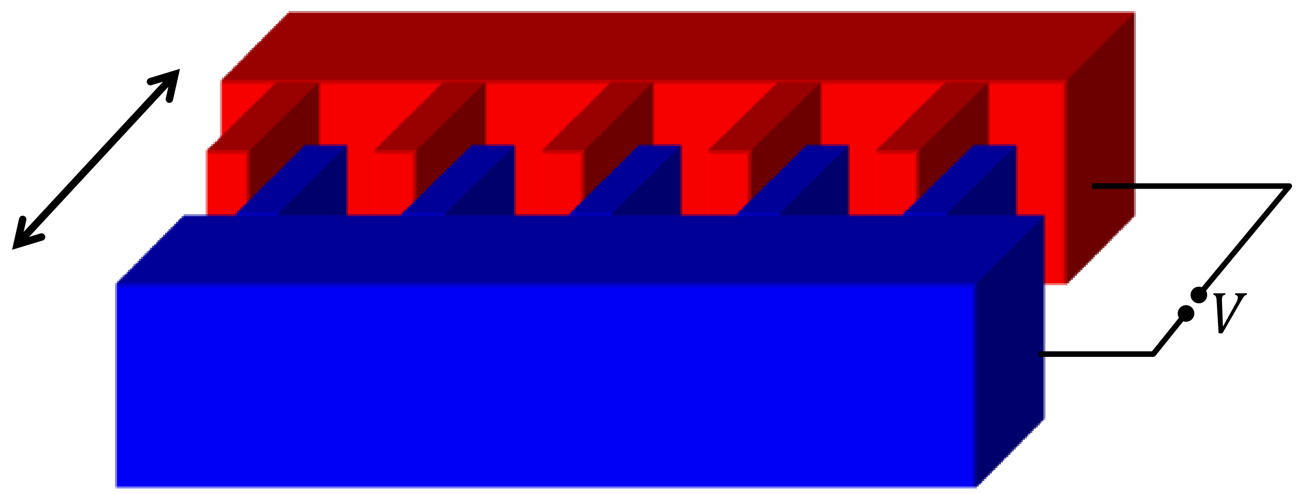


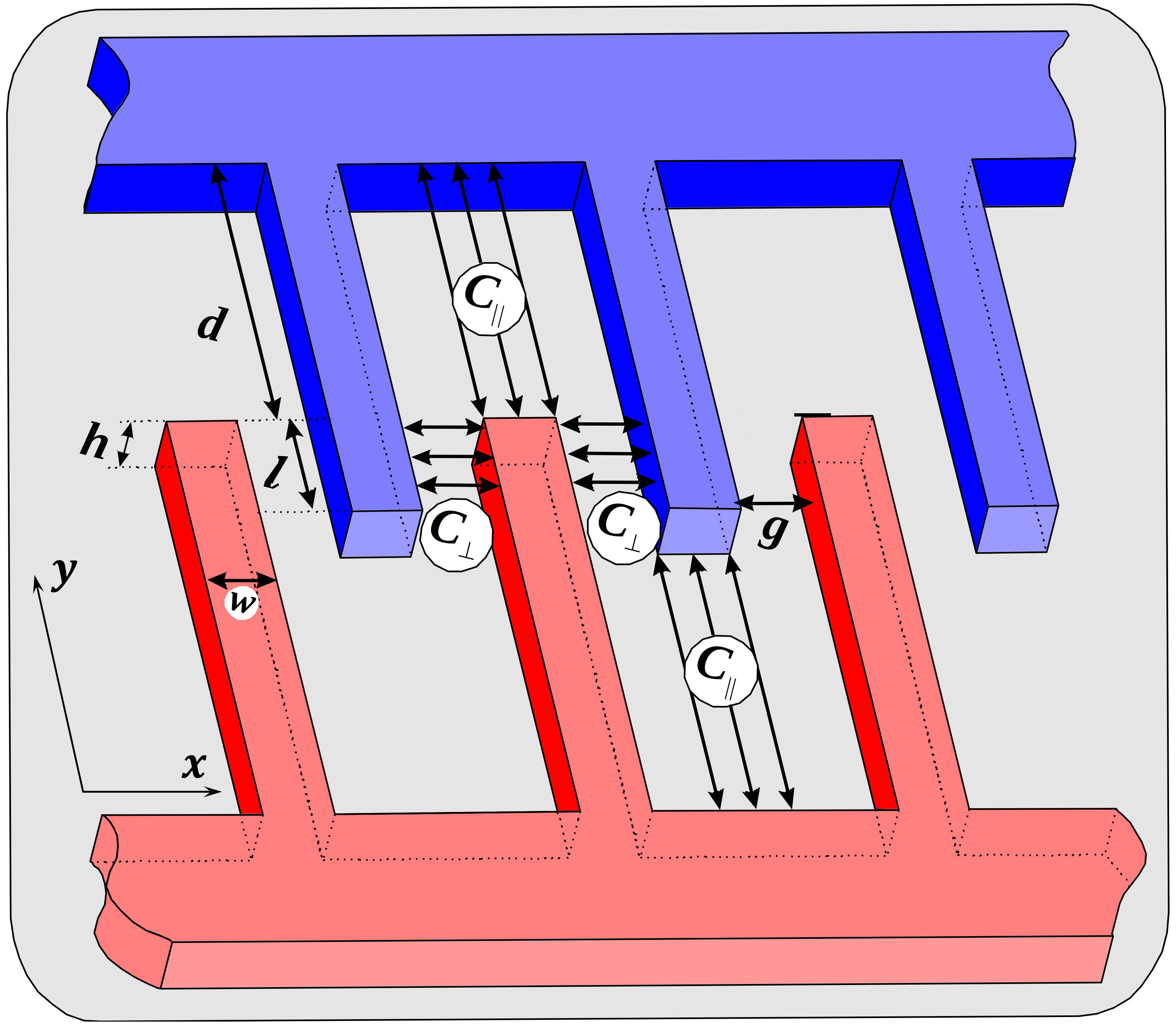
- Voltage applied between two conductive surfaces
- Capacitor $\quad C = \frac{\varepsilon_r \varepsilon_0 A}{d-z}$
  - $F_{act} = \frac{1}{2}\frac{\partial C}{\partial z}V^2 = \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 A}{(d-z)^2}V^2$
- Nonlinearity
  - With Voltage: Force is proportional to V^2, to have a force at a frequency ω:
    - We apply a sinusoidal signal at $\frac{\omega}{2}$
    - We apply a DC+ac signal at ω
  - With motion:
    - Taylor expansion: $F_{act} = \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 A}{(d-z)^2}V^2 \approx \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 A}{d^2}V^2\left(1 + \frac{2z}{d} + 3\left(\frac{z}{d}\right)^2 + o\left(\left(\frac{z}{d}\right)^3\right)\right)$
    - Total Force: $F_{act} - F_{spring} = \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 A}{d^2}V^2 - \left(k - \frac{\varepsilon_r \varepsilon_0 A}{d^3}V^2\right)z + \frac{3}{2}\frac{\varepsilon_r \varepsilon_0 A}{d^4}V^2 z^2 + o\left(\left(\frac{z}{d}\right)^3\right)$

Electrostatic Actuation (4) – Comb drive

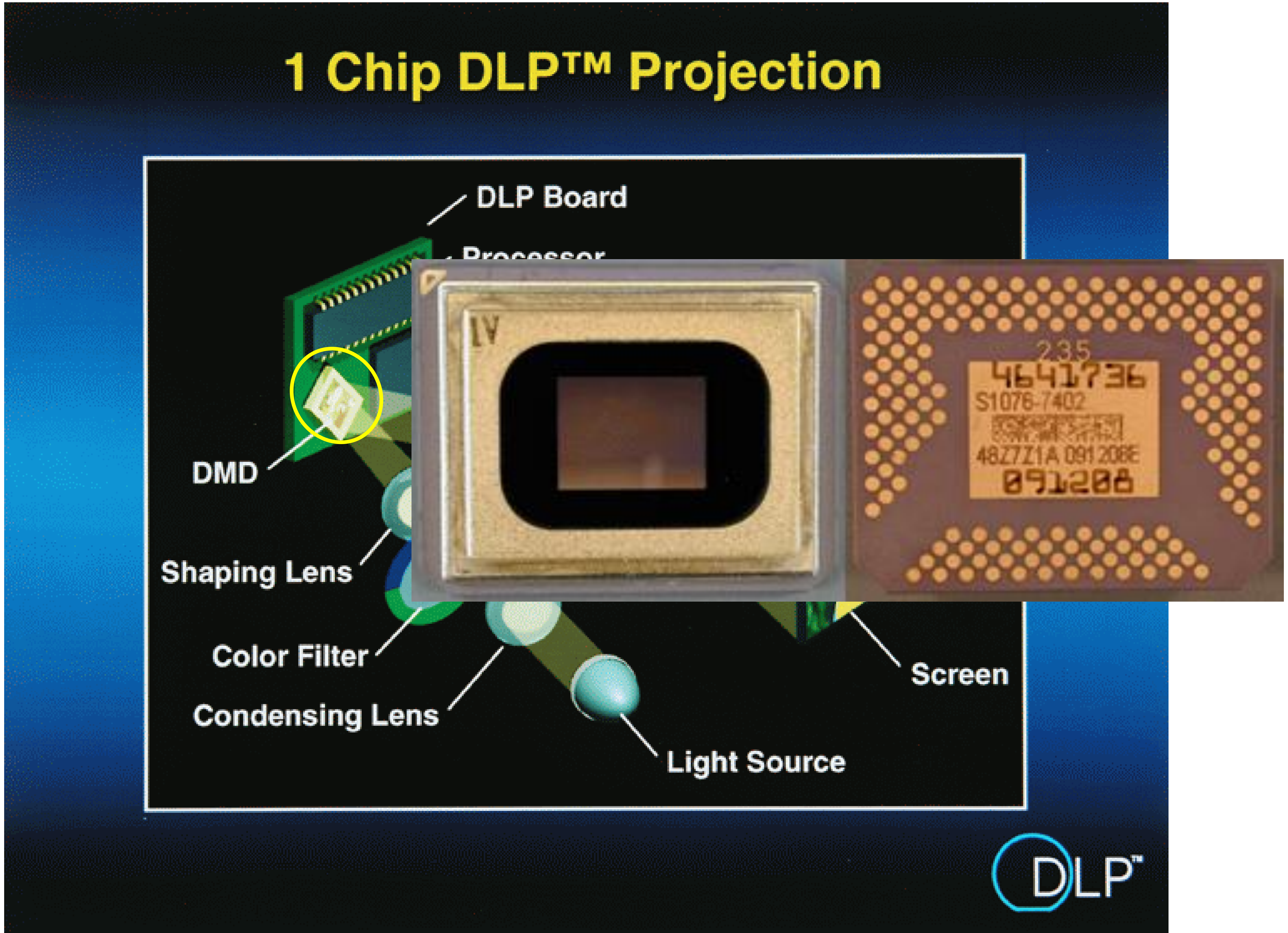
- $F = \frac{1}{2}\frac{\partial C}{\partial \xi}V^2$
- Capacitors:
  - $C_{\perp} = \varepsilon_r\varepsilon_0\frac{h(l+y)}{g}; \quad C_{\parallel} = \varepsilon_r\varepsilon_0\frac{hw}{d-y}$
  - $C_{tot} = 2\varepsilon_r\varepsilon_0 h\left(\frac{l+y}{g} + \frac{w}{d-y}\right) \times N_{fingers}$
  - $C_{tot} \approx 2\varepsilon_r\varepsilon_0 h\frac{l+y}{g} \times N_{fingers}$

  - $F_{act} = \varepsilon_r\varepsilon_0\frac{h}{g}V^2 \times N_{fingers}$



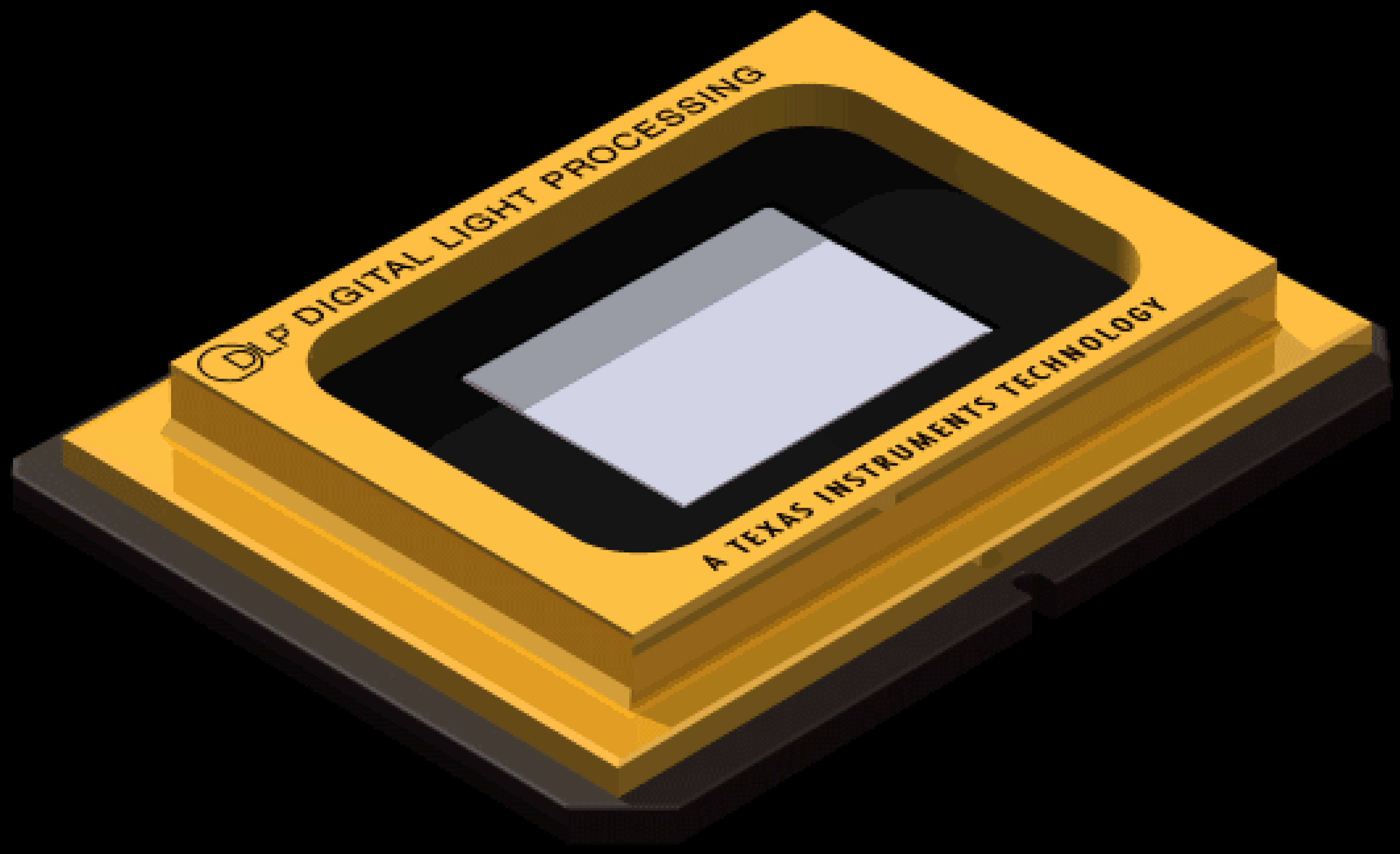


Electrostatic Actuation (5) – Example Texas Instruments DLP & DMD

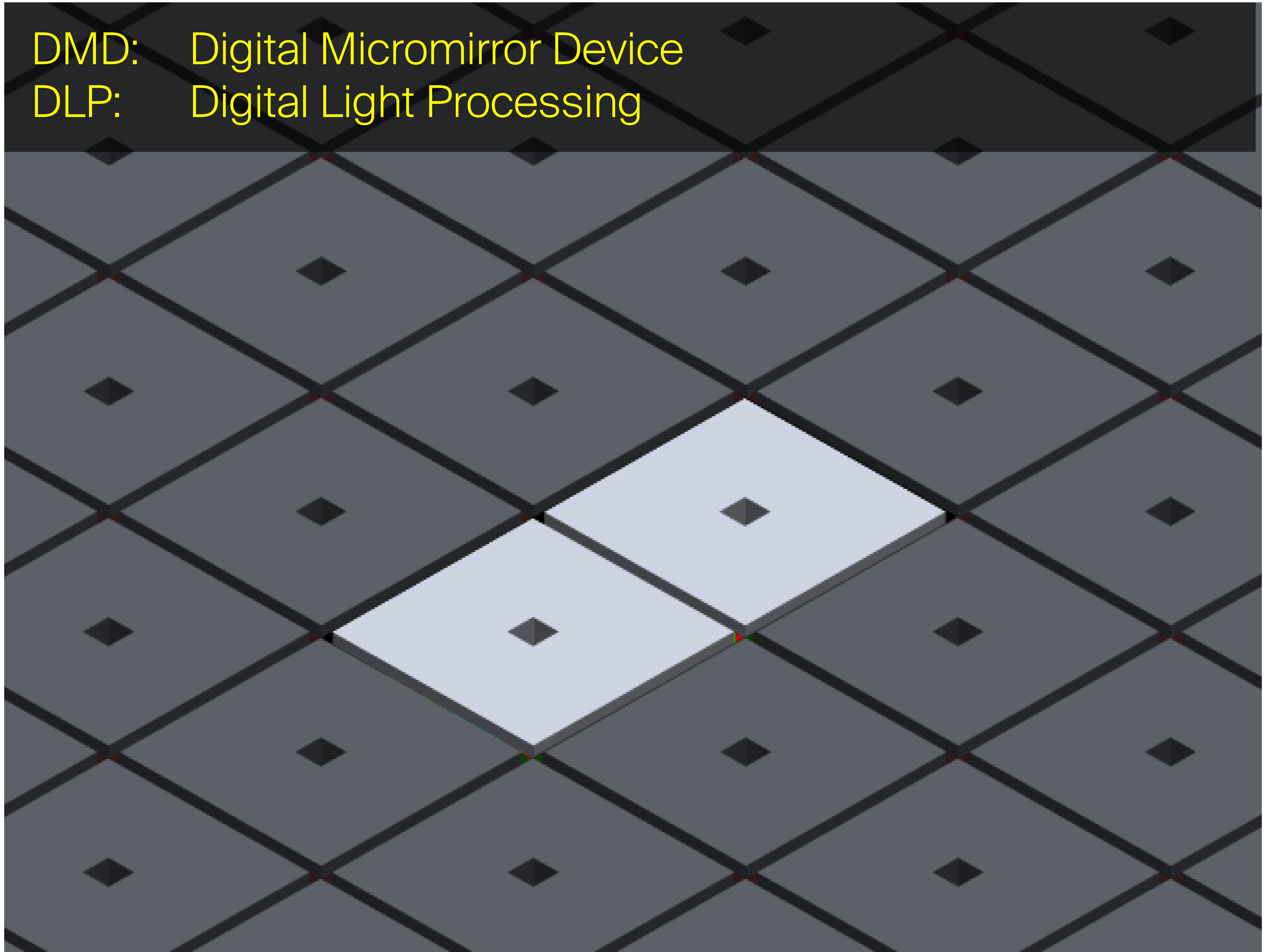


Electrostatic Actuation (5) – Example Texas Instruments DLP & DMD

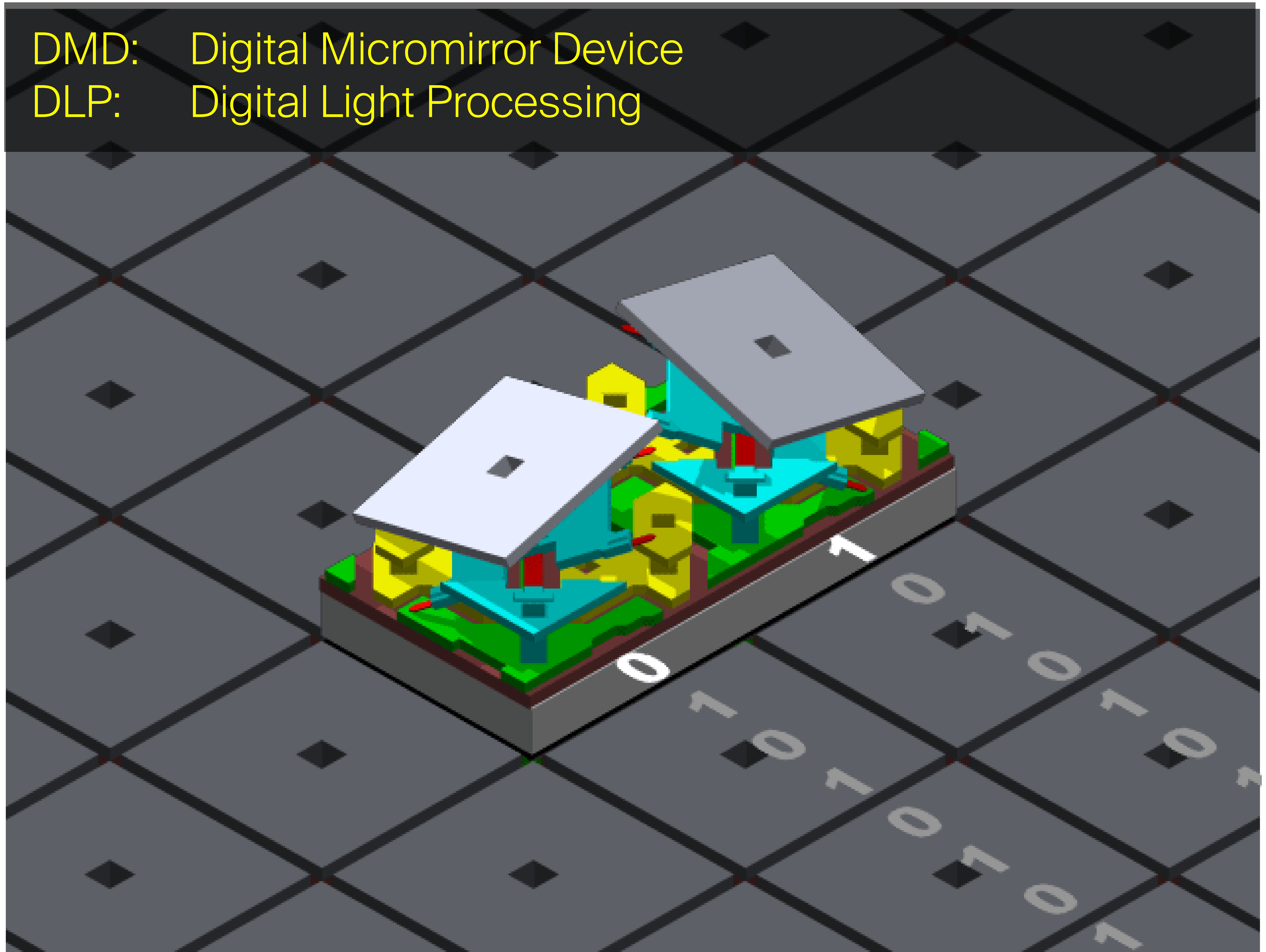
DMD: Digital Micromirror Device
DLP: Digital Light Processing



Electrostatic Actuation (5) – Example Texas Instruments DLP & DMD



Electrostatic Actuation (5) – Example Texas Instruments DLP & DMD



Transduction in the microscale

Actuation

- Pressure
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- Force
  - Magnetic force
  - Electrostatic force
- Expansion
  - Piezoelectric
  - Thermal
    - Electro-thermal
    - Opto-thermal

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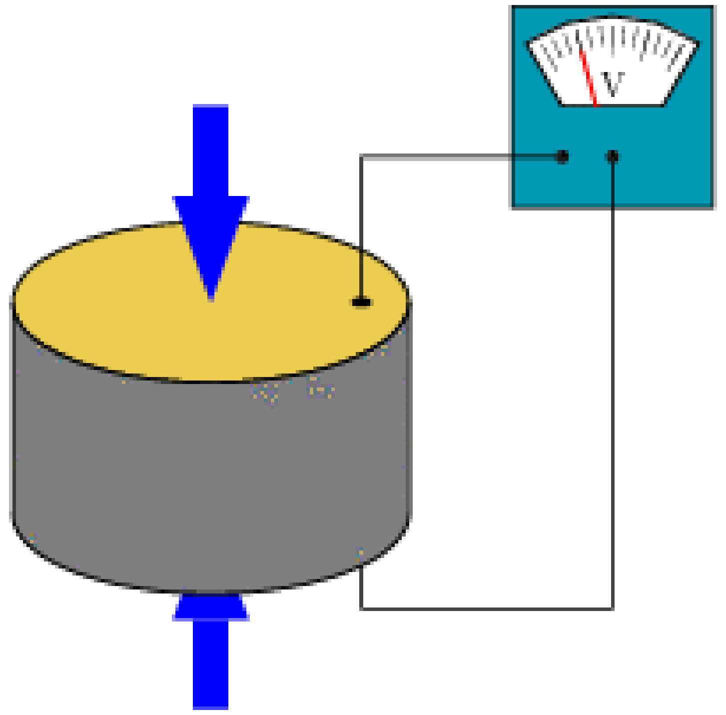
- “Seeing”
  - Optical lever
  - Interferometers
- Associated with a Force
  - Magnetomotive
  - Capacitive
- Associated with deformation
  - Piezoelectric
  - Change in resistance
    - Piezo-metallic (metal gauges)
    - Piezoresistive

Actuation

Expansion-based Actuation

Piezoelectric Actuation (1)

- Piezoelectricity
  - Material property through which
    - An electric field turns into mechanical strain
    - A mechanical stress generates charges
  - It happens in materials without inversion symmetry
    - Unit lattice is not symmetric

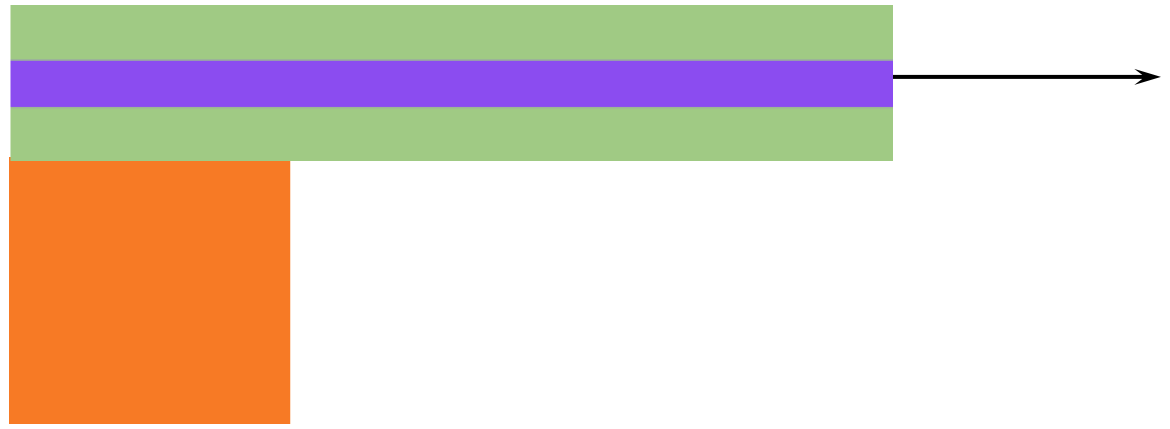


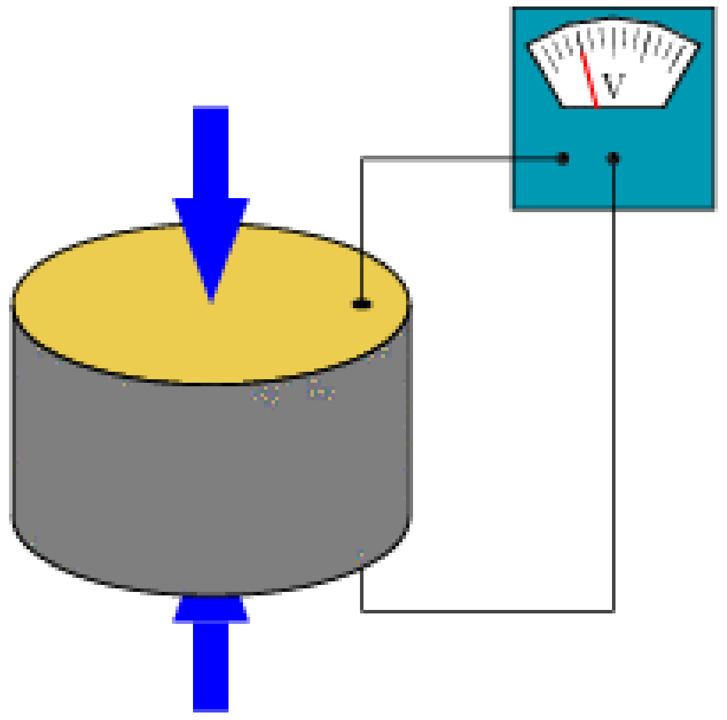
- Examples of materials:
  - AlN
  - AlScN
  - PZT
  - ZnO
  - LiNbO3
  - PMN-PT
  - Quartz

- Fast
- Reactive
- Linear
- Extremely high efficiency
- Small displacements (direct expansion)
- Engineering of neutral axis (coupling through bending moment)
- Needs 3 or 4 layers to work
- Difficult to obtain, only for selected materials

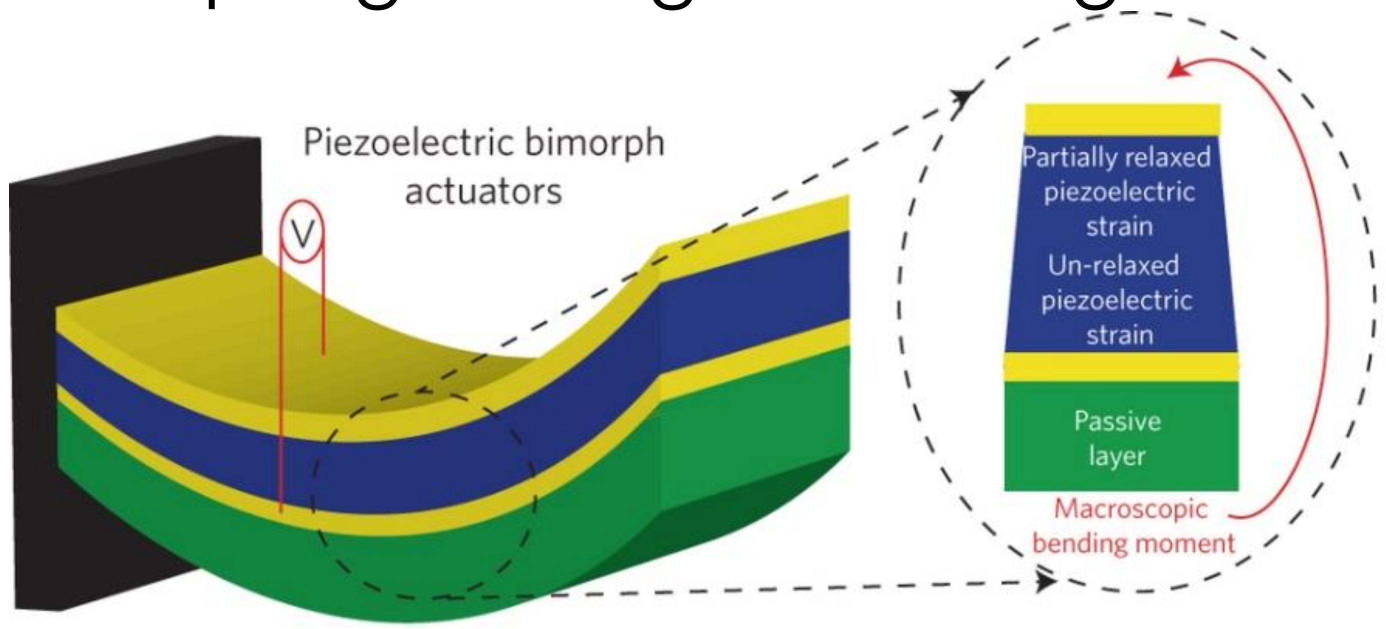
Piezoelectric Actuation (2)

- Piezoelectricity
  - An electric field turns into mechanical strain
  - Direct expansion → $\boldsymbol{x} = \boldsymbol{d_{33}V}$



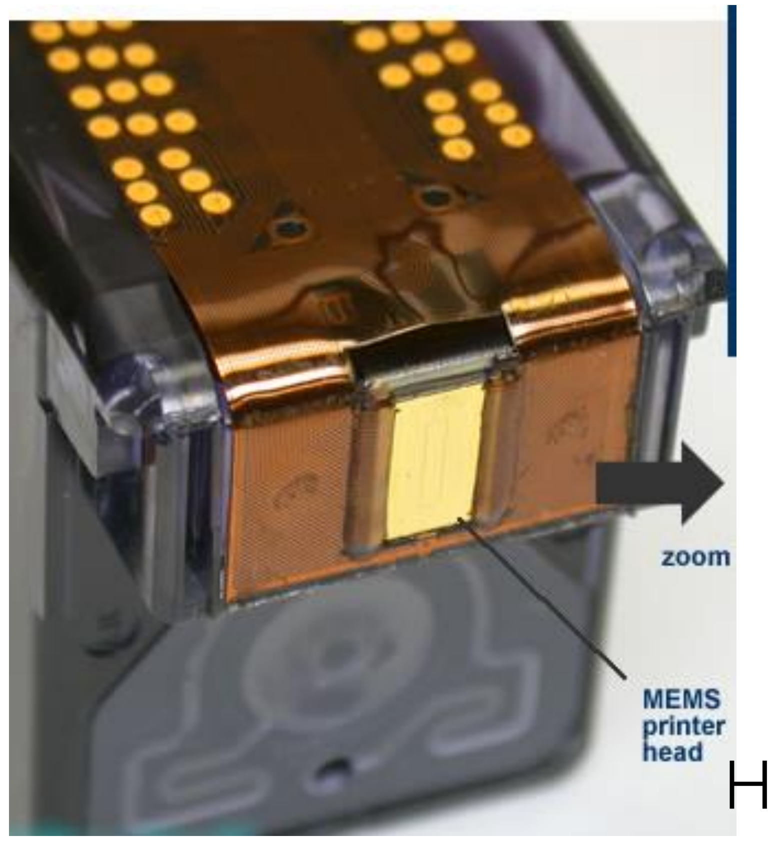


  - Coupling through bending moment→ $\boldsymbol{x} = \chi_A \frac{\boldsymbol{d_{31} z_{offset} L^2}}{\boldsymbol{t^3}} \boldsymbol{V}$

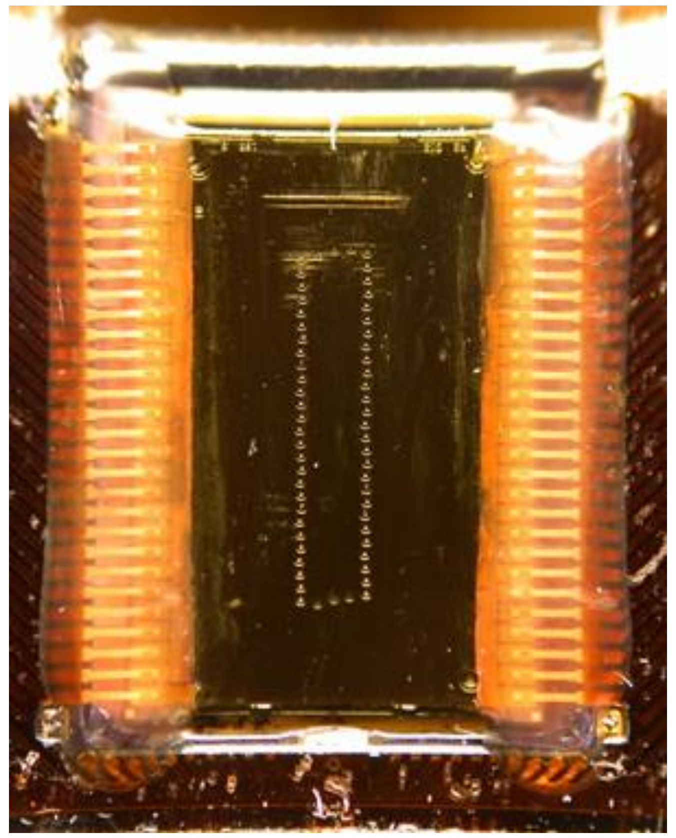


Piezoelectric Actuation - Example

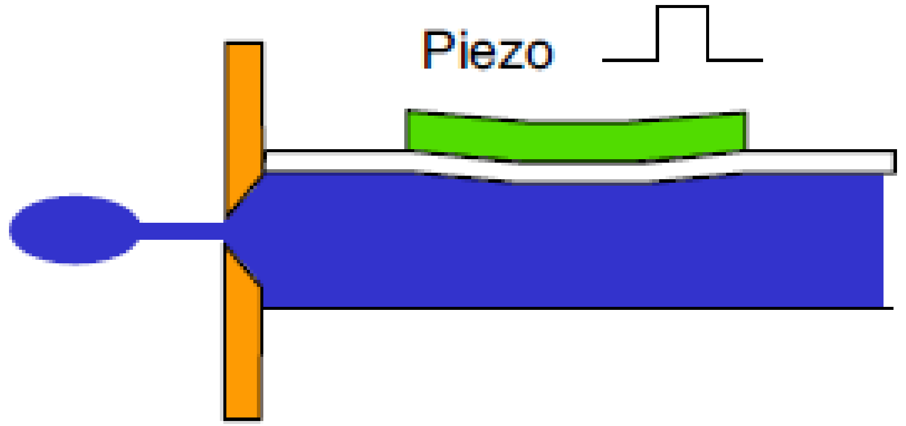
- Inkjet printheads – Drop on Demand (DoD)



HP



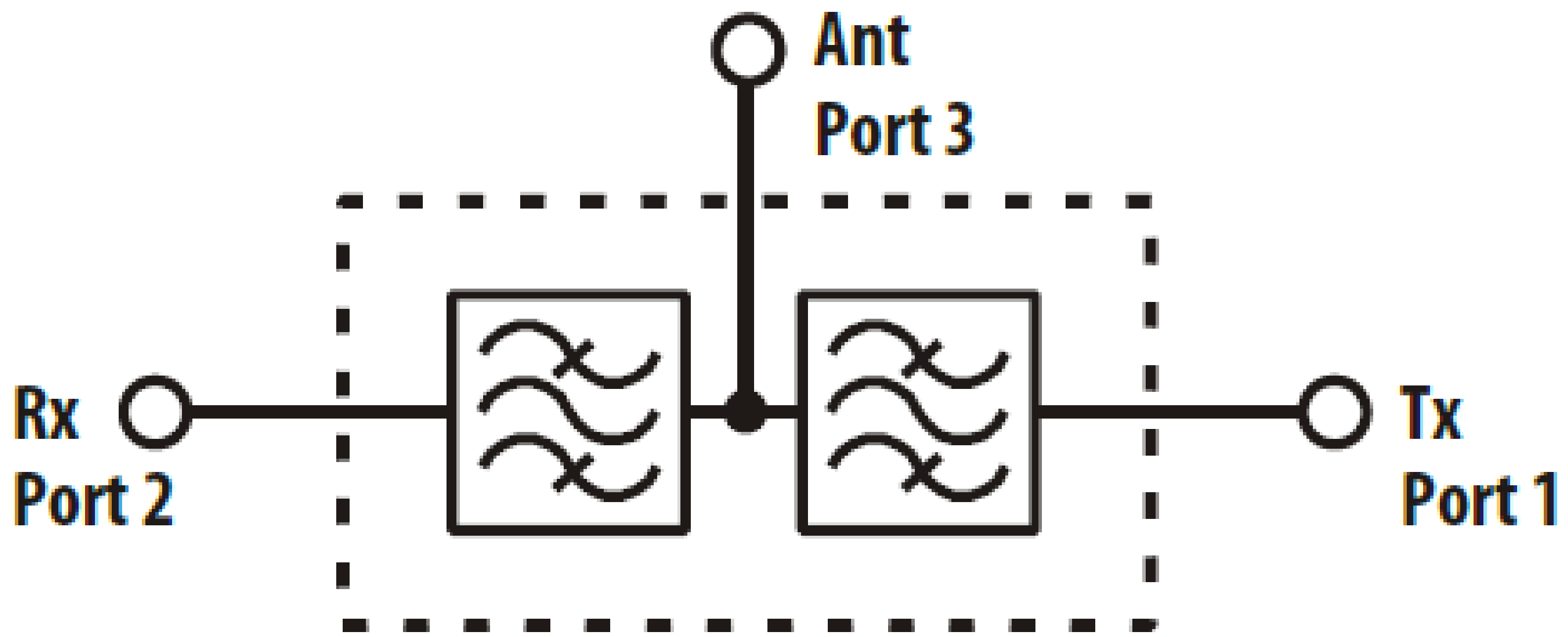
Piezo

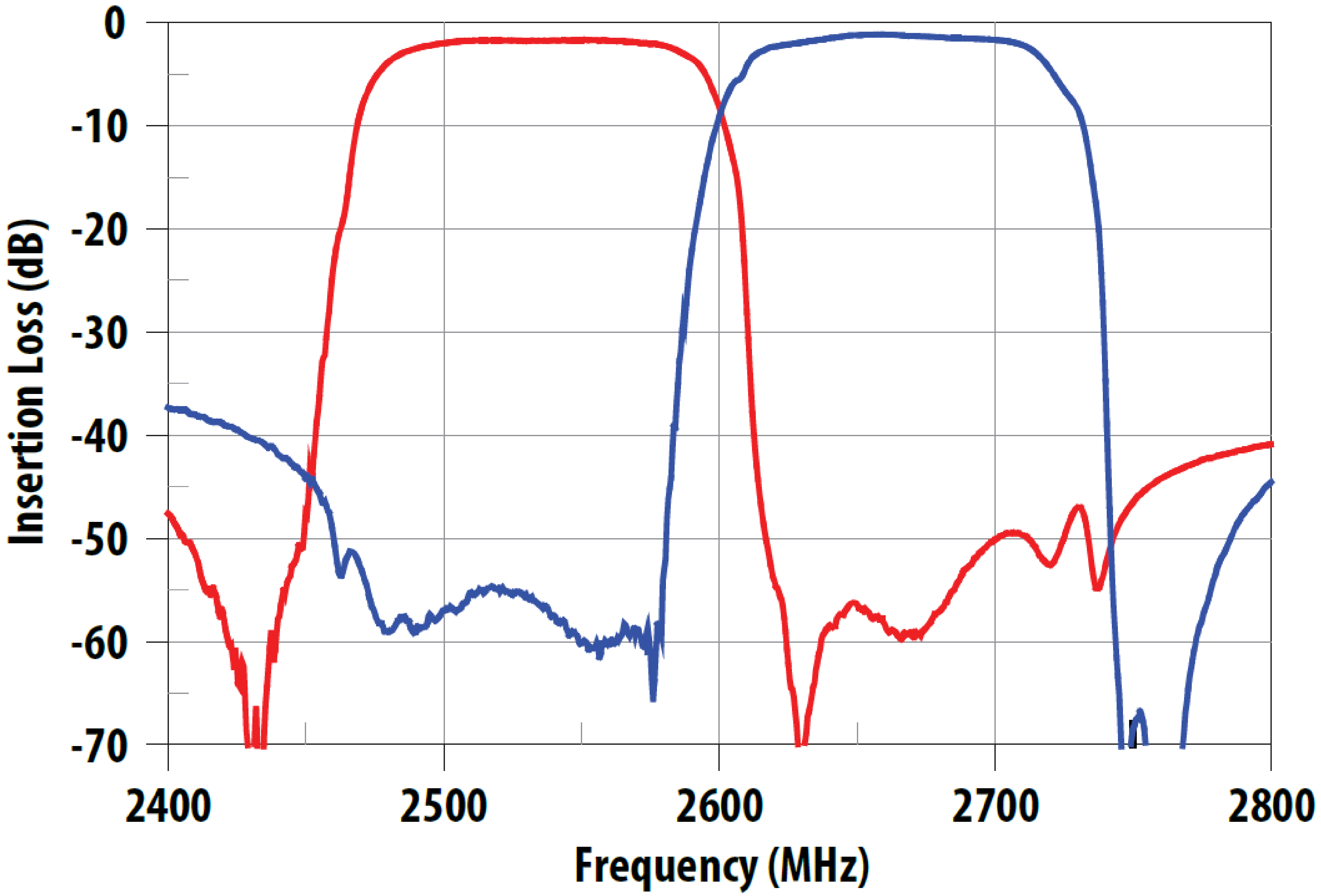


- Piezo crystal deforms when electrical pulse applied – many different architectures

Piezoelectric Actuation - Example

- Duplexers
  - Fundamental part of wireless communication
  - Received signal and transmitted signal happen at different frequencies
  - Need for controlled bandwidth and sharp rejection





Thermal Actuation (1)

- Based on expansion of materials due to temperature

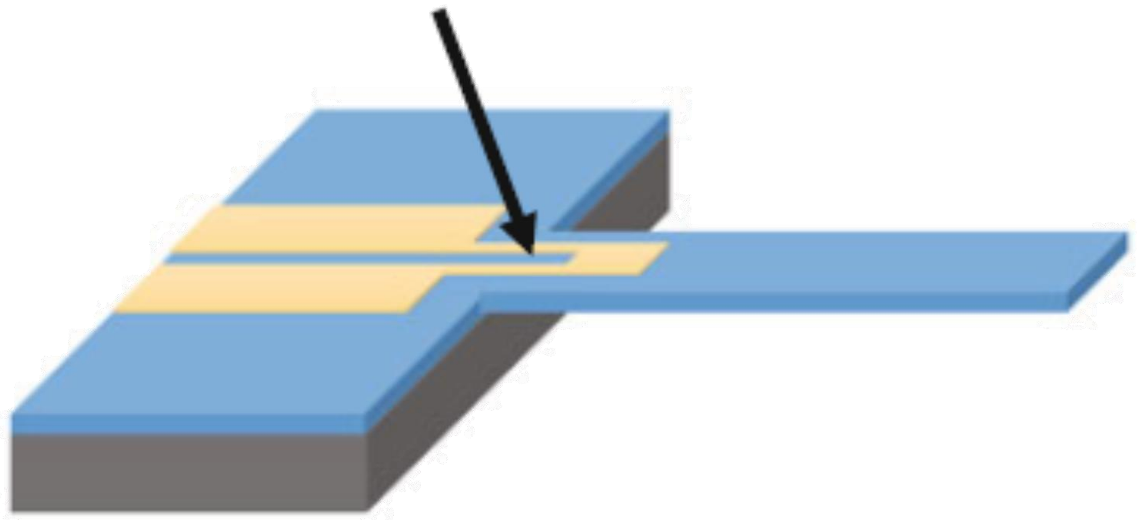
- Actuation can be based on:
  - Direct expansion
  - Coupled through bending moment

  - Works for every material
  - High efficiency
  - No need to have top electrode (2 layers is enough)
  - Small displacements (direct expansion)
  - Engineering of neutral axis (coupling through bending moment)
  - Dissipative
  - Speed is determined by design (might be slow)

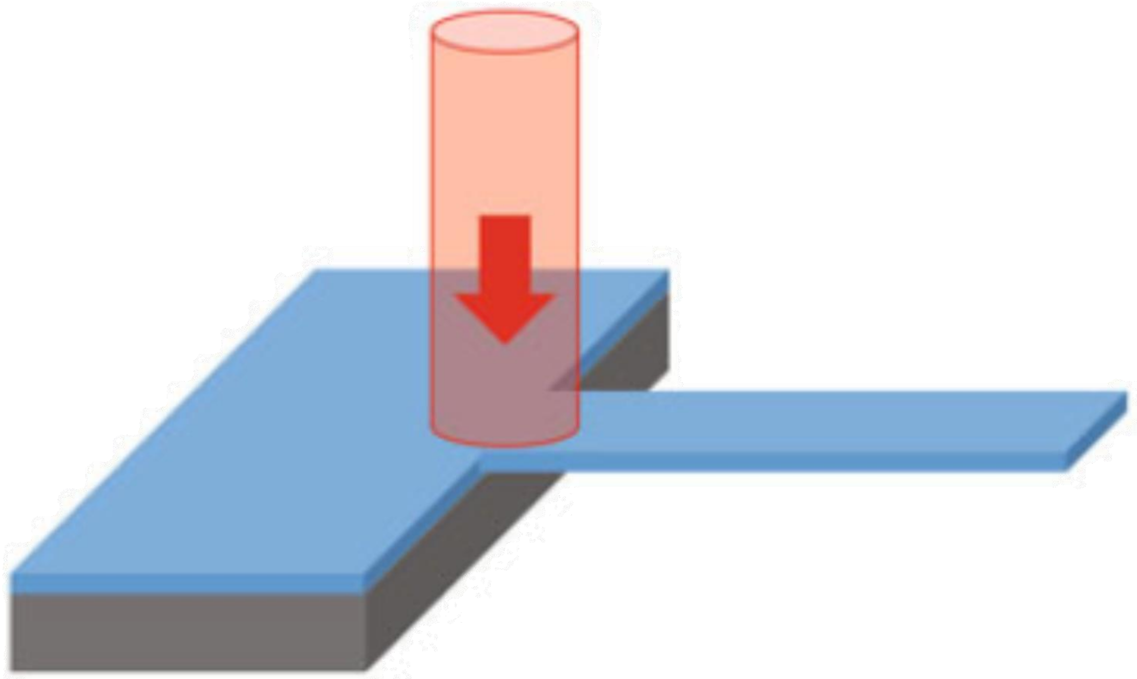
- To consider: it is not the CTE but CTE·Young's modulus what matters

Thermal Actuation (2)

- Based on expansion of materials due to temperature
- Temperature increase can be caused by
  - Joule heating (electrical current)
    - $\Delta T \sim \frac{P}{\kappa_{th}} \frac{L}{t \cdot w} \sim \frac{V^2}{\rho_{el} \cdot \kappa_{th}}$
    - Nonlinear with voltage
  - Light absorption
    - $\Delta T \sim \frac{P_{abs}}{\kappa_{th}} \frac{L}{t \cdot w} \sim \frac{\alpha_{abs}}{\kappa_{th}} P_{laser} \frac{L}{tw}$



Resistive heating



Photothermal heating

EPFL

Thermal Actuation (3)

- Based on expansion of materials due to temperature
- Temperature increase can be caused by
  - Joule heating (electrical current)
  - Light absorption

- Deformation can be:
  - Via direct expansion
    - $x = \alpha_{eff} \cdot \Delta T$
  - Via bending moment
    - $x = \boldsymbol{\alpha_{eff} \frac{t_{heater} z_{offset}}{t^3} L^2 \Delta T}$

Thermal Actuation - Example

- Bimorph actuator
  - Polyimide, silicon nitride bimorph with TiW heater in between
  - Polyimide on top expands more than nitride
  - Two chips of 8 x 8 actuators: X,Y and rotation possible
  - For conveying / micromanipulation small objects and walking micro-robots

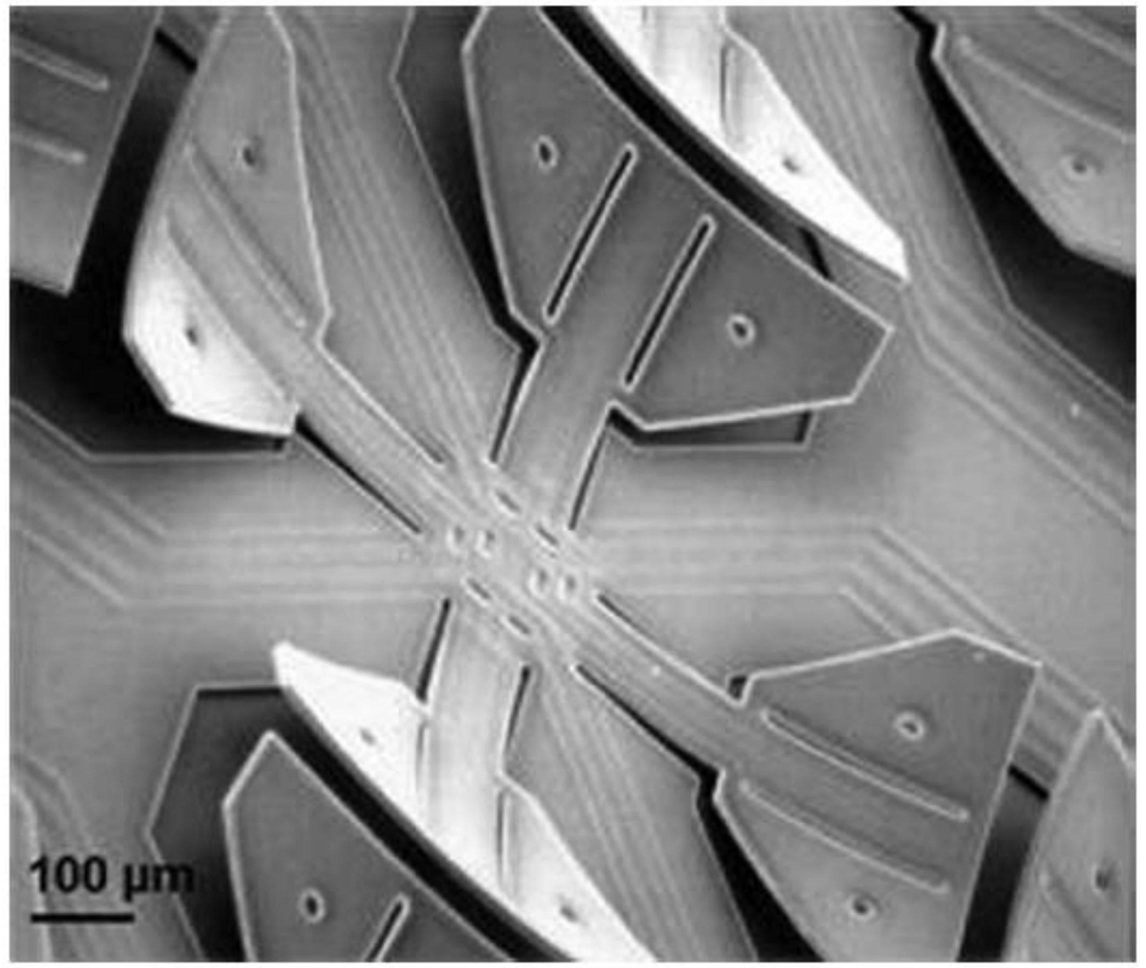


Fig. 3. SEM image of motion pixels [34]. Each motion pixel has an area of 1.1 mm × 1.1 mm. The approximate height of a cilium at room temperature is 117 μm. The thickness, width, and length of a cilium are 10.1, 430, and 550 μm, respectively. (Picture by J. Suh)

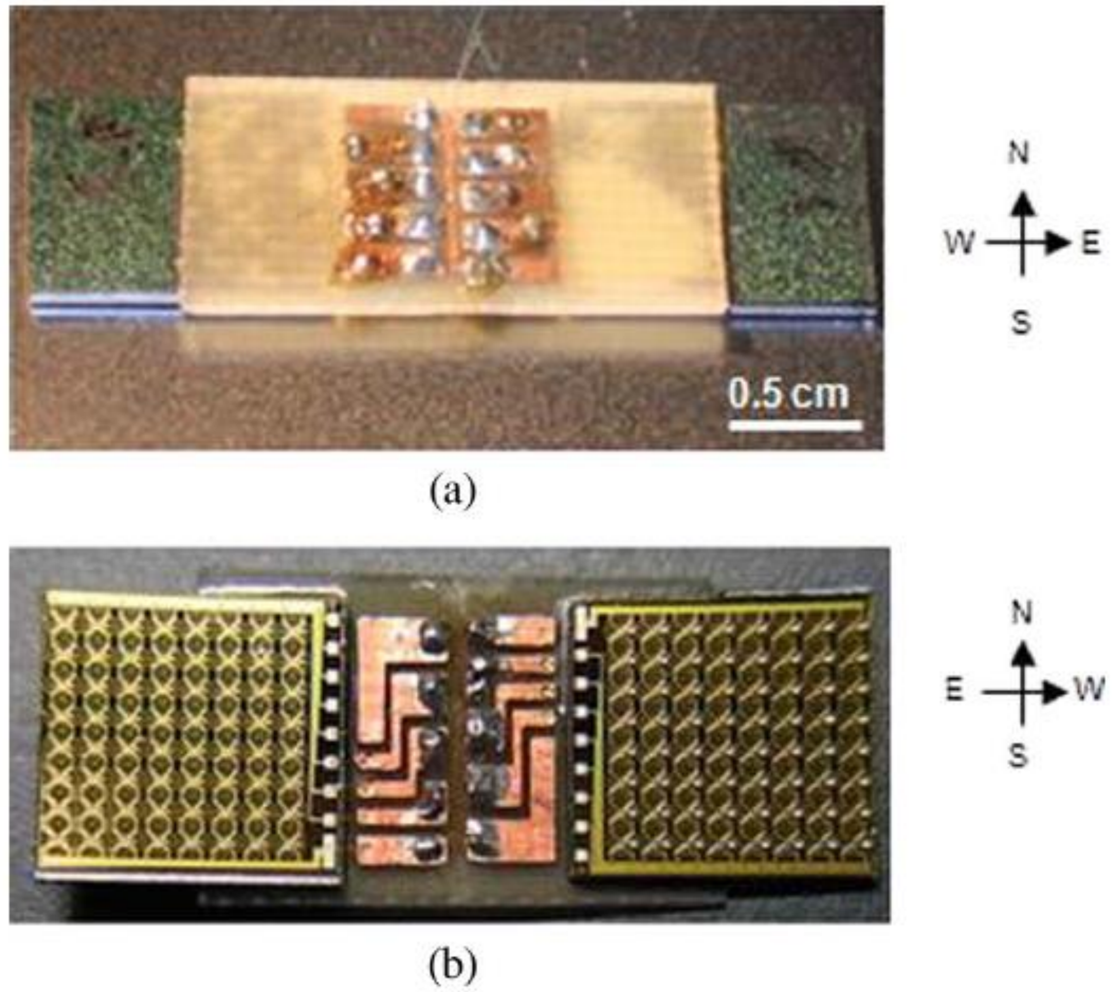


Fig. 2. (a) Top and (b) bottom views of the microrobot. The two cilia chips can be seen attached and wire bonded to a PCB backbone. Each cilia chip contains an 8 × 8 array of "motion pixels" (i.e., a group of four orthogonal cilia). The usage of two chips increases the stability and allows rotational motion.

E. Yegân Erdem *et al.*, J. Micromechanical Systems, vol. 19 (2010) 433

Thermal Actuation - Example

- Electrothermal actuator
  - Made of electroplated Ni

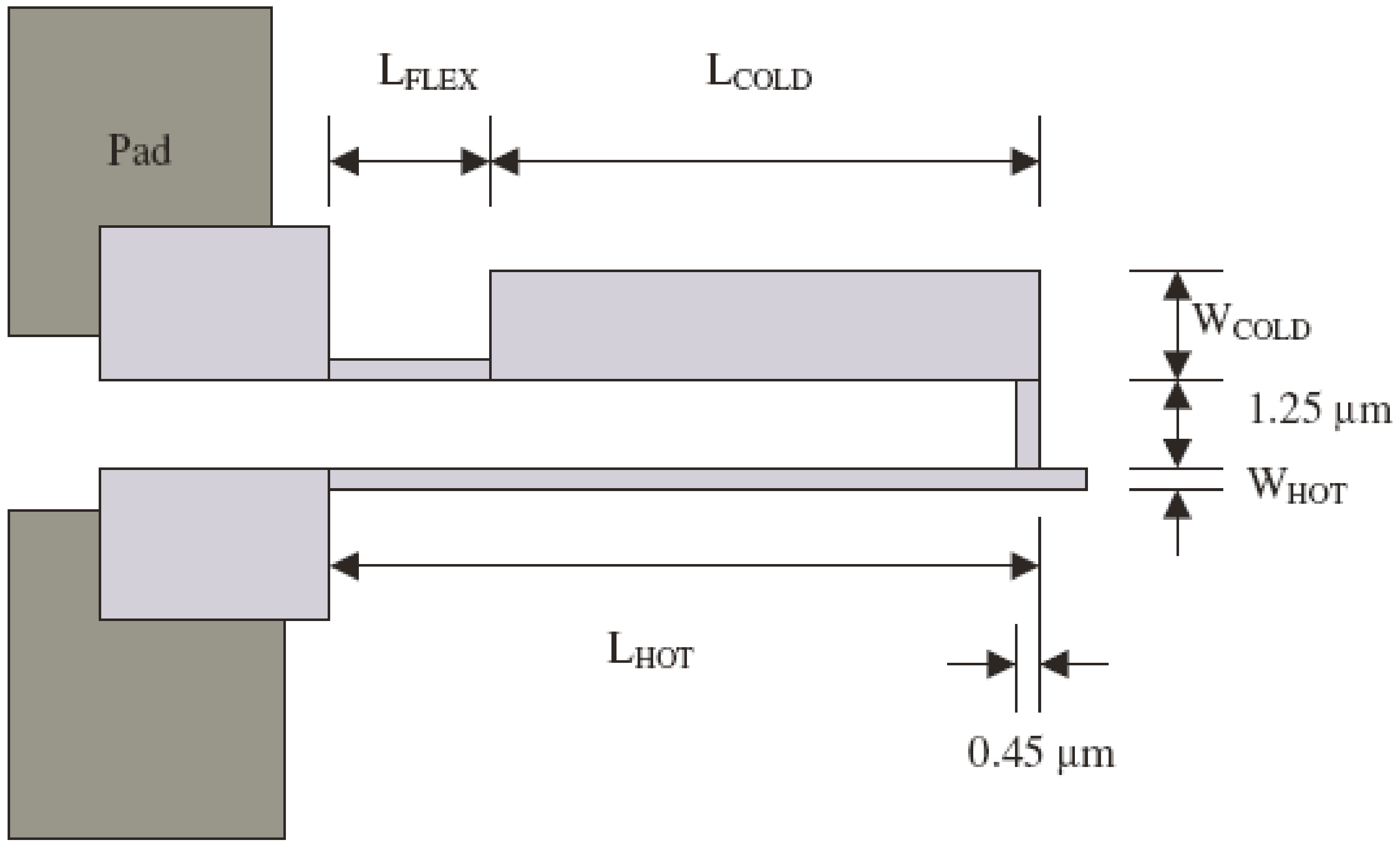
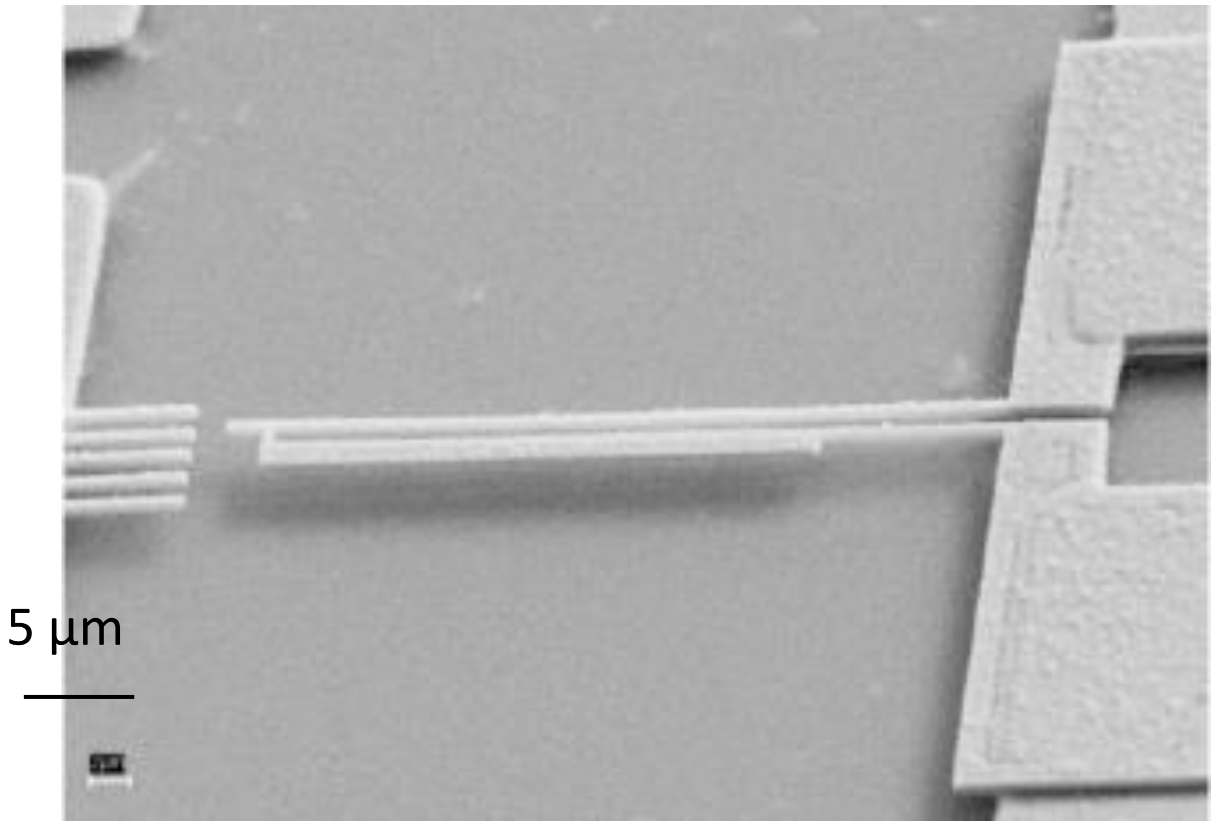
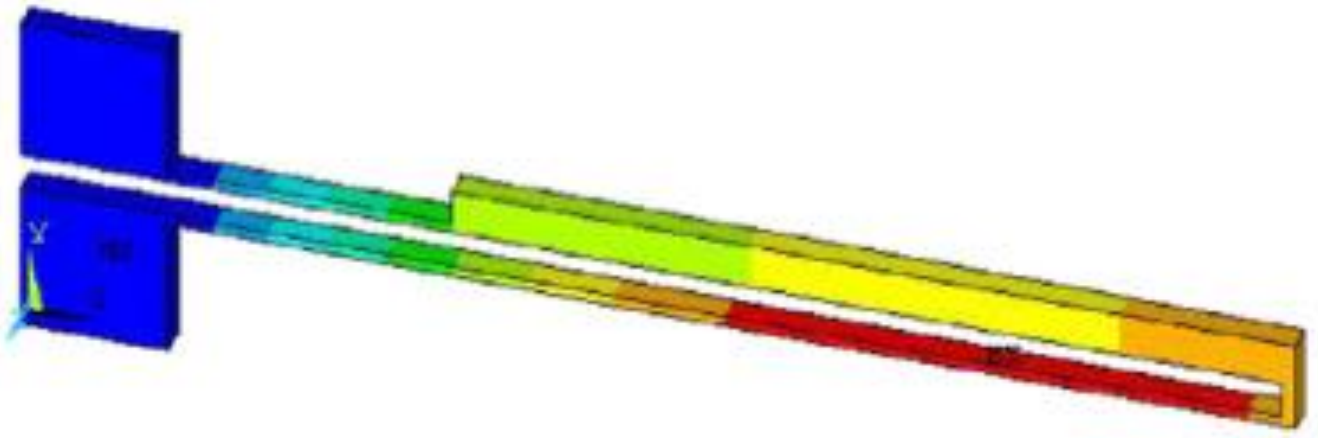


Figure 1. A schematic drawing of sub-micron electrothermal actuators with the geometrical parameters.

Table 2. The material properties of electroplated nickel used for FEM.

Properties	Value	Unit
Young's modulus, E [9]	200	GPa
Poisson's ratio, ν	0.31	
Thermal expansion coefficient, α [10]	17	ppm K^{-1}
Thermal conductivity, κ [10]	91	W $(m\ K)^{-1}$
Resistivity, ρ	15	$\mu\Omega$ cm



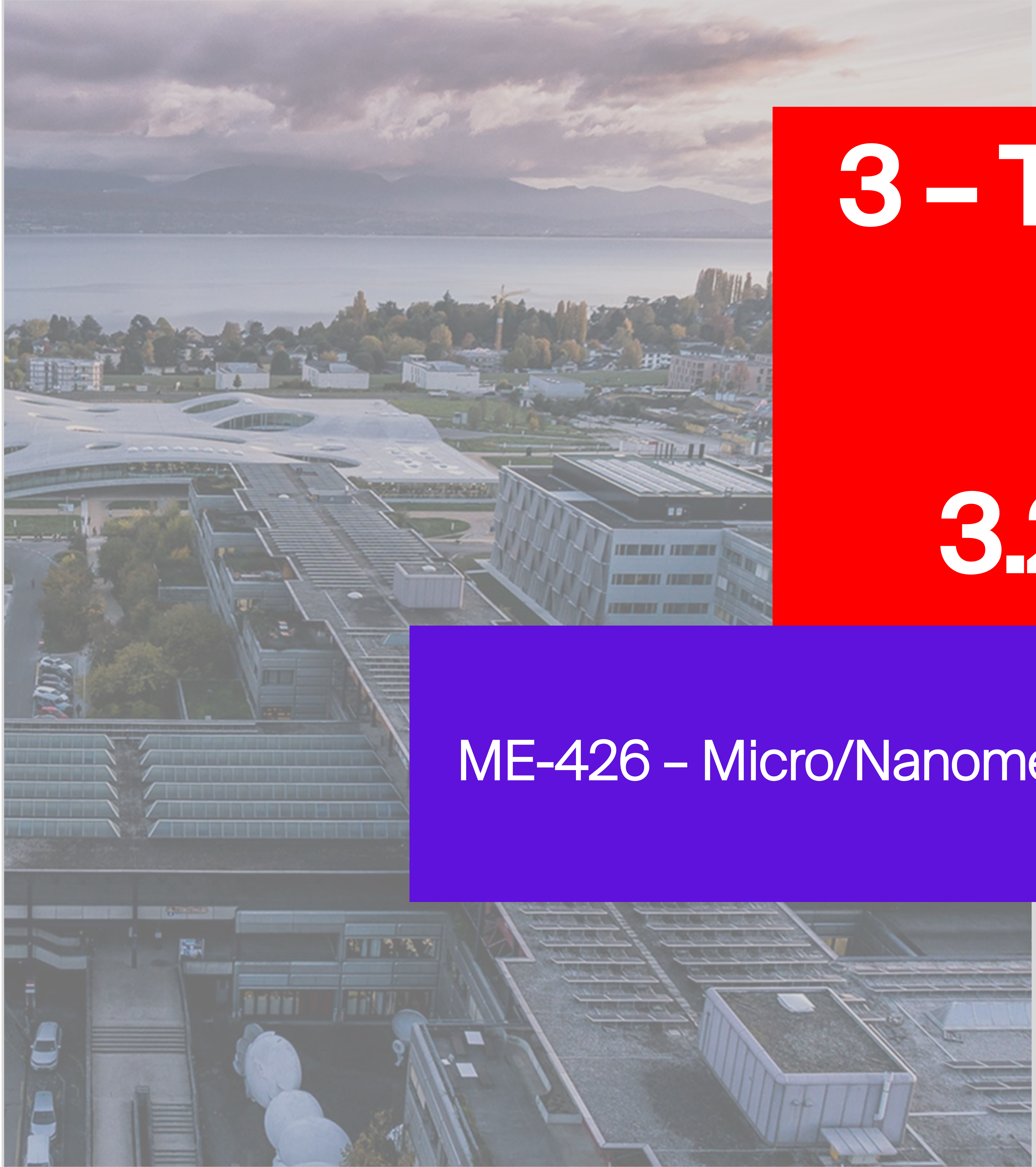


Jeong-Soo Lee et al. J. Micromech. Microeng. 15 (2005) 322–327

EPFL

3 – Transduction of the motion

3.2 – Detection



ME-426 – Micro/Nanomechanical Devices

Prof. Guillermo Villanueva

École polytechnique fédérale de Lausanne

Introduction

- Detection
- “seeing”
- Associated with a force
- Associated with a deformation

Transduction in the microscale

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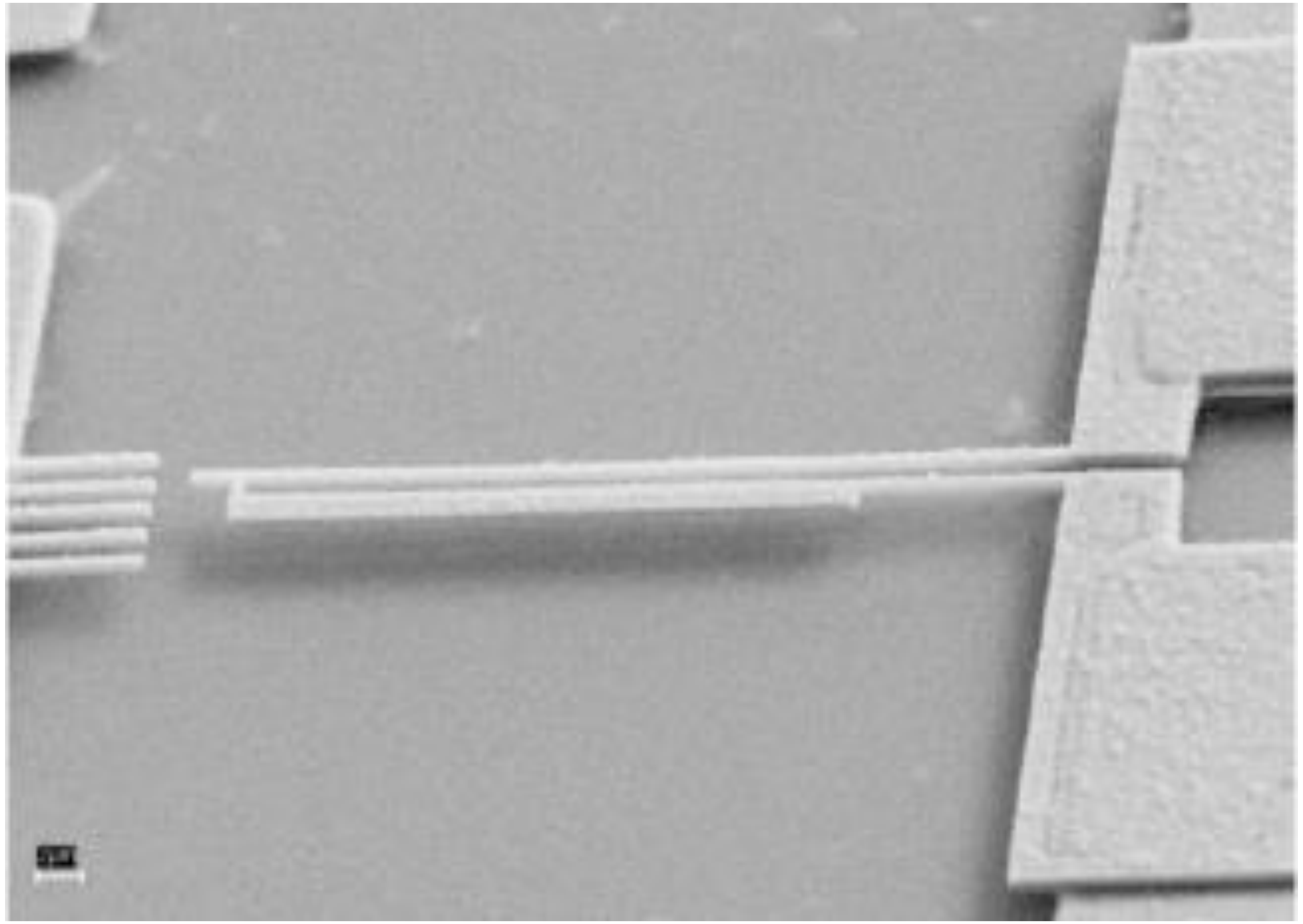
EPFL

Detection

“Seeing”

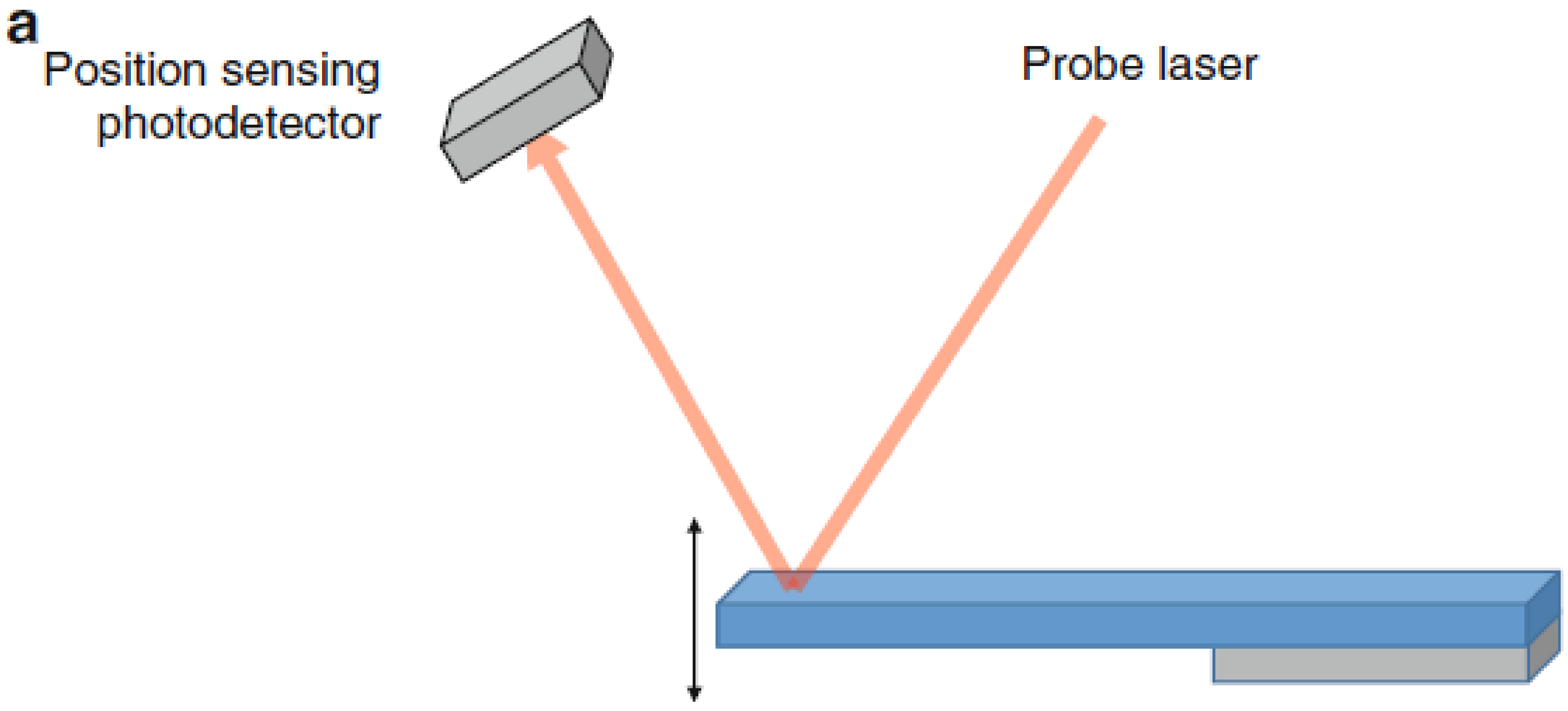
Direct Detection

- Counting bars
  - Very bad resolution
  - It complicates design



Optical Lever Detection

- A probing laser reflects on the mechanical device
- The reflection is captured by a PSD (position sensing detector)
- Final position in detector depends on
  - Derivative of deflection
  - Distance from beam to detector



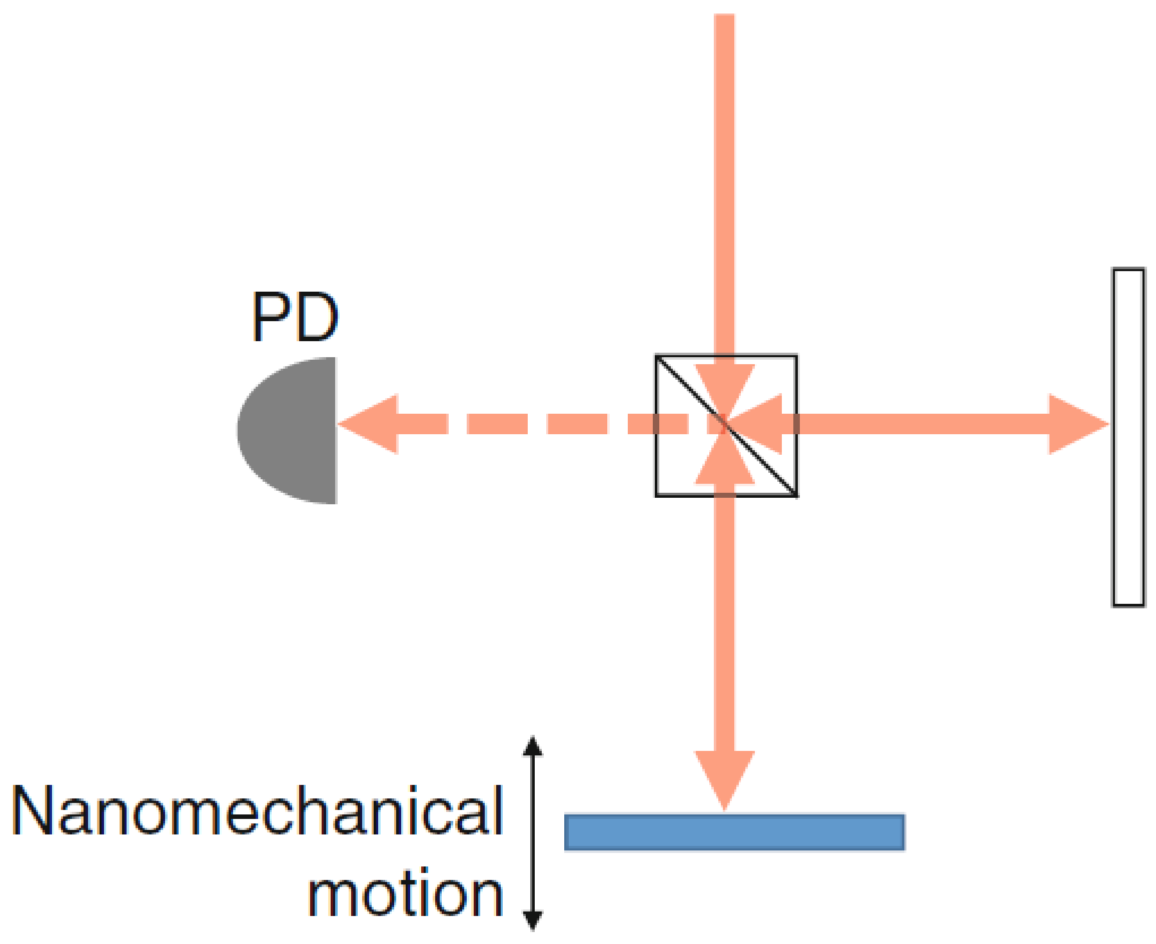
  - Very easy to implement
  - Good resolution
  - Not possible to integrate
  - Alignment issues
  - Diffraction problems for small devices ($w \leq \lambda$)

Optical Interferometer Detection

- Laser is split in two paths
- The length of one of the paths is modulated via the motion
- This causes the combined power to be strongly dependent on deflection
- Different types of interferometers could be used
  - Michelson
  - Mach-Zehnder
  - Fabry-Perot
  - Doppler

  - Very accurate (more for higher finesse)
  - Nonlinear
  - Difficult to integrate

Michelson interferometer



Detection

Associated with a Force

Transduction in the microscale

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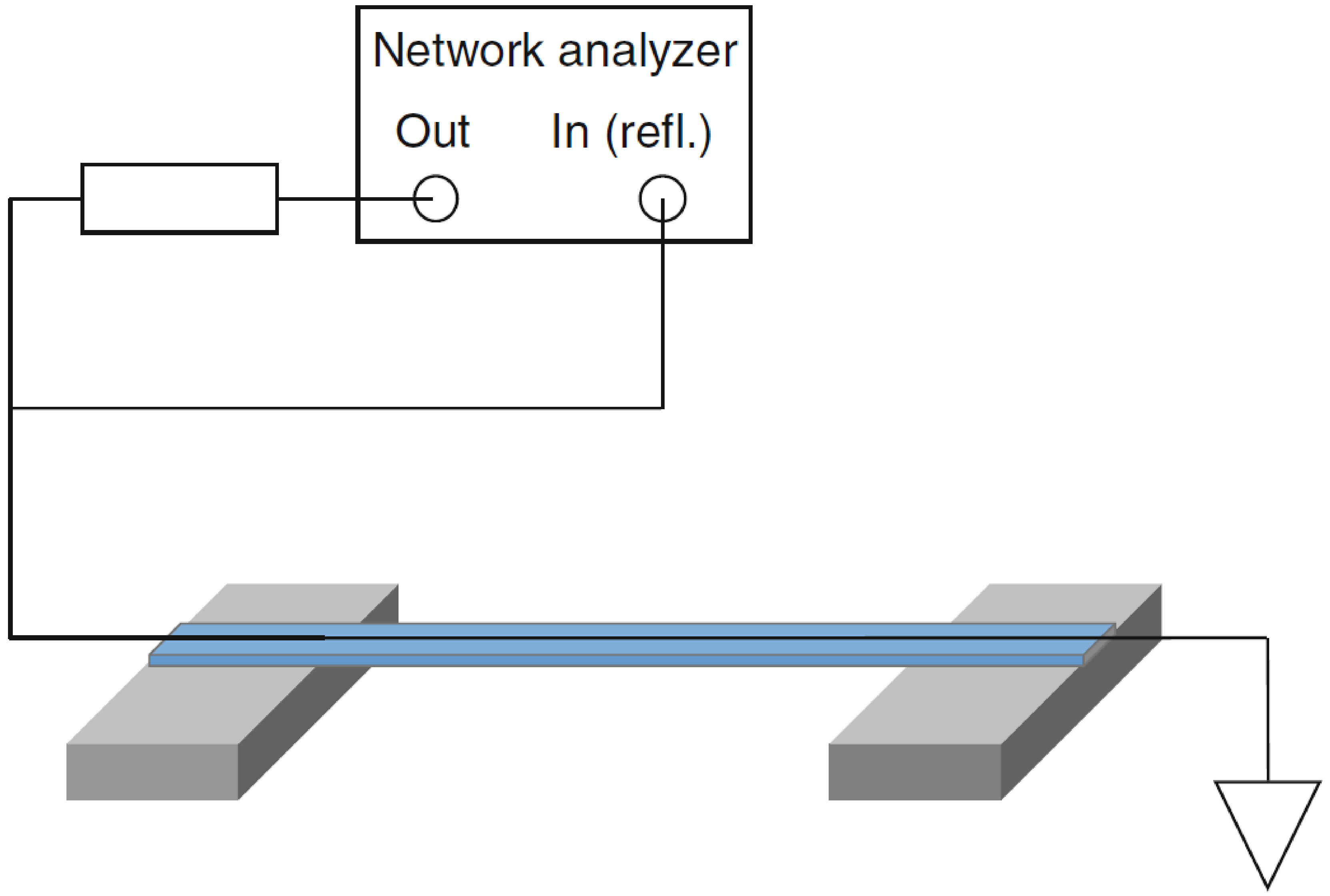
    - Piezo-metallic (metal gauges)
    - Piezoresistive

Magnetomotive Detection

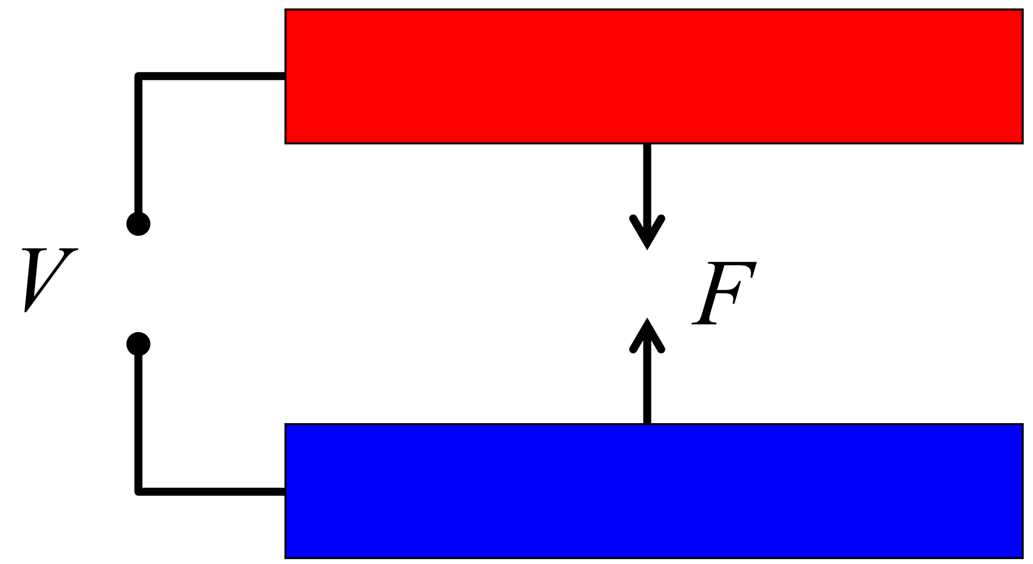
- Metal lines on MEMS
  - External magnetic field
  - We can consider that device is part of a metallic loop (is connected)
  - Faraday's law of induction:
  - $V_{emf} = -\frac{\partial \Phi}{\partial t} = -B\frac{\partial A_{loop}}{\partial t} \approx -BL\frac{\partial x}{\partial t} = -BL\dot{x}$

  - Very simple fabrication
  - Linear
  - Difficult to integrate
  - Heating of MEMS
  - Only for dynamic – proportional to velocity

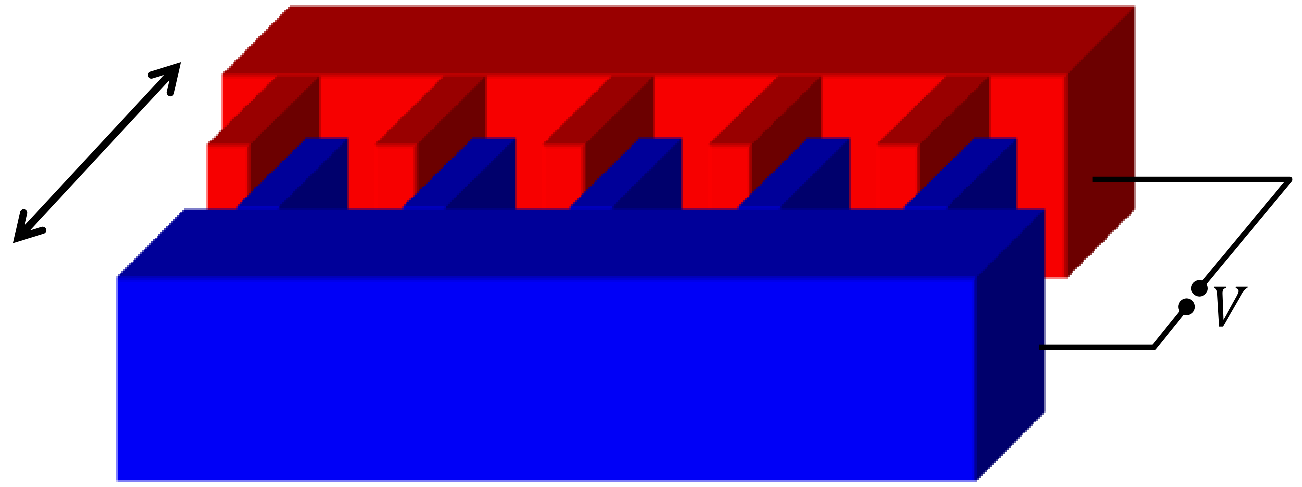


Capacitive Detection (1)

- Voltage applied between two conductive surfaces
- With movement → Capacitance changes

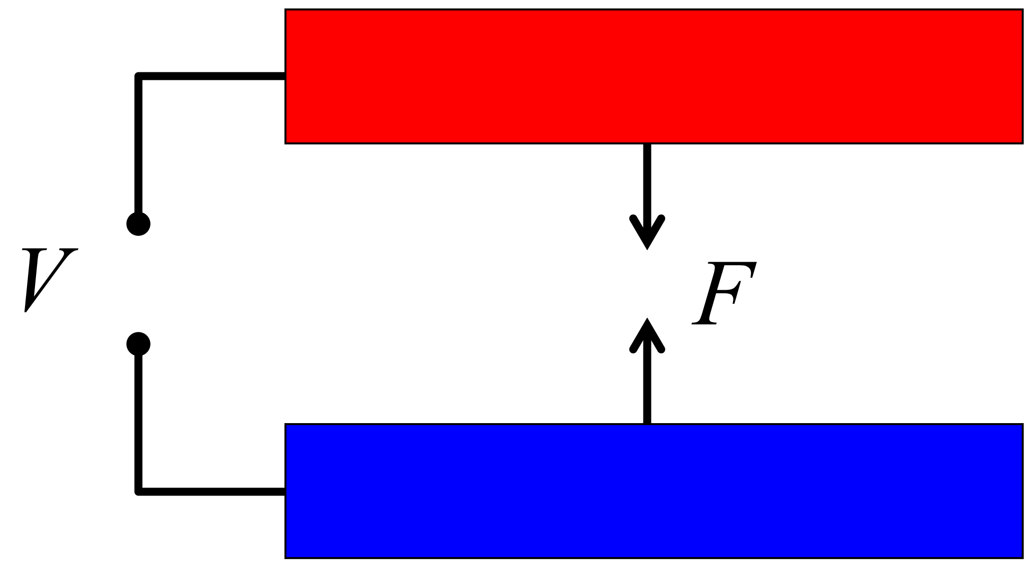


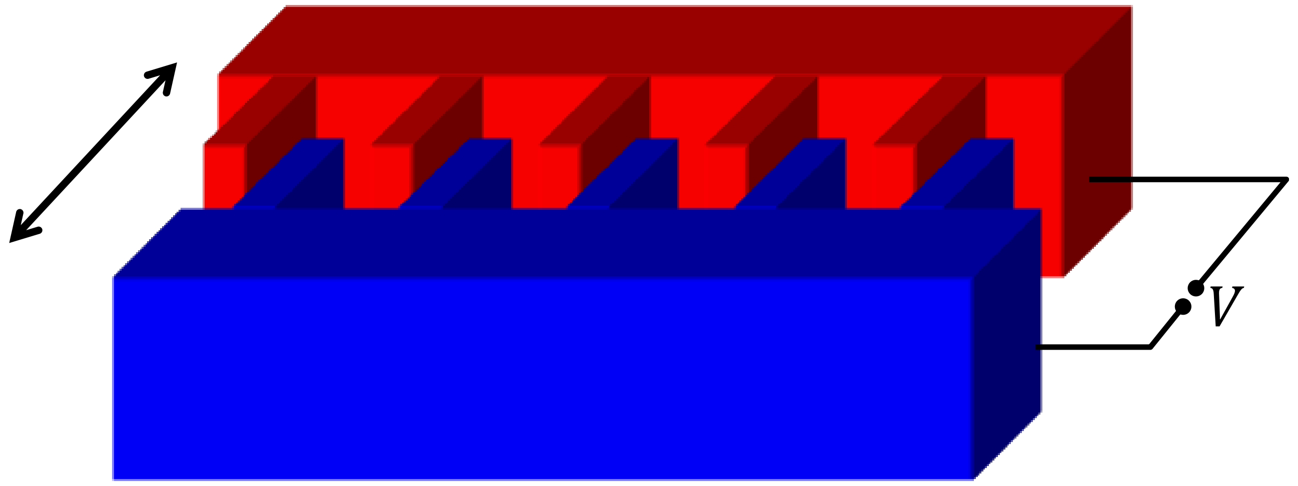
- Fast, Reactive, low power consumption
- Possible to do comb-drive
- Nonlinear
- Low efficiency
- Background

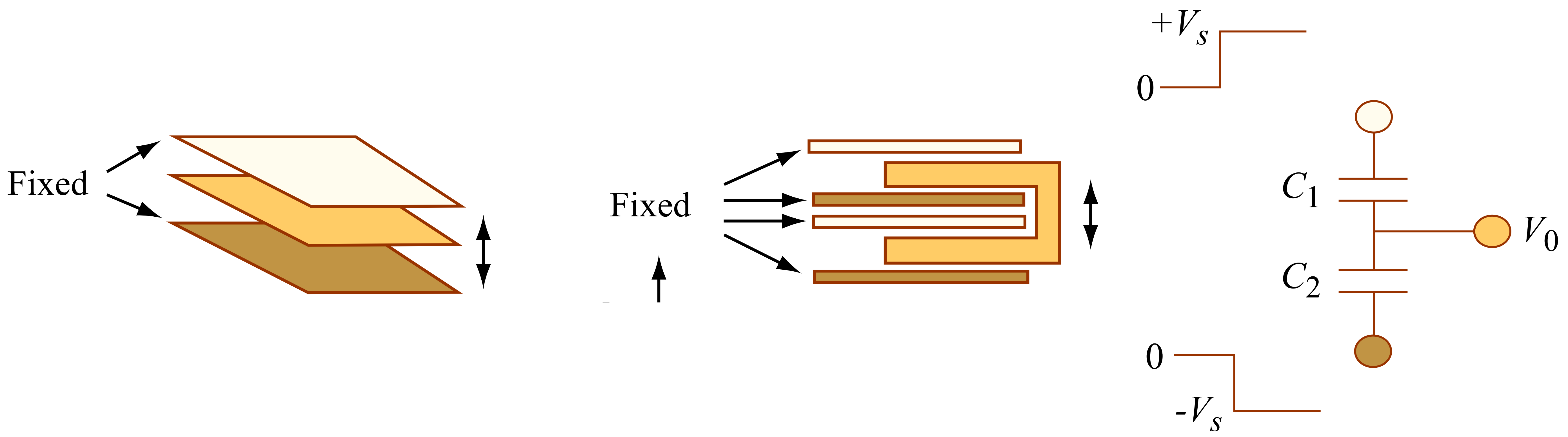


Capacitive Detection (2)

- Voltage applied between two conductive surfaces
- With movement → Capacitance changes
  - Impedance bridge
    - $V_0 = \frac{C_1 - C_2}{C_1 + C_2} V_s = \frac{g_2 - g_1}{g_1 + g_2} V_s$
    - Typically with actuation and detection in different electrodes





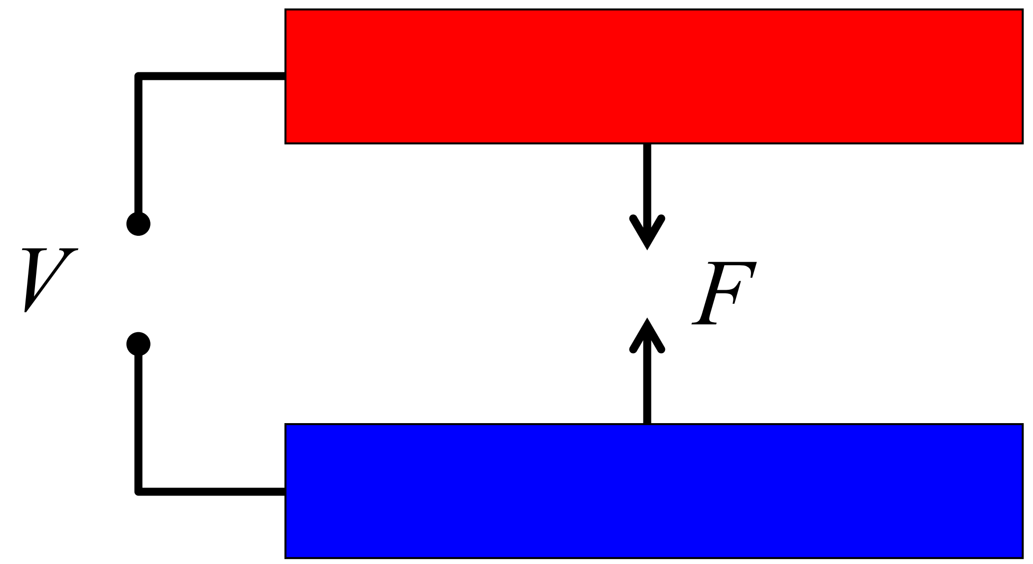


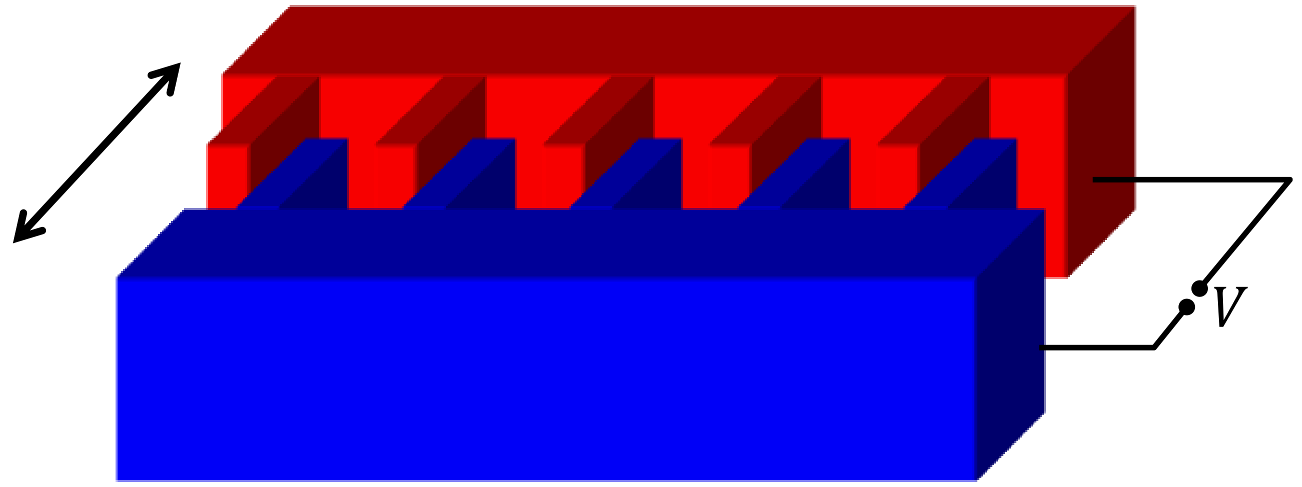
Capacitive Detection (3)

- Voltage applied between two conductive surfaces
- With movement → Capacitance changes
  - Impedance bridge
  - Current detection:
    - $I = \frac{\partial Q}{\partial t} = \frac{\partial (CV)}{\partial t} = C\frac{\partial V}{\partial t} + V\frac{\partial C}{\partial t}$

$$\rightarrow \mathrm{I} = I_{back} + I_{motion} = I_{back} + V\frac{\varepsilon_r\varepsilon_0 A}{(d-z)^2}\frac{\partial z}{\partial t}$$

$$\rightarrow \mathrm{I} = I_{back} + V\frac{\varepsilon_r\varepsilon_0 A}{d^2}\frac{\partial z}{\partial t}\left(1 + 2\frac{z}{d} + 3\left(\frac{z}{d}\right)^2 + \cdots\right)$$





Detection

Associated with Deformation

Transduction in the microscale

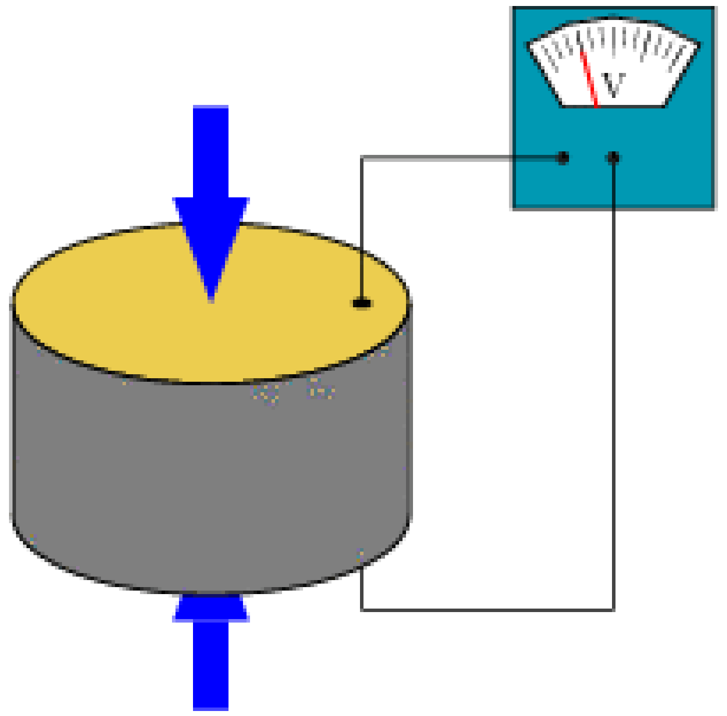
Actuation

- Pressure
  - Shape Memory Polymers
- Force
  - Magnetic force
  - Electrostatic force
- Expansion
  - Piezoelectric
  - Thermal
    - Electro-thermal
    - Opto-thermal

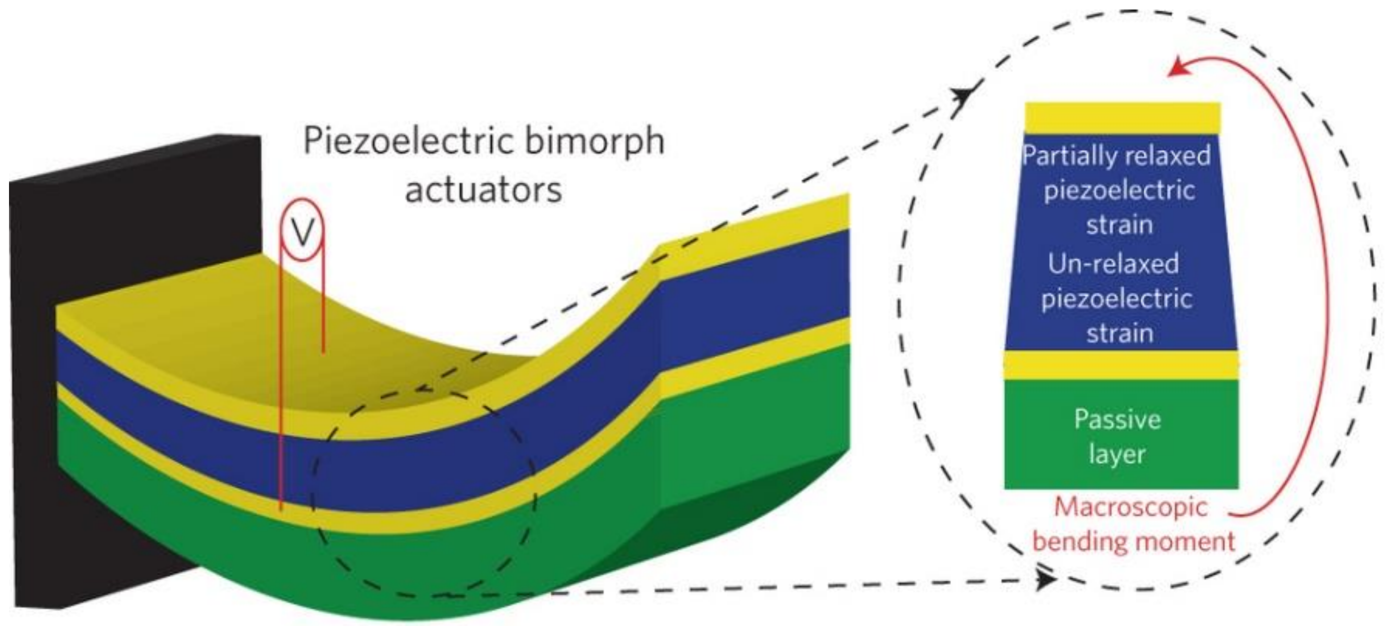
Detection

- "Seeing"
  - Optical lever
  - Interferometers
- Associated with a Force
  - Magnetomotive
  - Capacitive
- Associated with deformation
  - Piezoelectric
  - Change in resistance
    - Piezo-metallic (metal gauges)
    - Piezoresistive

Piezoelectric Detection (1)

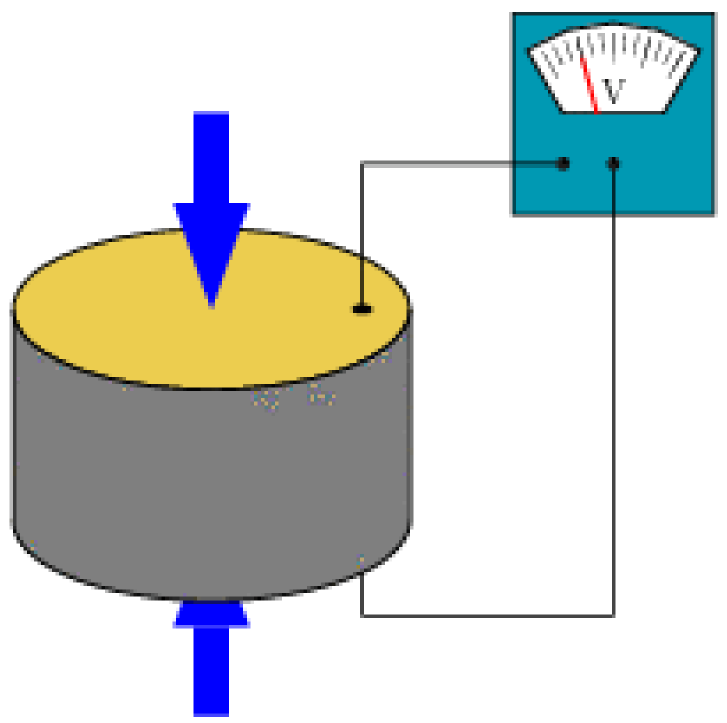


- Piezoelectricity
  - A mechanical stress generates charges
  - It can also be coupled through bending moment



  - Fast
  - Reactive
  - Linear
  - Extremely high efficiency
  - Small displacements (direct expansion)
  - Engineering of neutral axis (coupling through bending moment)
  - Needs 3 or 4 layers to work
  - Difficult to obtain, only for selected materials
  - Background if combined with actuation

Piezoelectric Detection (2)



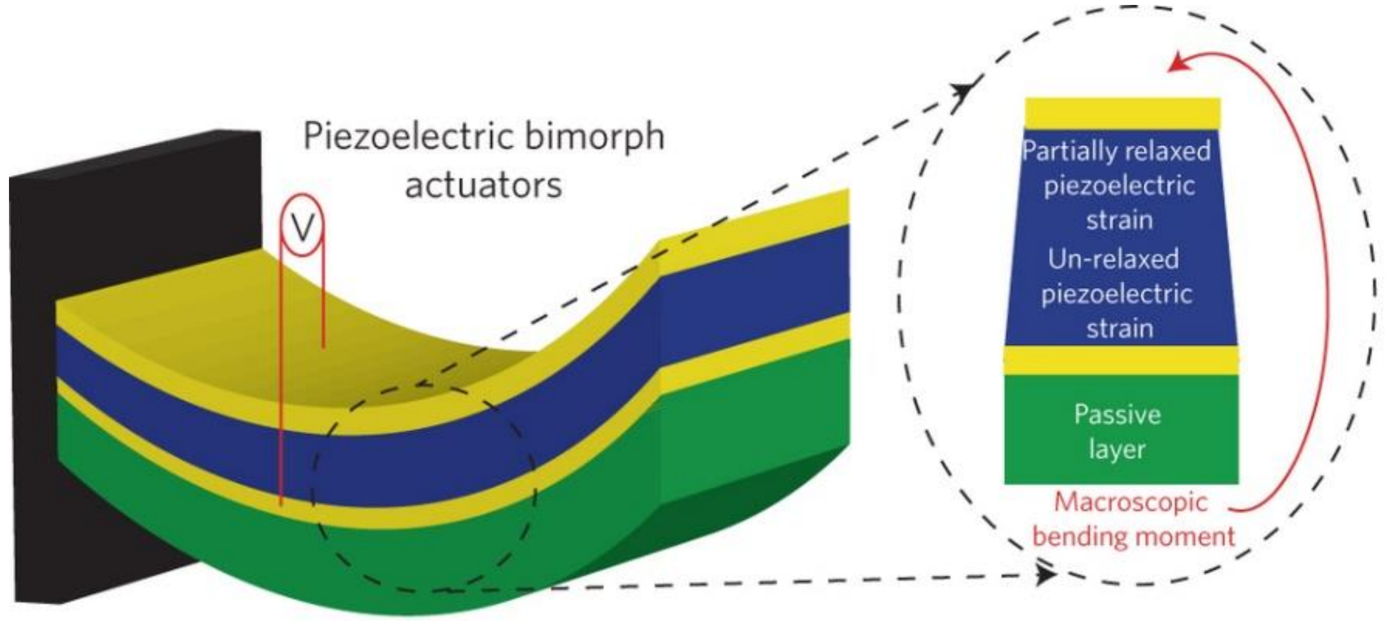
- Piezoelectricity
  - A mechanical stress generates charges
  - Direct expansion:
    - $J_D = \frac{\partial D}{\partial t} \rightarrow I = d_{33} E \frac{A}{t_{PZE}} \frac{\partial x}{\partial t} \rightarrow I = j\omega d_{33} E \frac{A}{t_{PZE}} x$
    - With actuation: $I = j\omega \left(C_0 + d_{33}^2 E \frac{A}{t_{PZE}} \right) V_{in} =$
      $$= j\omega \left(\frac{\varepsilon_r \varepsilon_0 A}{t_{PZE}} + d_{33}^2 E \frac{A}{t_{PZE}} \right) V_{in} = j\omega \frac{A}{t_{PZE}} V_{in} \left(\varepsilon_r \varepsilon_0 + d_{33}^2 E \right)$$
    - Electromechanical efficiency: $k_t^2 = \frac{d_{33}^2 E}{\varepsilon_r \varepsilon_0}$

Piezoelectric Detection (3)

- Piezoelectricity
  - A mechanical stress generates charges
  - Coupled through bending moment:
    - $J_D = \frac{\partial D}{\partial t} \rightarrow I = d_{31}E\frac{wz_{offset}}{L}\frac{\partial x}{\partial t} \rightarrow I = j\omega d_{31}E\frac{wz_{offset}}{L}x$
    - With actuation: $I = j\omega\left(C_0 + d_{31}^2 E\frac{wz_{offset}^2}{t^3}L\right)V_{in} =$

$$= j\omega\left(\frac{\varepsilon_r\varepsilon_0 A}{t_{PZE}} + d_{31}^2 E\frac{wz_{offset}^2}{t^3}L\right)V_{in} = j\omega\frac{A}{t_{PZE}}V_{in}\left(\varepsilon_r\varepsilon_0 + d_{31}^2 E\frac{z_{offset}^2 t_{PZE}}{t^3}\right)$$

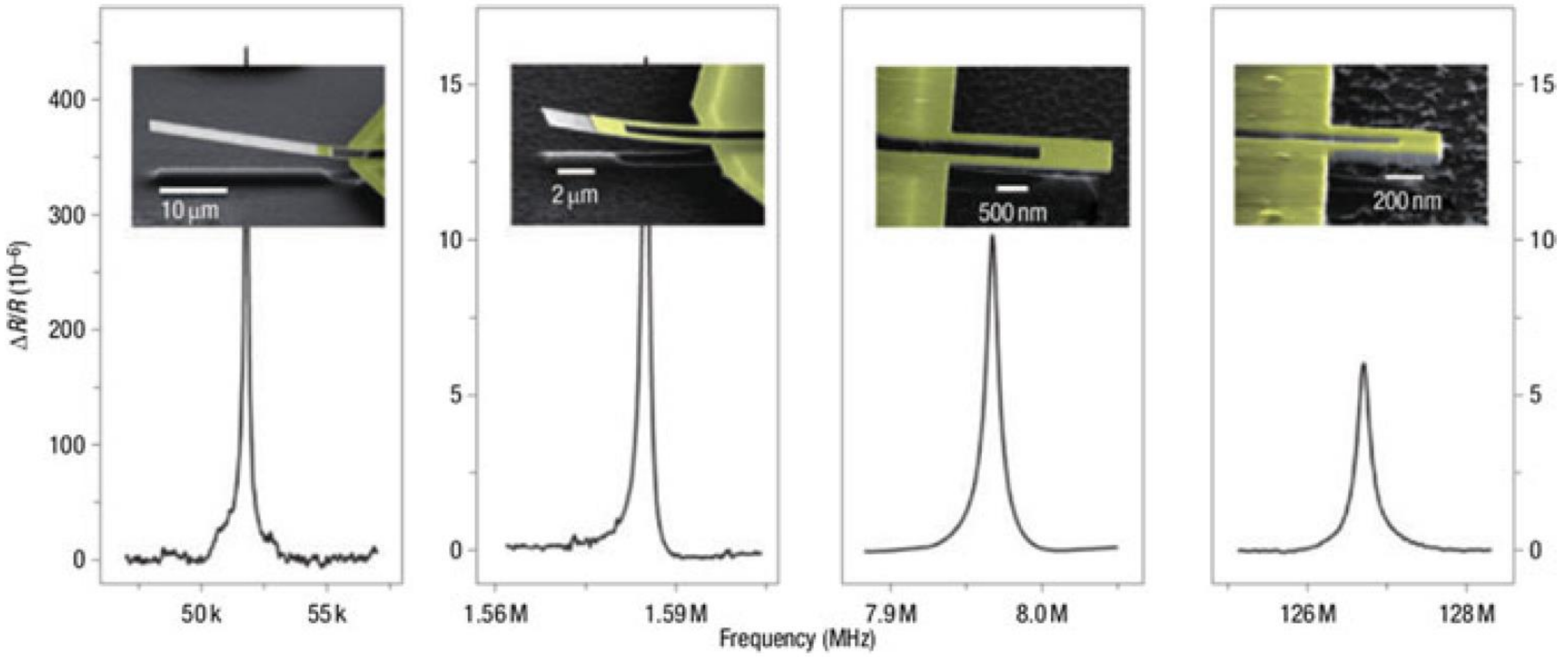
    - Electromechanical efficiency: $k_t^2 = \frac{d_{31}^2 E}{\varepsilon_r\varepsilon_0} \times \frac{z_{offset}^2 t_{PZE}}{t^3}$



Piezometallic Detection

- Metal lines on MEMS
- When deformation happens on the metal line, resistance changes
  - $R = \rho \frac{L}{wt} \rightarrow \frac{\delta R}{R_0} = \frac{\delta L}{L} - \frac{\delta w}{w} - \frac{\delta t}{t} = (uniaxial) = \frac{\delta L}{L}(1 + 2\nu) \sim \varepsilon_{long}(1 + 2\nu)$

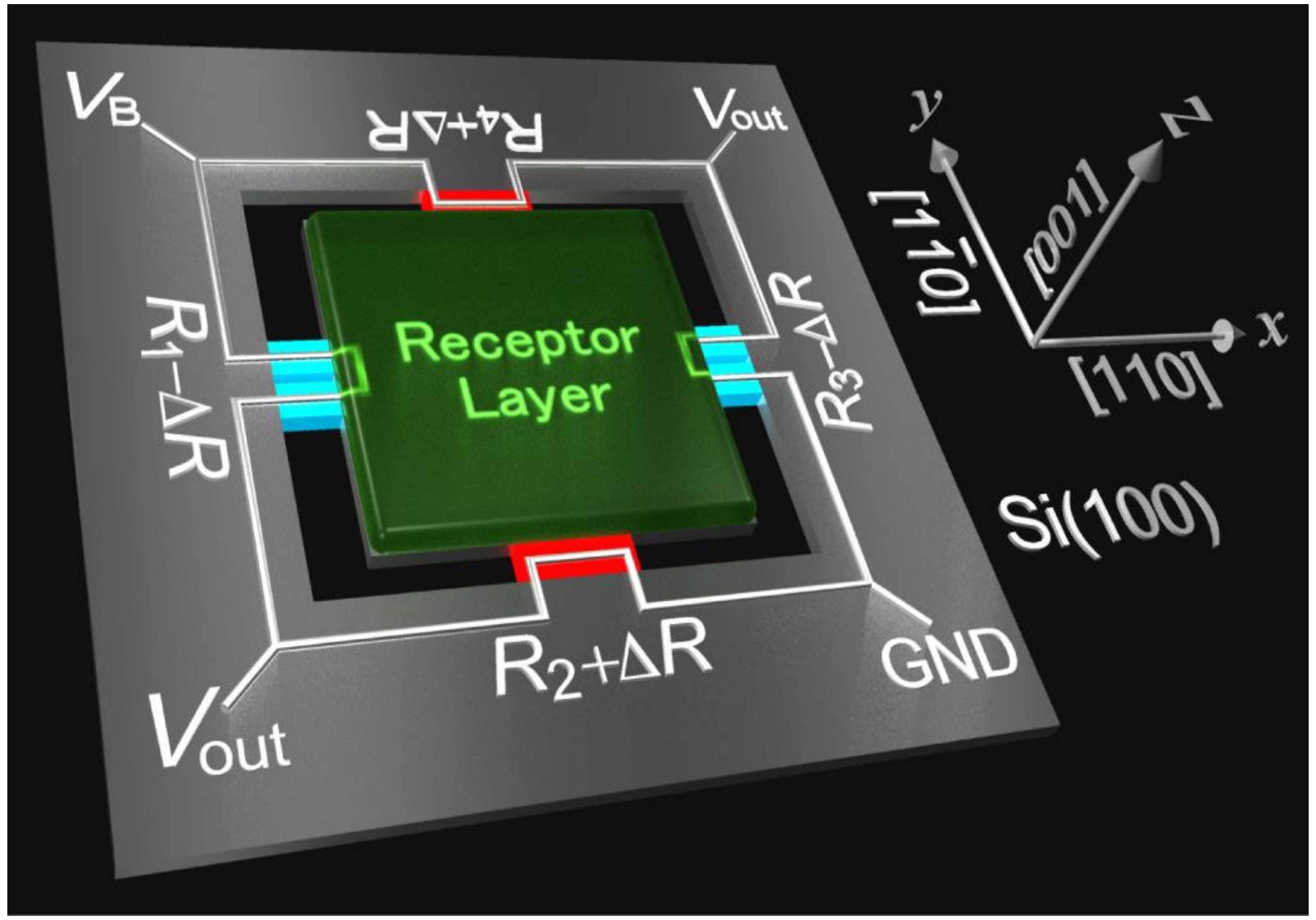
  - Large bandwidth
  - Low noise
  - Easy 50ohm matchir
  - Low responsivity
  - Dissipative



Piezoresistive Detection

- Semiconductor resistances on MEMS
  - Silicon (p or n doped)
  - Germanium
- When deformation happens on the resistor, resistance changes
  - $R = \rho \frac{L}{wt} \rightarrow \frac{\delta R}{R_0} = \frac{\delta \rho}{\rho} + \frac{\delta L}{L} - \frac{\delta w}{w} - \frac{\delta t}{t} = (uniaxial) = \varepsilon_{long}\left(1 + 2\nu + \frac{\pi_{long}}{E}\right)$

  - High responsivity
  - Easy to build Wheatstone bridge
  - High noise
  - Small bandwidth
  - Dissipative



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Ideal requirements for MEMS transduction

- Low power consumption
- High electro-mechanical efficiency
- Robust to mechanical/environment conditions
- Small footprint
- Linear
- Fast response
- Large deformation
- Large force

  - In reality: trade-off. Final choice depends on each particular application