Advanced MEMS and Microsystems

Dr. Danick Briand, Prof. Niels Quack, Prof. Guillermo Villanueva

TRANSDUCTION

Guillermo Villanueva

Definition of a transducer in 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

- **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

Actuation

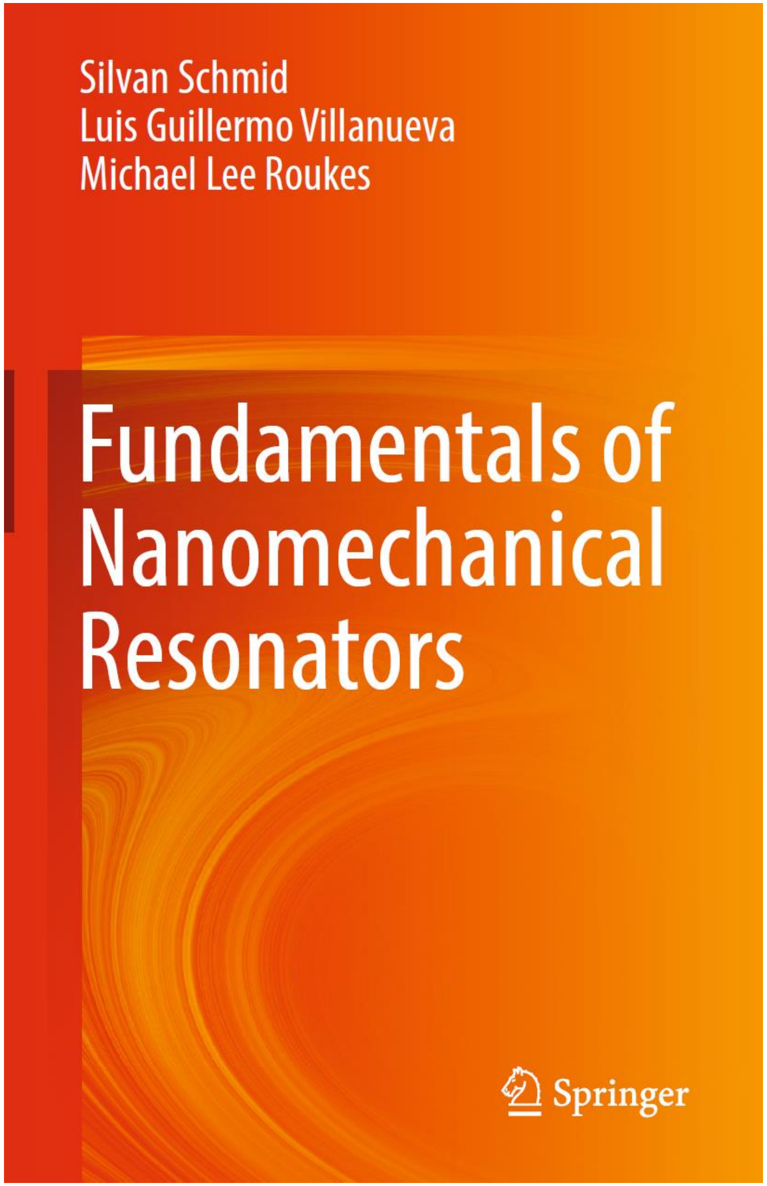
- **Pressure**
  - Shape Memory Polymers
- **Force**
  - Magnetic force
  - Electrostatic force
- **Expansion**
  - Piezoelectric
  - Thermal
    - Electro-thermal
    - Opto-thermal

Detection

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

Transduction in the microscale

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

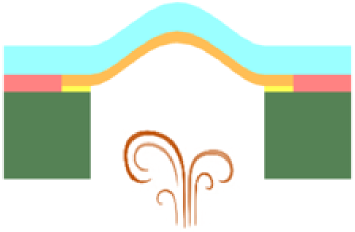


http://link.springer.com/content/pdf/10.1007%2F978-3-319-28691-4_4.pdf

SHAPE MEMORY POLYMER

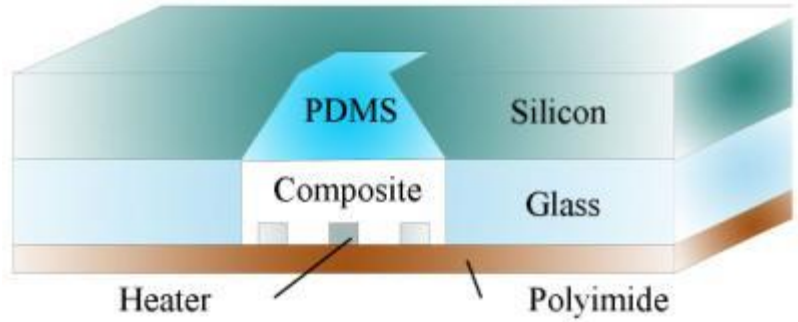
Shape Memory Polymer

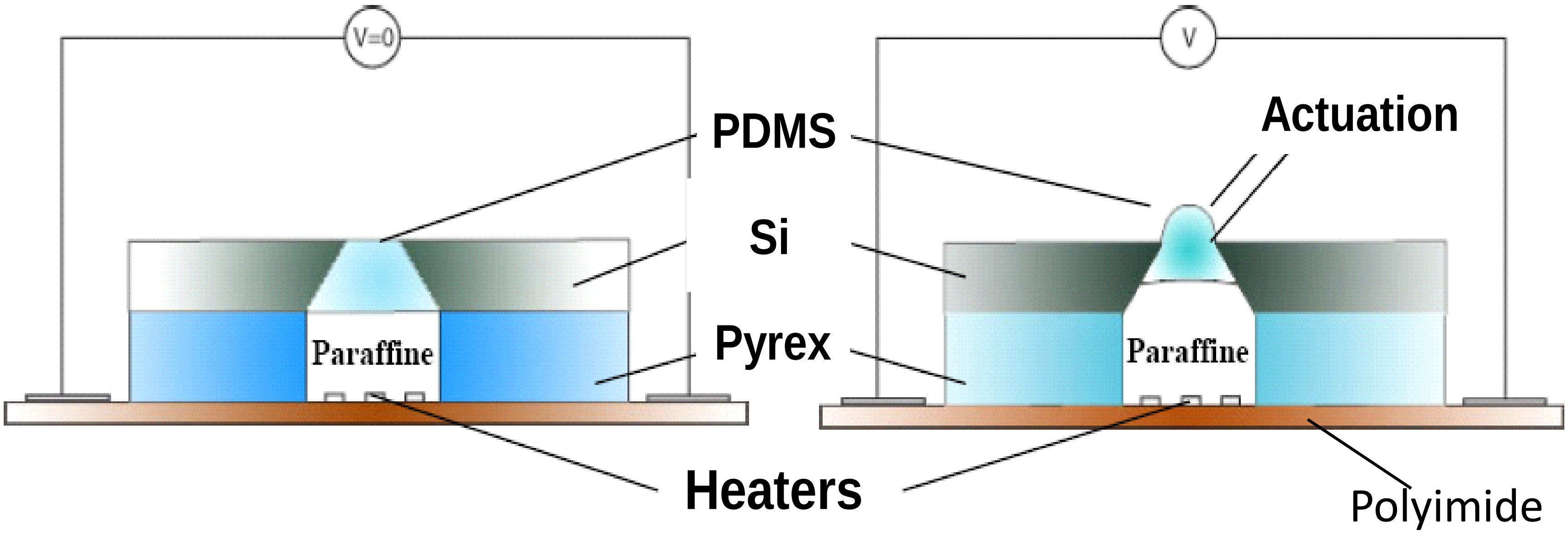
- **Pressure deforms**
- **To maximize deformation**
  - **Softer polymer**
- **To keep force**
  - **Phase change!**



Phase change actuators

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





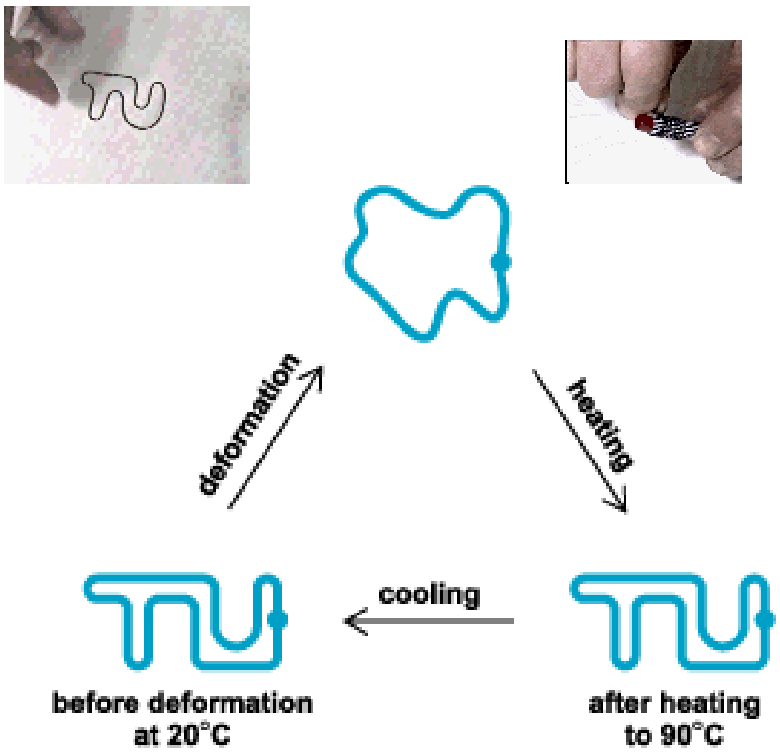
From EPFL-SAMLAB

Shape memory alloy actuator

- In the martensite phase, Nitinol can be bent into various shapes.

- To fix the "parent shape" (as it is called), the metal must be held in position and heated to about 500 ° C. The high temperature "causes the atoms to arrange themselves into the most compact and regular pattern possible" resulting in a rigid cubic arrangement known as the austenite phase.

- Above the transition temperature, Nitinol reverts from the martensite to the austenite phase which changes it back into its parent shape. This cycle can be repeated millions of times if strain kept below 2%



- Displacement: tens of microns up to millimeter

http://www.youtube.com/watch?v=Xs_0gQ4Rop0

http://www.smaterial.com/SMA/phenomena/phenomena.html

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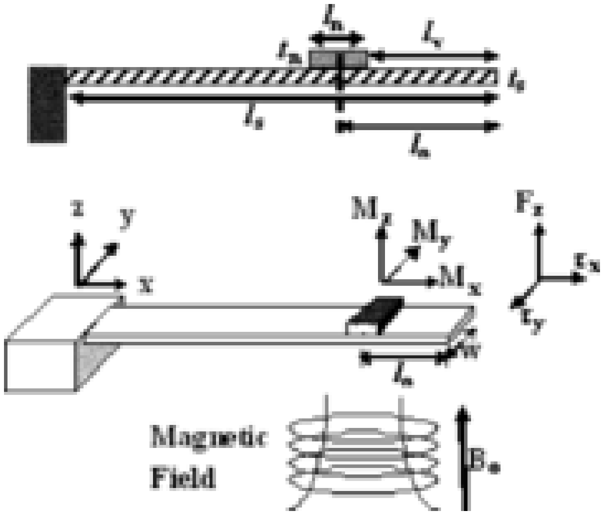
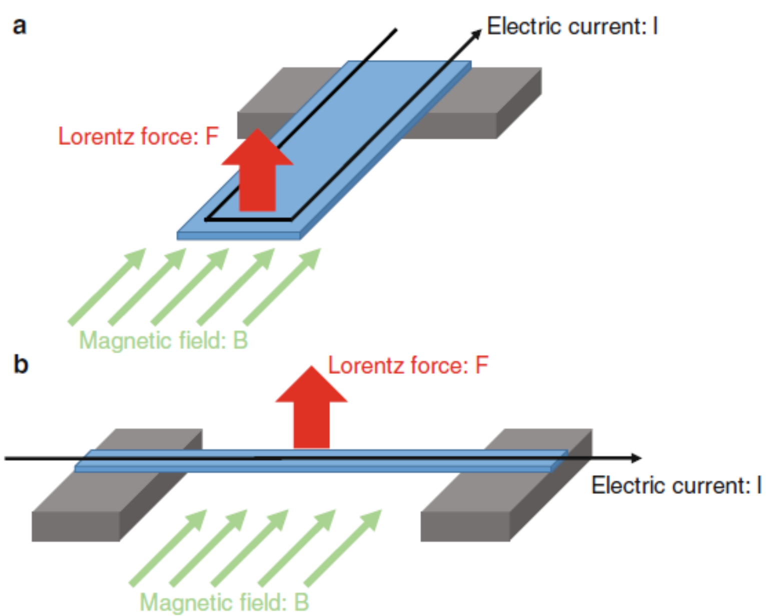
FORCE-BASED ACTUATION

- **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

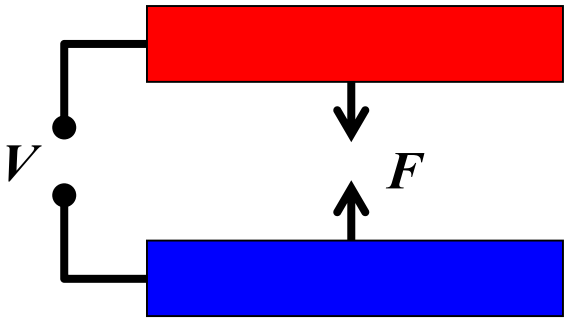


- **Metal lines on MEMS**
  - Lorentz force
  - $\vec{F} = q\,\vec{v} \times \vec{B} = l \cdot \vec{I} \times \vec{B}$
  - External magnetic field is typically constant
  - Current on the MEMS and Force is generated
  - Very simple fabrication
  - Difficult to integrate
  - Heating of MEMS

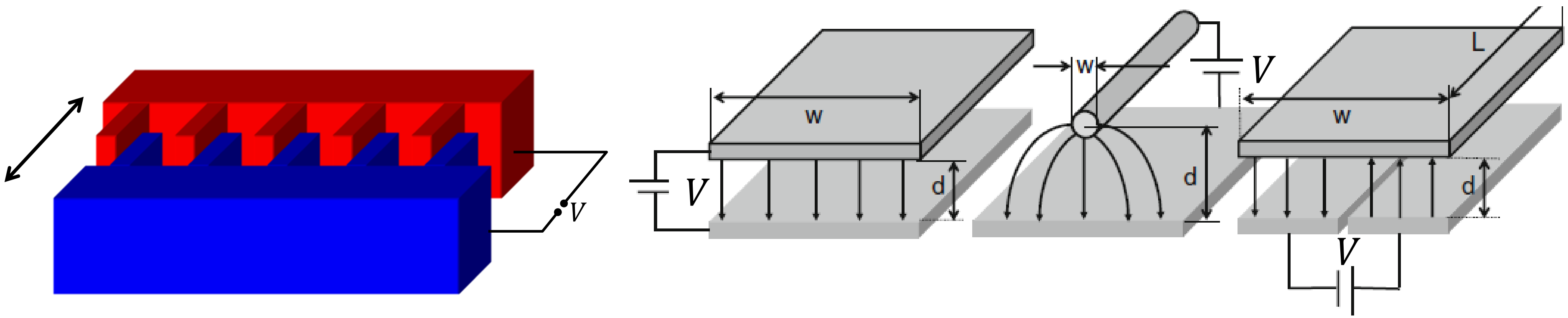


Electrostatic Actuation (more on week 5)

- **Voltage applied between two conductive surfaces**
- **Capacitor**
  - $F = \frac{1}{2}\frac{\partial C}{\partial d}V^2 = \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 A}{d^2}V^2$
  - Very fast, speed tuned via Voltage
  - Purely reactive coupling
  - Very low power consumption
  - Possible to do comb-drive
  - Nonlinear
  - Pull-in voltage
  - Only attractive



- **To recall: the gap is usually air, but can be solid**



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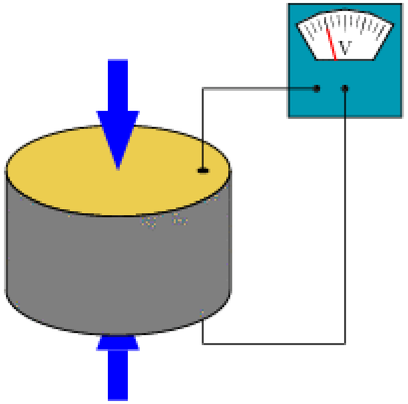
EXPANSION-BASED ACTUATION

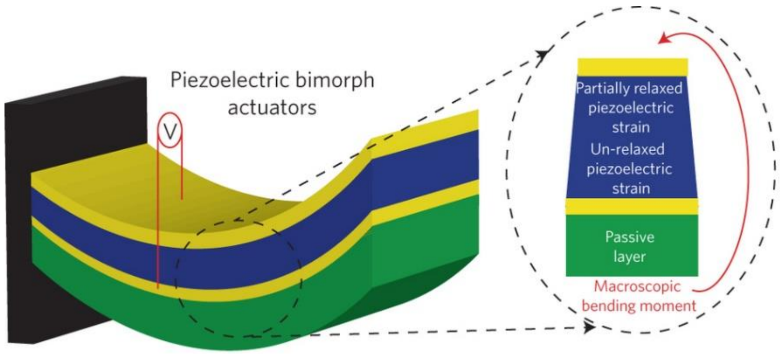
Piezoelectric Actuation (more on week 7)

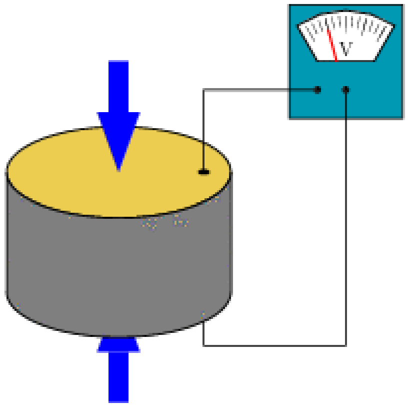
- **Piezoelectricity**
  - **Material property through which**
    - **An electric field turns into mechanical strain**
    - **A mechanical stress generates charges**
  - **It happens in materials without inversion symmetry**
    - **Unit lattice is not symmetric**
- **Examples of materials:**
  - **AlN**
  - **AlScN**
  - **PZT**
  - **ZnO**
  - **LiNbO3**
  - **PMN-PT**
  - **Quartz**



Piezoelectric Actuation (more on week 7)

- **Piezoelectricity**
  - **An electric field turns into mechanical strain**
  - **Direct expansion** → $x = d_{33}V$
  - **Coupling through bending moment**→ $x = \frac{d_{31} z_{offset} L^2}{t^3} V$



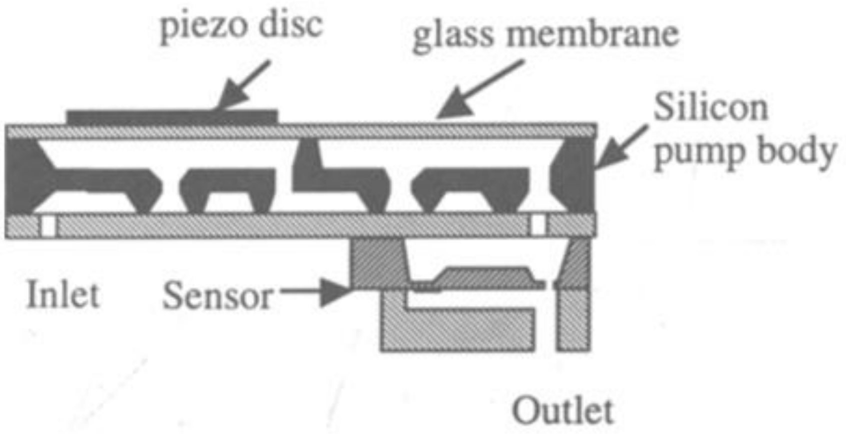


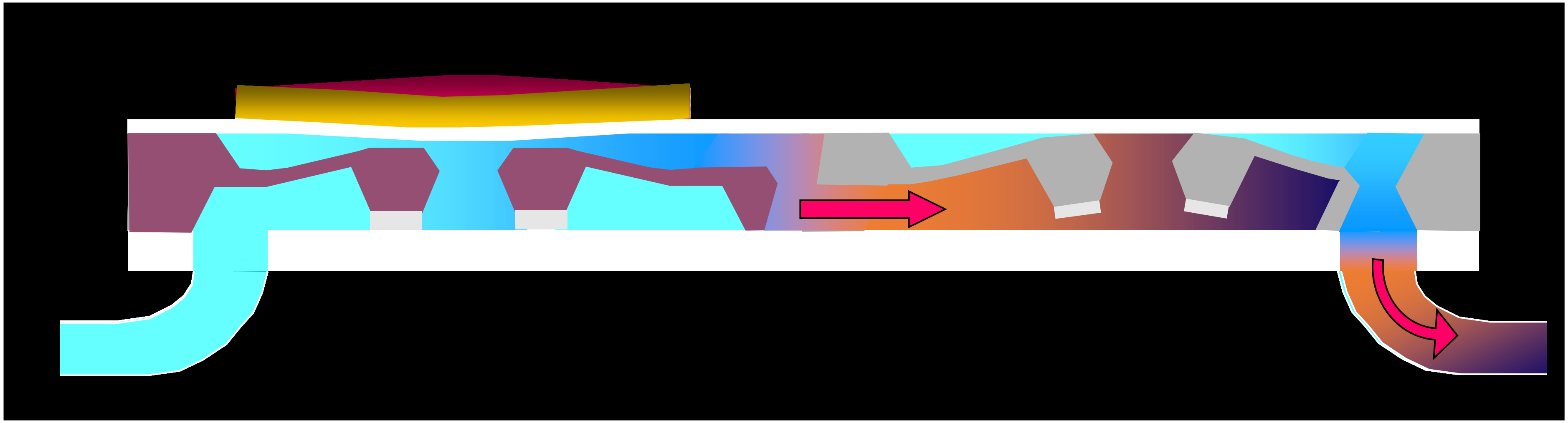
  - **Fast**
  - **Reactive**
  - **Linear**
  - **Extremely high efficiency**
  - **Small displacements (direct expansion)**
  - **Engineering of neutral axis (coupling through bending moment)**
  - **Needs 3 or 4 layers to work**
  - **Difficult to obtain, only for selected materials**

Piezoelectric Actuation - Example

Micro-pumps

- Piezoelectric actuation
- Piezoelectric disk transferred on the membrane



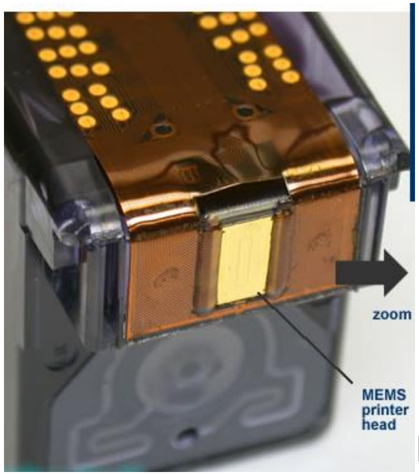


Gass, V., van der Schoot, B.H., Jeanneret, S., de Rooij, N.F. Sens. Actuators A, 1994, 43 (1-3), 335-338

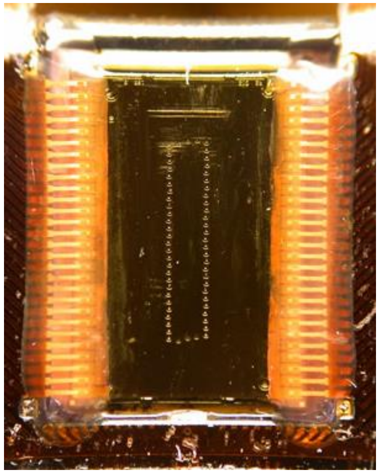
Piezoelectric Actuation - Example

Inkjet printheads

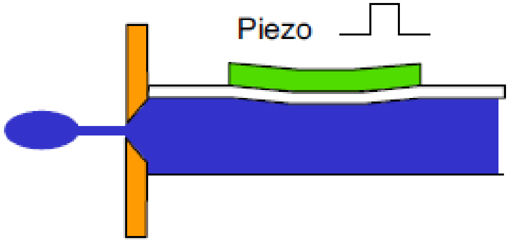
- Drop on Demand (DoD)



HP



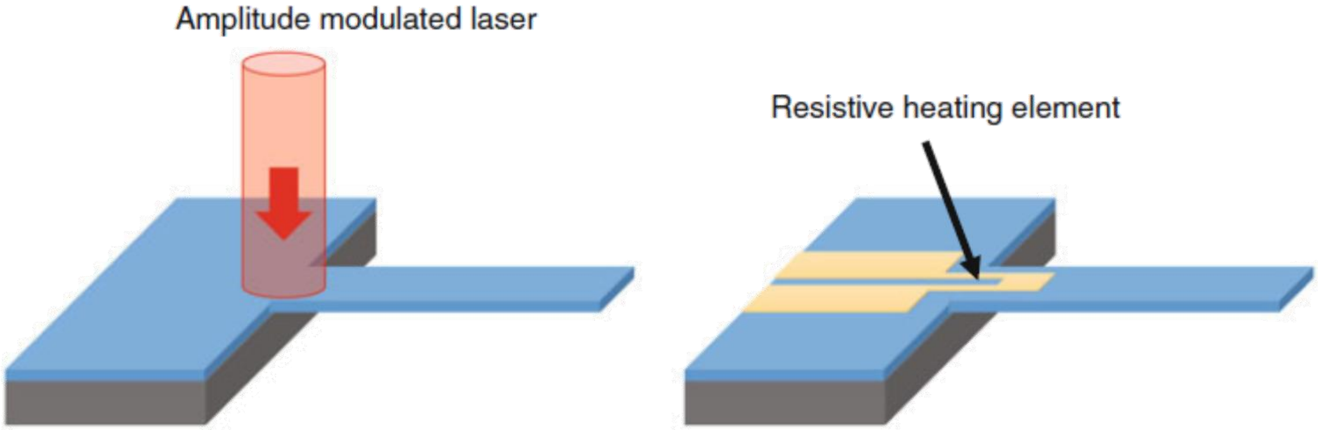
Piezo



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

Thermal Actuation

- Based on expansion of materials due to temperature
- Actuation can be based on:
  - Direct expansion
  - Coupled through bending moment
- Temperature increase can be caused by
  - Joule heating (electrical current)
    - $\rightarrow x \sim \frac{\alpha_{heater}}{\kappa_{th}} \frac{t_{heater} z_{offset}}{t^4} \frac{L^3}{w} \cdot P \approx \frac{\alpha_{heater}}{\kappa_{th}} \frac{t_{heater} z_{offset} L^2}{t^3} \frac{V^2}{\rho_{el}}$
  - Light absorption
    - $\rightarrow x \sim \frac{\alpha_{heater}}{\kappa_{th}} \frac{t_{heater} z_{offset}}{t^4} \frac{L^3}{w} \cdot P \approx \frac{\alpha_{heater}}{\kappa_{th}} \frac{t_{heater} z_{offset}}{t^4} \frac{L^3}{w} \alpha_{abs} P_{laser}$



Photothermal heating

Resistive heating

Thermal Actuation

- Based on expansion of materials due to temperature
- Temperature increase can be caused by
  - Joule heating (electrical current)
  - Light absorption
- 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 recall: it is not the CTE but CTE·Young's modulus what matters

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

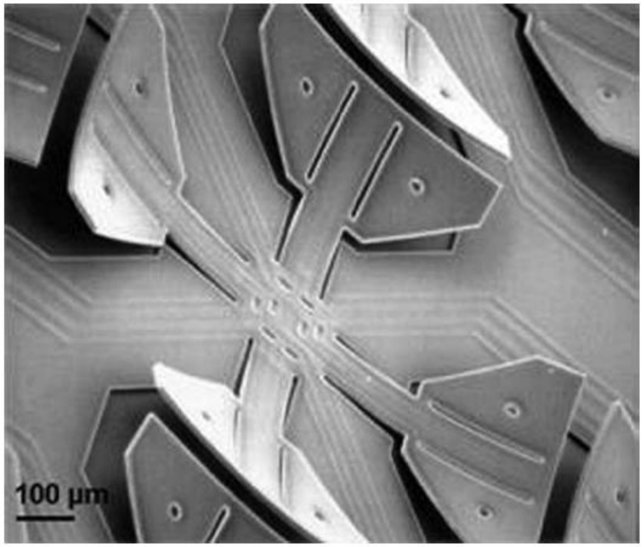


Fig. 3. SEM image of motion pixels [34]. Each motion pixel has an area of 1.1 mm × 1.1 mm. The approximate height of a cilium at room temperature is 117 μm. The thickness, width, and length of a cilium are 10.1, 430, and 550 μm, respectively. (Picture by J. Suh)

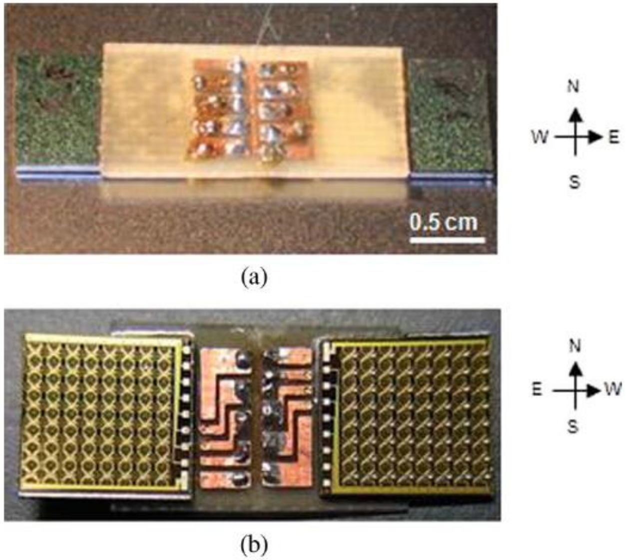


Fig. 2. (a) Top and (b) bottom views of the microrobot. The two cilia chips can be seen attached and wire bonded to a PCB backbone. Each cilia chip contains an 8 × 8 array of "motion pixels" (i.e., a group of four orthogonal cilia). The usage of two chips increases the stability and allows rotational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

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

Thermal Actuation - Example

Electrothermal actuator

- Made of electroplated Ni

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

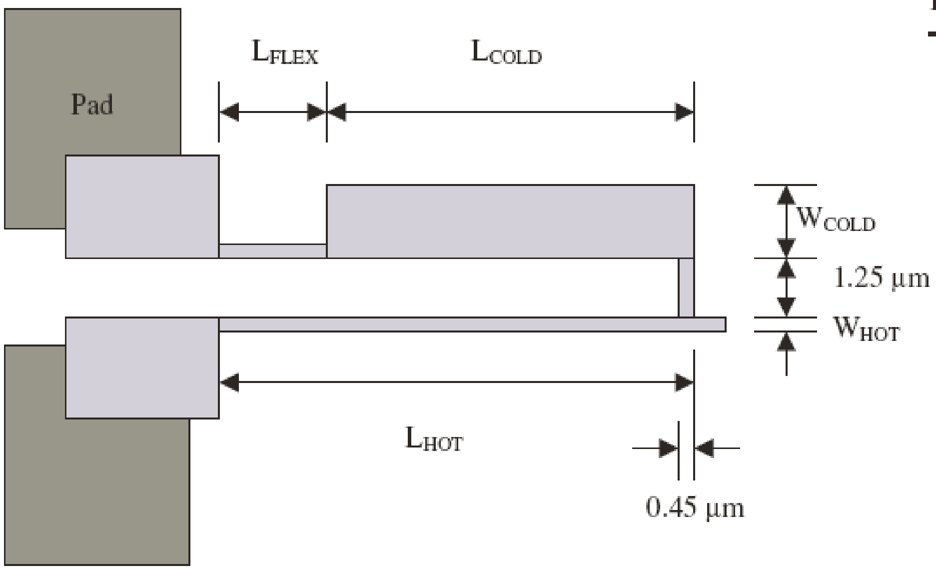
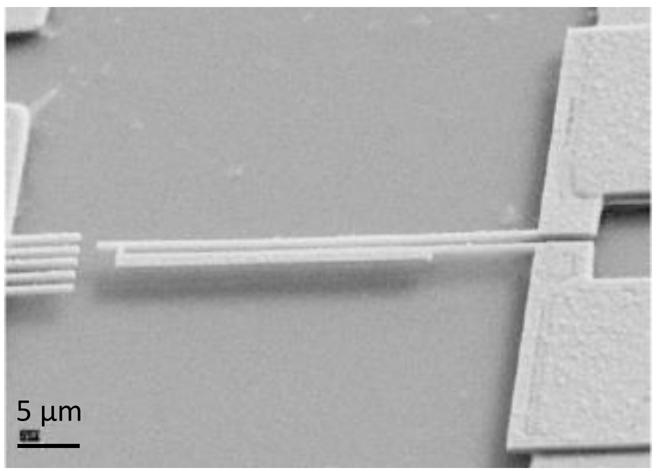
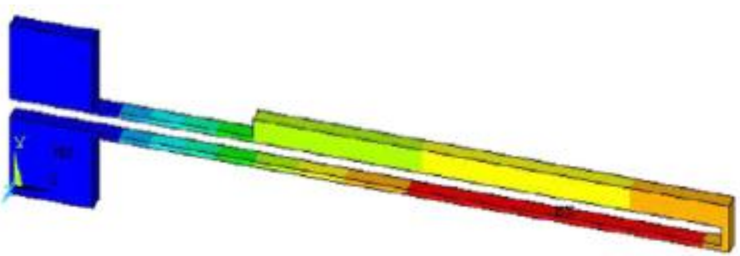


Figure 1. A schematic drawing of sub-micron electrothermal actuators with the geometrical parameters.





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

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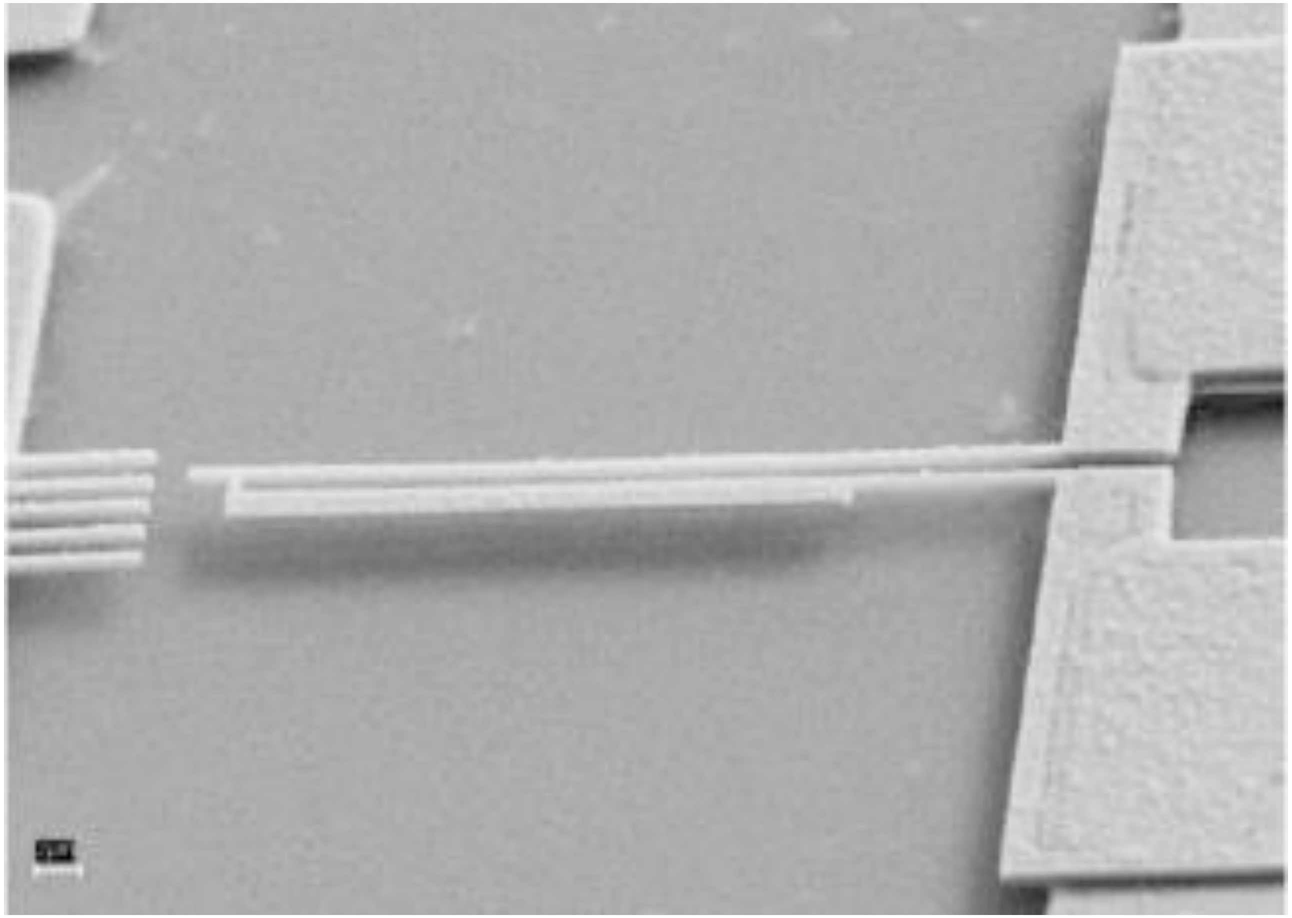
“SEEING”

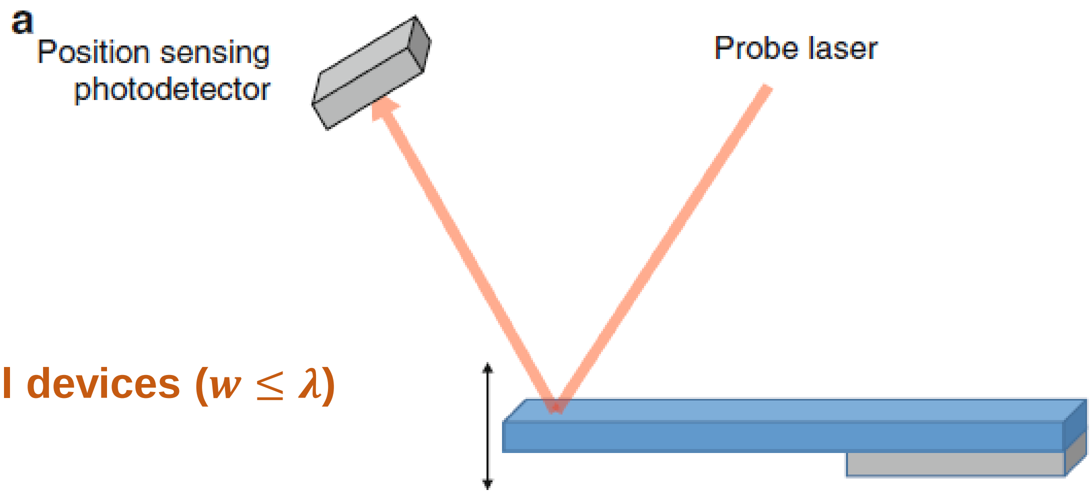
Direct Detection

- **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



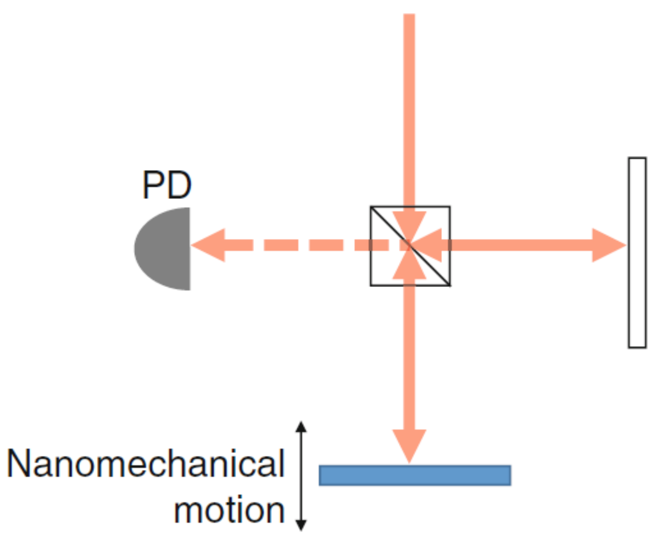
  - Very easy to implement
  - Good resolution
  - Not possible to integrate
  - Alignment issues
  - Diffraction problems for small devices ($w \leq \lambda$)

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



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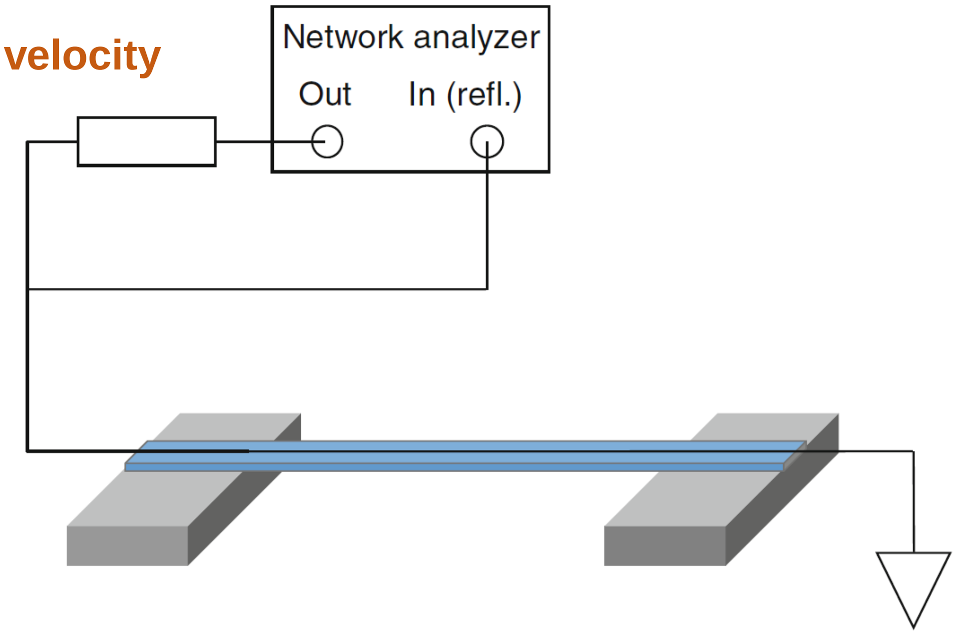
ASSOCIATED WITH A FORCE

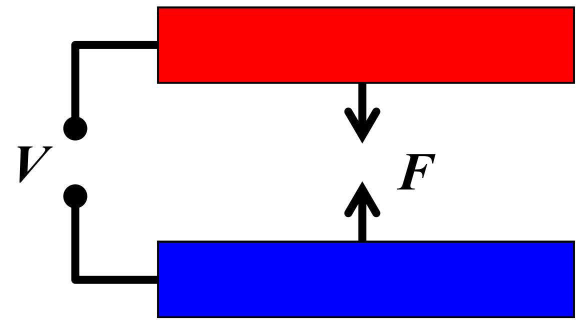
Magnetomotive Detection

- **Metal lines on MEMS**
  - **External magnetic field**
  - **We can consider that device is part of a metallic loop (is connected)**
  - $V_{emf} = -\frac{\partial \Phi}{\partial t} = -B\frac{\partial A_{loop}}{\partial t} \approx -BL\frac{\partial x}{\partial t} = -BL\dot{x}$
  - **Very simple fabrication**
  - **Difficult to integrate**
  - **Heating of MEMS**
  - **Only for dynamic – proportional to velocity**

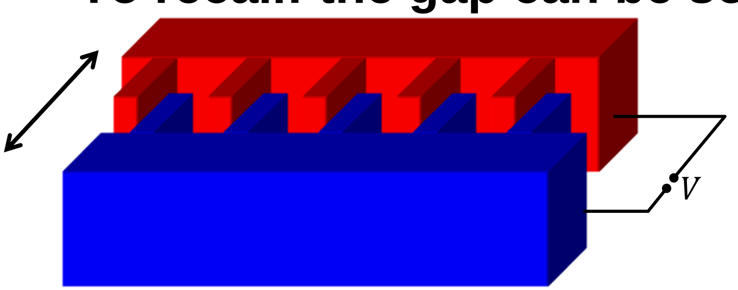


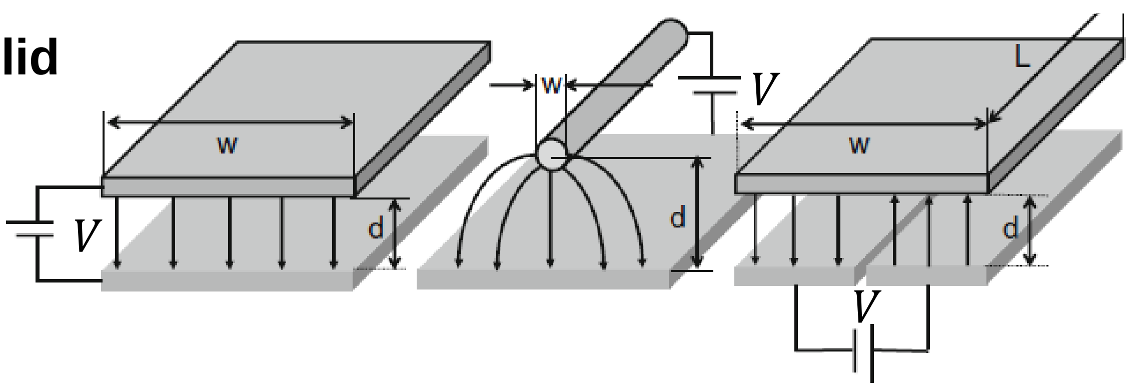
Capacitive Detection

- Voltage applied between two conductive surfaces
- With movement → Capacitance changes
  - ➢ Impedance bridge (more next week)
    - $\delta V = \frac{1}{4}\frac{\delta C}{C}V$
    - Typically with actuation and detection in different electrodes
  - ➢ Current detection:
    - $I = \frac{\partial (CV)}{\partial t} = V\frac{\partial C}{\partial t} + C\frac{\partial V}{\partial t}$



  - ➢ Fast, Reactive, low power consumption
  - ➢ Possible to do comb-drive
  - ➢ Nonlinear, Low efficiency
  - ➢ Background
- To recall: the gap can be solid





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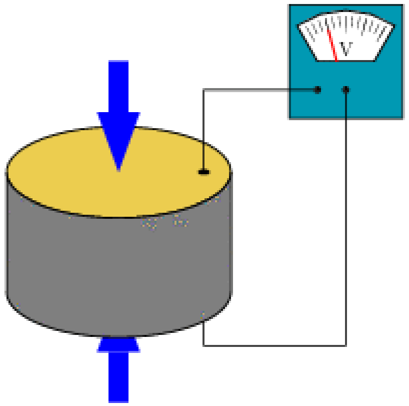
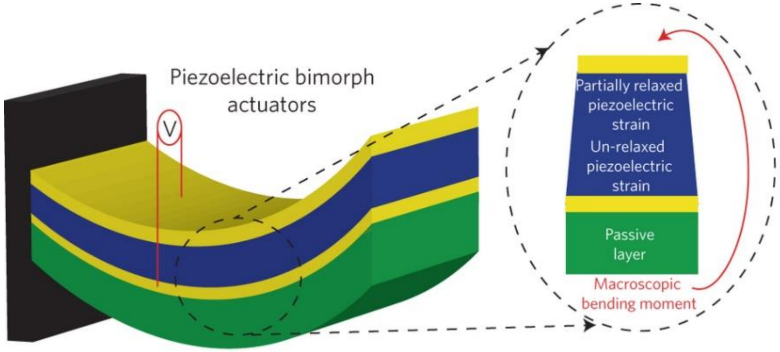
ASSOCIATED WITH DEFORMATION

Piezoelectric Detection (more on week 7)

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





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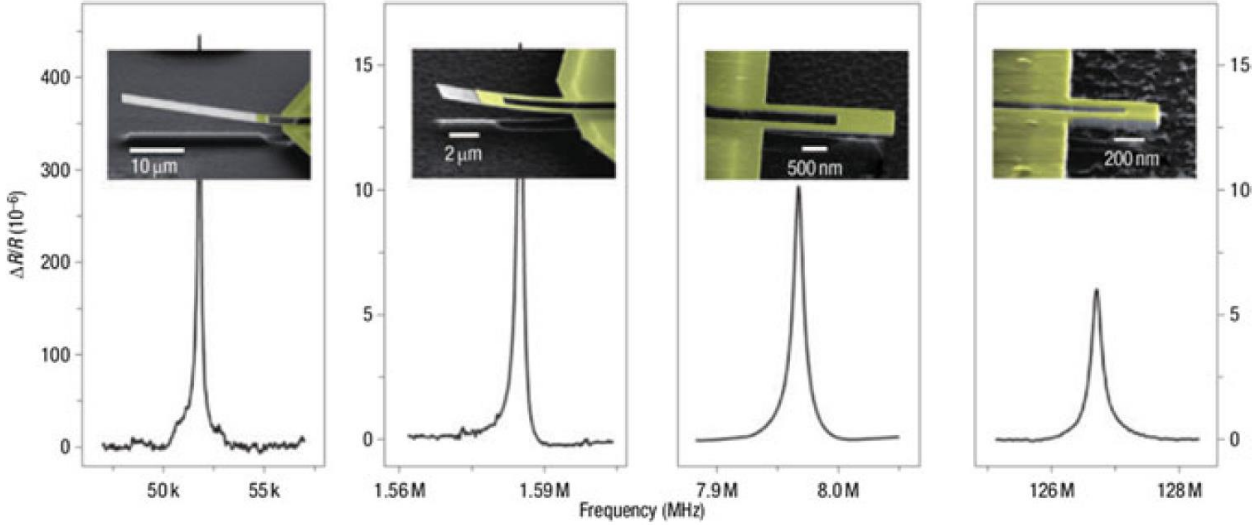
- **Reactive**
- **Linear**
- **Extremely high efficiency**
- **Small displacements (direct expansion)**
- **Engineering of neutral axis (coupling through bending moment)**
- **Needs 3 or 4 layers to work**
- **Difficult to obtain, only for selected materials**
- **Background if combined with actuation**

Piezometallic Detection

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

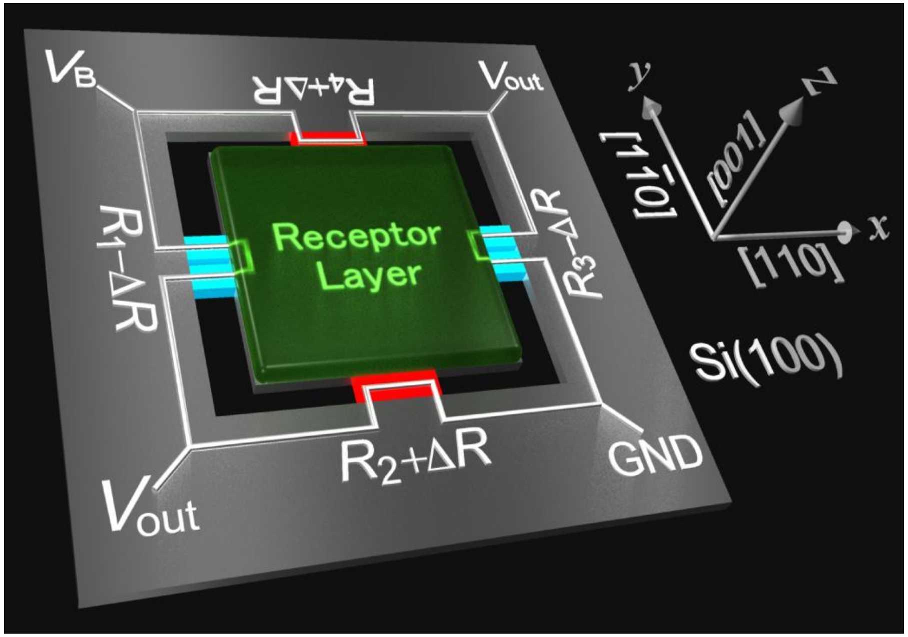
  - Large bandwidth
  - Low noise
  - Easy 50ohm matching
  - Low responsivity
  - Dissipative



Piezoresistive Detection (more next week)

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

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**