6. Micro- and nanomechanics – MEMS and NEMS

Repetition from last lecture

- How is the band structure of conductors different from insulators?
- What two types of (semi)conductivity do we know?
- What happens at the junction when we connect P and N type semiconductors?
- Name the electronic device utilising external photons impacting the area of the PN junction creating electron-hole pairs?
- What are the logic gates of current microprocessors made of?
- Name 3 problems we are facing while further miniaturising semiconductor structures in microelectronics?

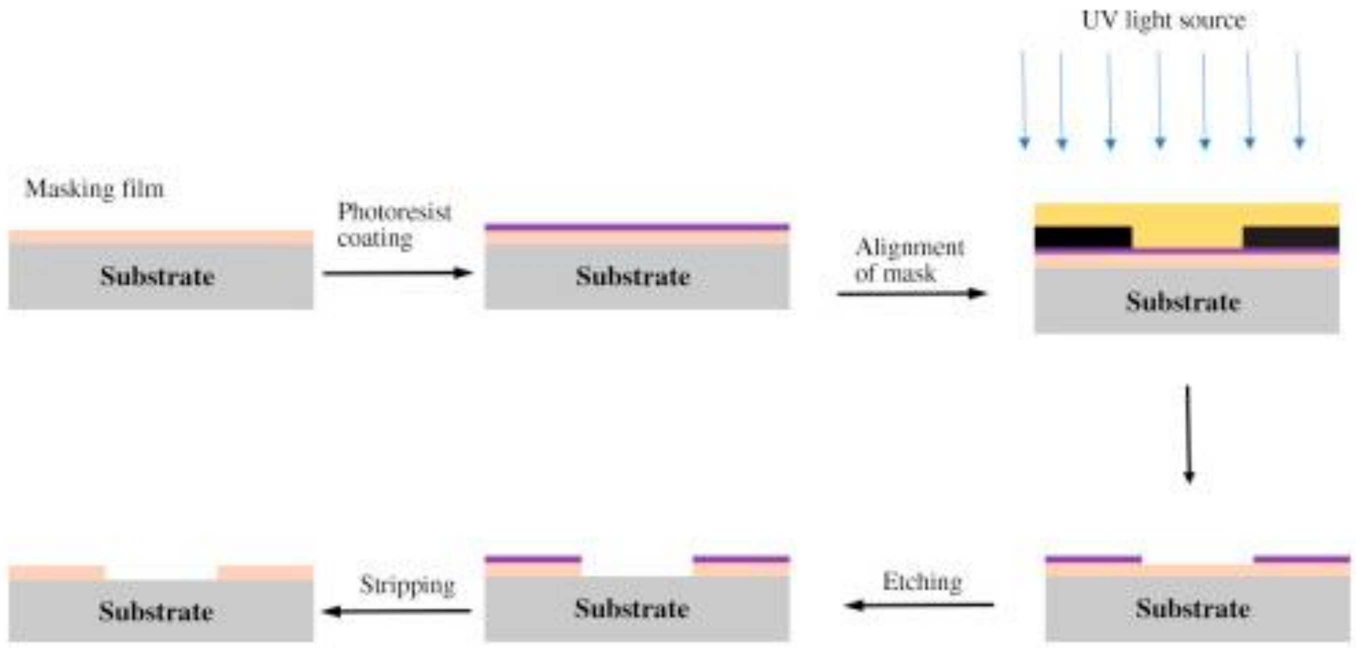
Introduction

- Using micro- and nanomachining, we are now able to prepare a range of miniature electronically controlled devices that take advantage of mechanical, electrical, magnetic, optical and biological phenomena
- Mechanical and chemical properties are primarily determined by the surface of the device and not by its volume, as in standard 'large' devices

- MEMS (Micro-electro-mechanical systems)
  - 100 nm – 1 mm
  - Electrical and optical switches, accelerometers, inkjet printheads,...
- NEMS (Nano-electro-mechanical systems)
  - < 100 nm
  - Spintronics, resonators, nanomechanical charge measurement,...

Photolithography

- 3 basic steps
  - Thin film deposition (vacuum evaporation, sputtering, spin coating, ...)
  - Patterning via mask (optical lithography, electron-beam lithography)
  - etching material and mask (wet chemical isotropic x anisotropic etching, plasma etching, reactive-ion etching)

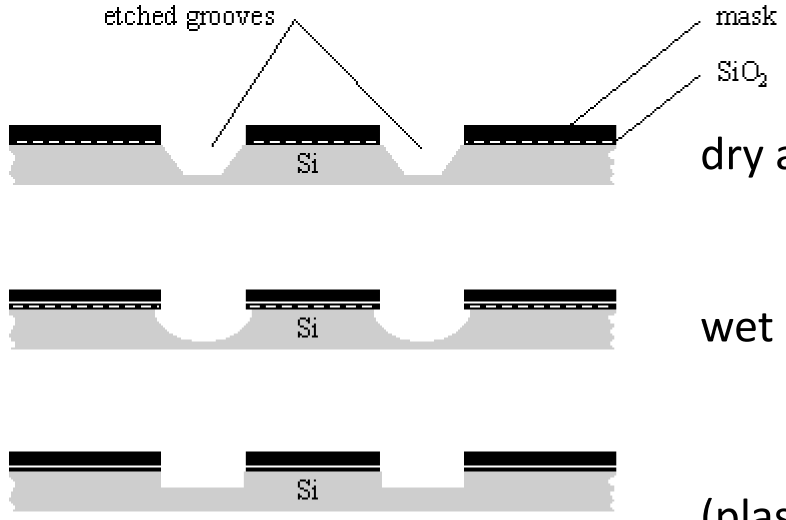


https://www.sciencedirect.com/book/9780128147764/self-cleaning-of-surfaces-and-water-droplet-mobility

MEMS Fabrication Methods – Volume Micromachining

- In lithography, the key step is etching the material under the mask
- Two main types - wet (chemical) and dry (plasma/ionic)
- Chemical
  - Isotropic – etching under the mask (underetching)
  - Anisotropic - different etch rates for different crystal planes
- Plasma
  - Possibility to prepare narrow and deep grooves without underetching (chip fabrication)

Etching



dry anisotropic

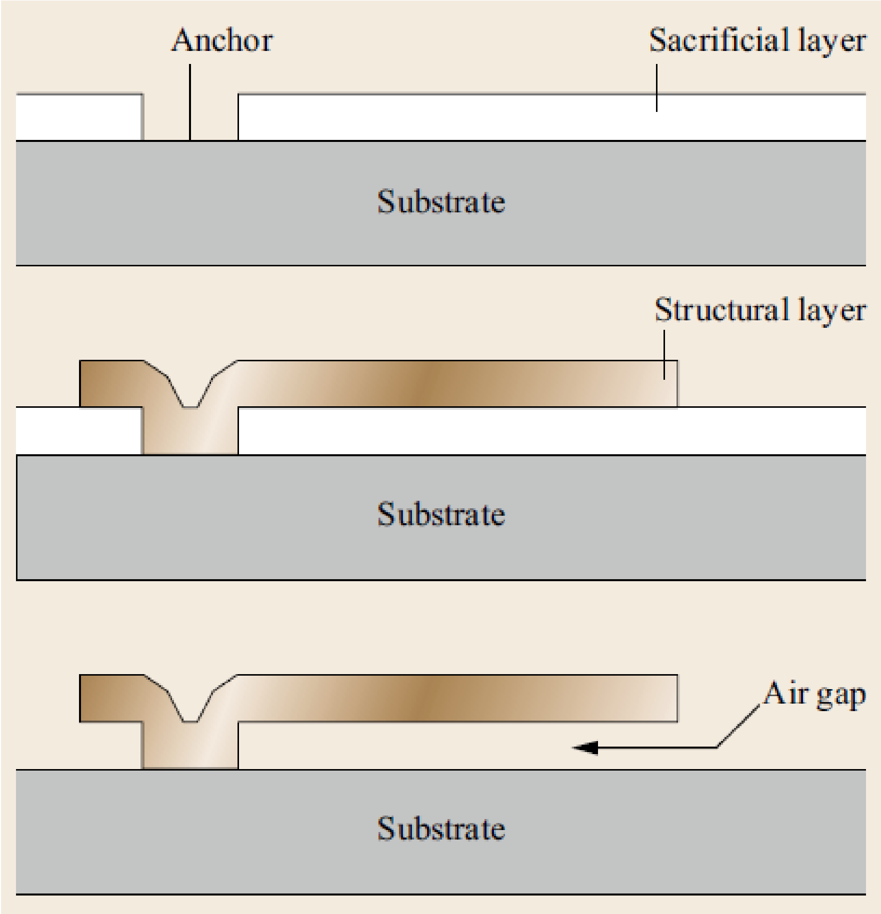
wet anisotropic

dry (plasma/ionic)

https://terpconnect.umd.edu/~sandborn/research/JPL_MEMS/microeng_bulk.html

MEMS Fabrication Methods – Surface Micromachining

- The structures are made from thin films deposited on the surface of the substrate
- 3D structures (e.g. hinges) can also be prepared by surface micromachining
- For microstructures with a very large aspect ratio, molds are often used for their fabrication (HEXSIL, HARPSS, LIGA)



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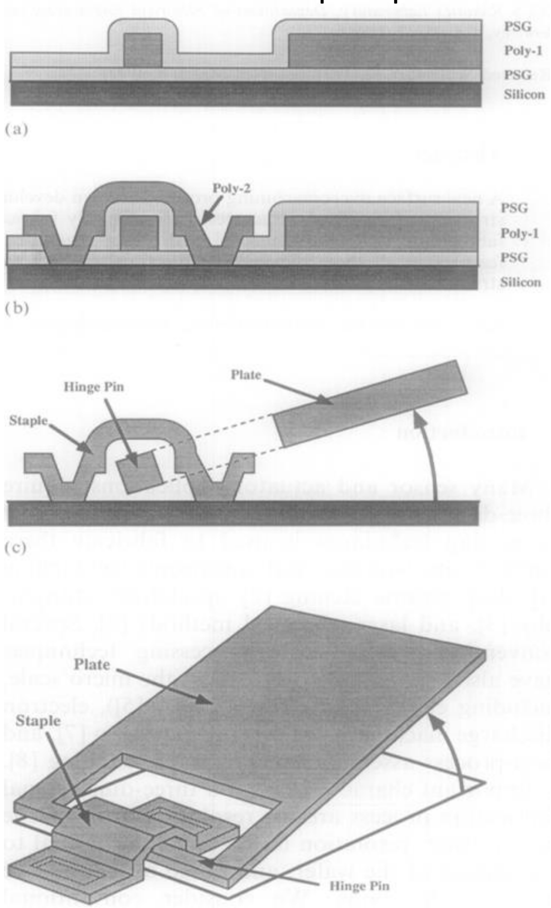
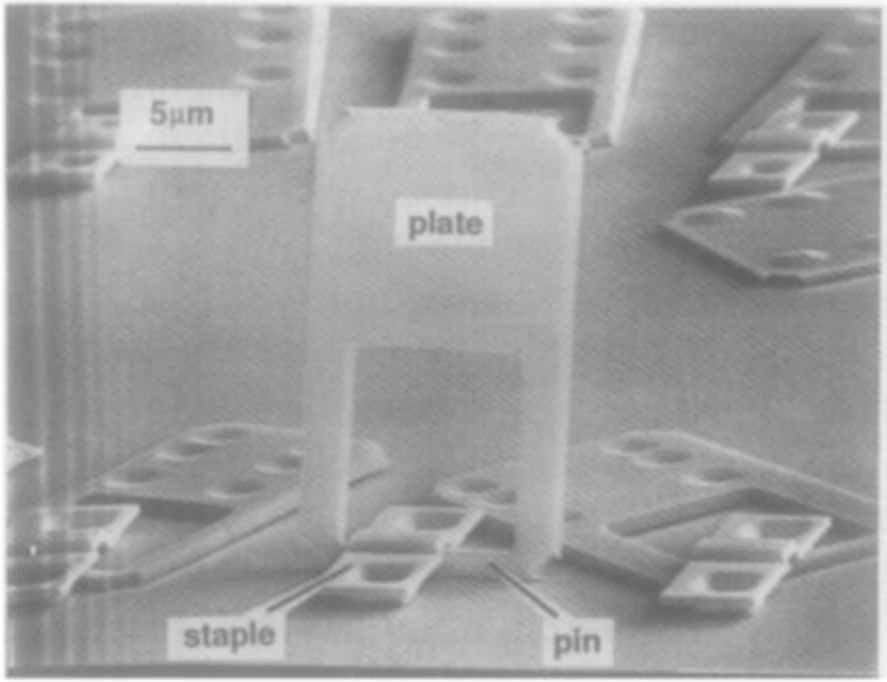
Fabrication of Hinges by Surface Micromachining

phospho silicate glass





https://lwlin.me.berkeley.edu/me119/papers/paper4.pdf

NEMS Fabrication Methods – E-Beam and Nano-Imprint Fabrication

- Electrons have a short wavelength and are therefore suitable for "drawing" or etching nanometre structures
- Nanoprinting is an extension of electron beam for mass production of structures
  - Using an electron beam and plasma etching, a stamp is made from a hard material and this is then imprinted onto a layer of resin. This is followed by deposition or etching as required

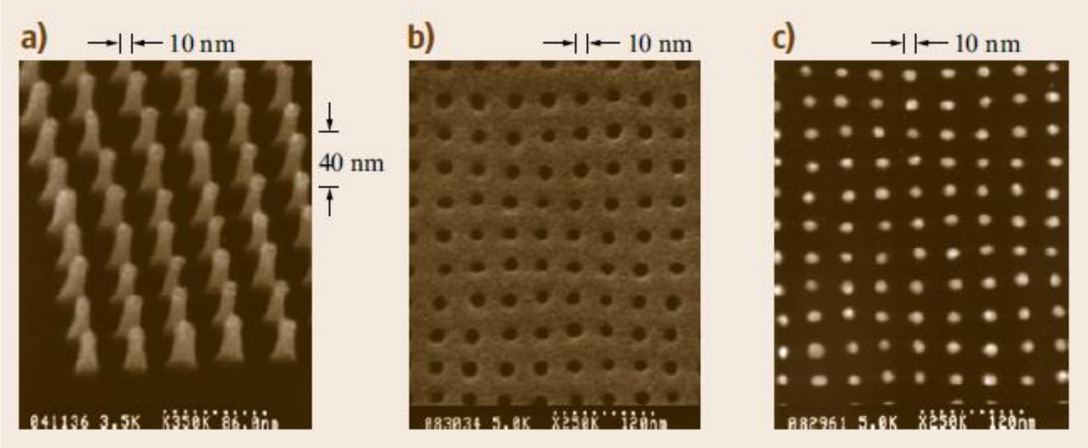


Fig. 5.2a–c Micrographs showing the basic steps of NIL, demonstrated by *Chou* and *Krauss* [5.4]. **(a)** NIL stamp in silicon with a 40 nm-period array of pillars with 40 nm height, **(b)** imprinted 10 nm-diameter holes in a thin polymer film (PMMA), **(c)** 10 nm metal dots after pattern transfer (lift-off), using the thin polymer layer as a mask

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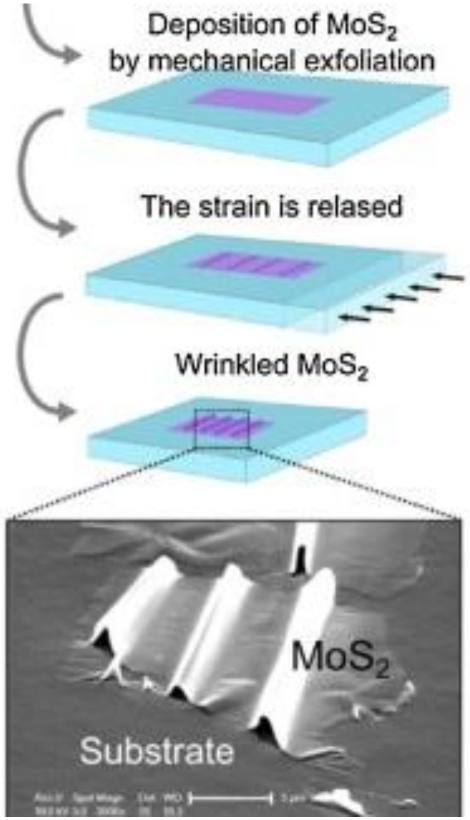
NEMS Fabrication Methods – Epitaxy and Strain Engineering

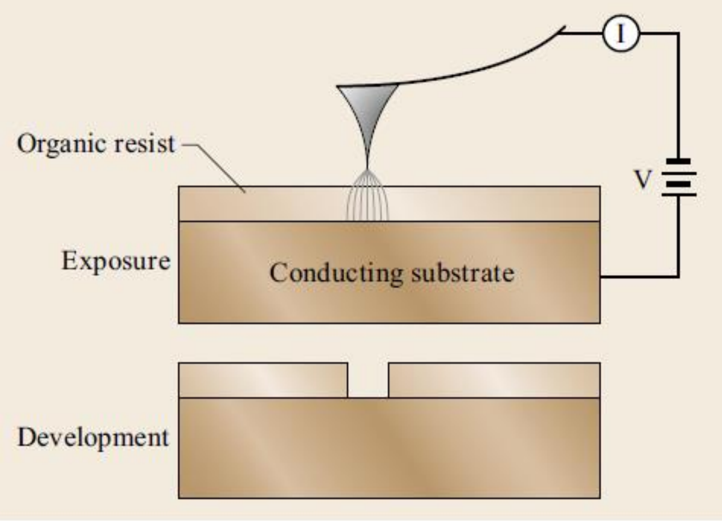
- Epitaxy – growth of a crystalline layer on the substrate, the crystalline structure of the layer is directly related to the crystalline structure of the substrate
- Molecular-beam epitaxy – deposition of atoms in ultrahigh vacuum
- Stress control – uses controlled release of elastic stress, 2D epitaxial layer cracks to form a 3D structure

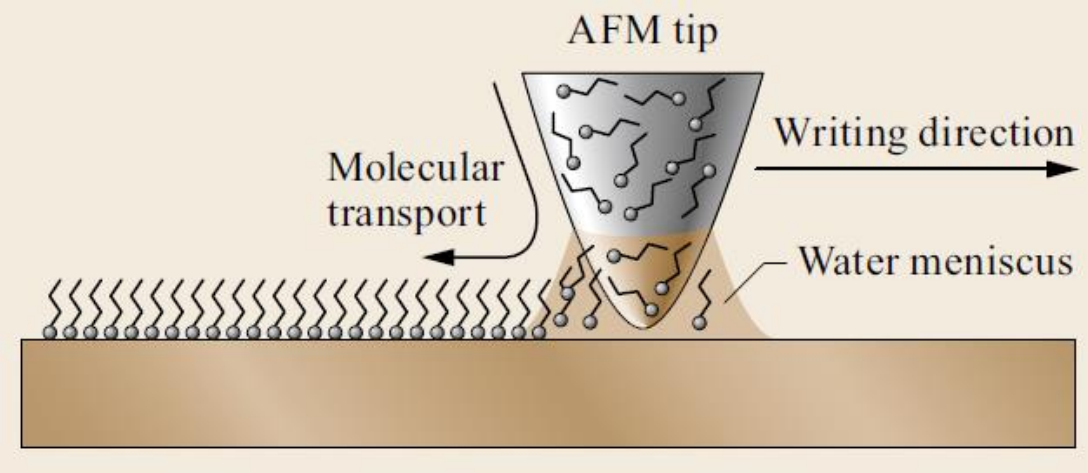


https://www.sciencedirect.com/science/article/abs/pii/S1748013217306345

NEMS Fabrication Methods – Scanning Probes

- SPM induced oxidation – voltage at the tip anodizes the conductive metal in its surroundings. The oxide can be etched
- SPM lithography – electrons emitted from the tip can expose the resist like in the e-beam lithography. No vacuum is required
- Dip-pen lithography – transport of molecules from tip to substrate. The rate of molecule transport (writing) and the resolution of the writing depend on the size of the aqueous meniscus around the tip that in turn depends on the relative humidity
- Scratching the surface with the tip – the method removes material





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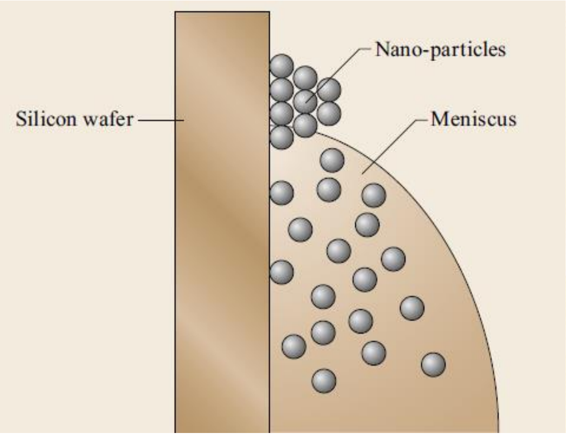
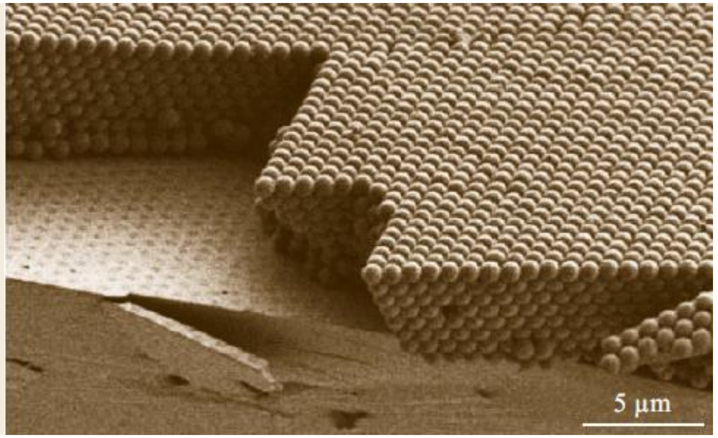
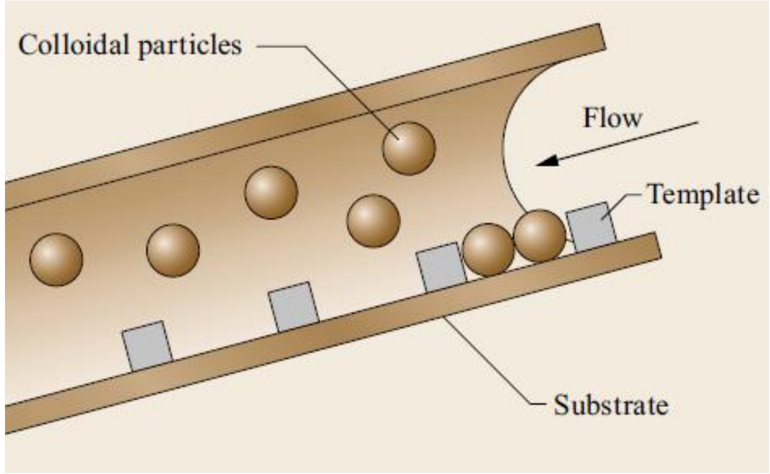
NEMS Fabrication Methods – Self-Assembly, Template Manufacturing

- Utilizing the principle of spontaneous physical ordering (reaching the minimum energy of the system) or chemical aggregation of the system
- Physical ordering – evaporation of a solution in a vertical position leads to the ordering of colloidal particles. Production of photonic crystals. It is also possible to use a structured surface – template-assisted self-assembly
- Matrix methods – chemically self-assembled molecules are deposited in a suitable porous form. For mass production.







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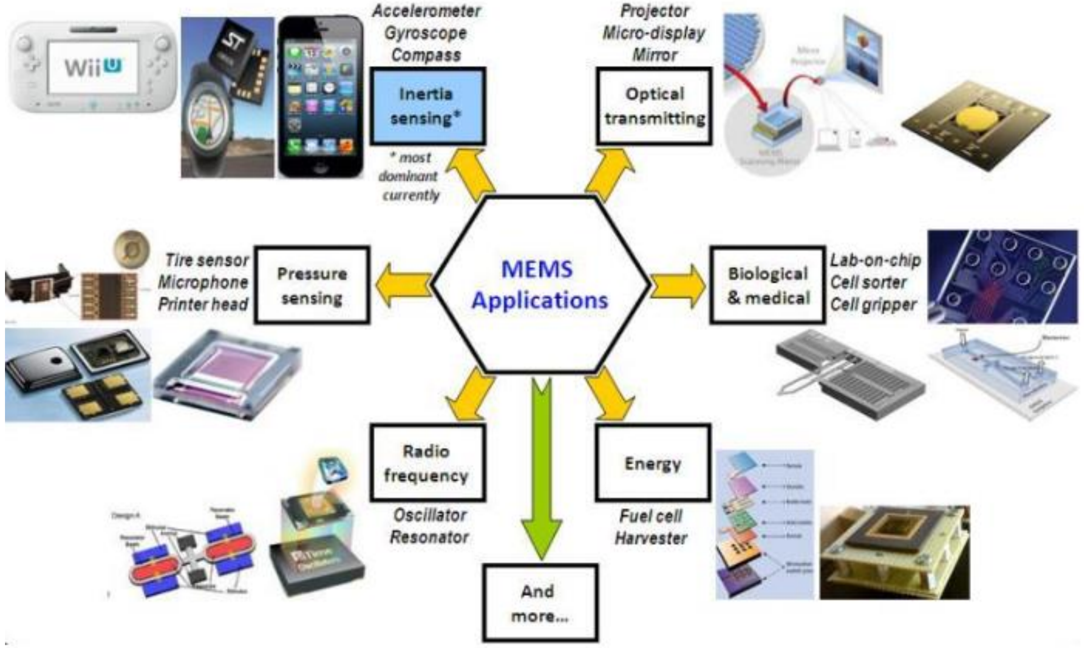
MEMS Applications

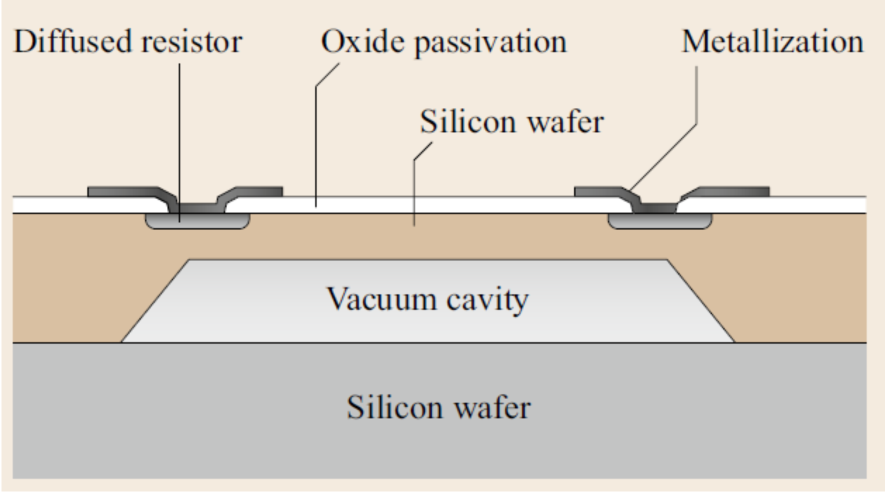
- Computer technology
- Microcircuits
- Robots
- Microprobes
- Microoptics
- Microfluidics
- Biomedicine
- ...



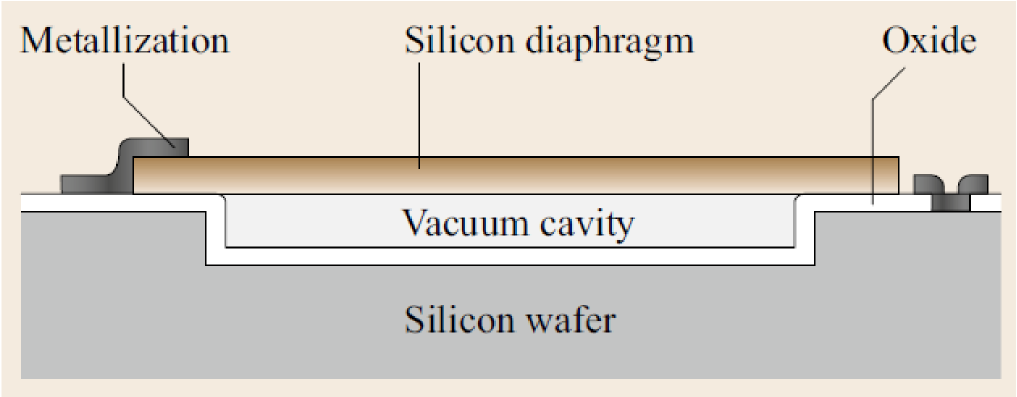
https://www.researchgate.net/publication/261432148_Adaptable_and_integrated_packaging_platform_for_MEMS-based_combo_sensors_utilizing_innovative_wafer-level_packaging_technologies

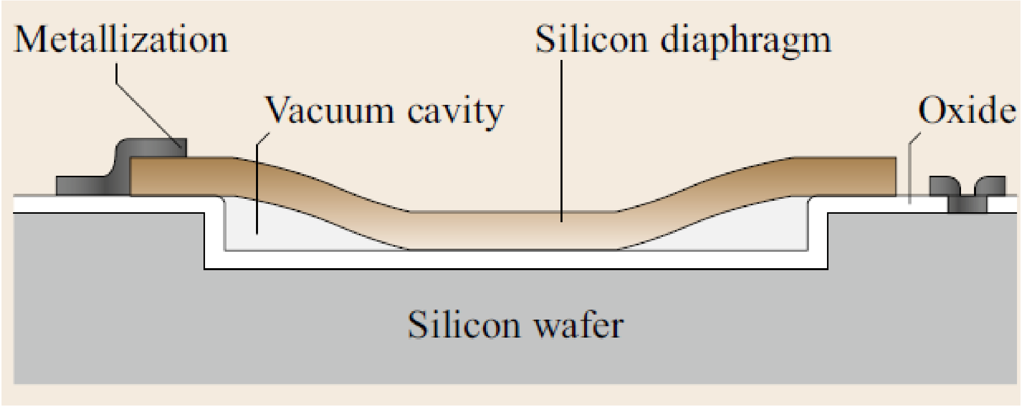
MEMS Devices – Pressure Sensor

- Piezoresistive



- Capacitive





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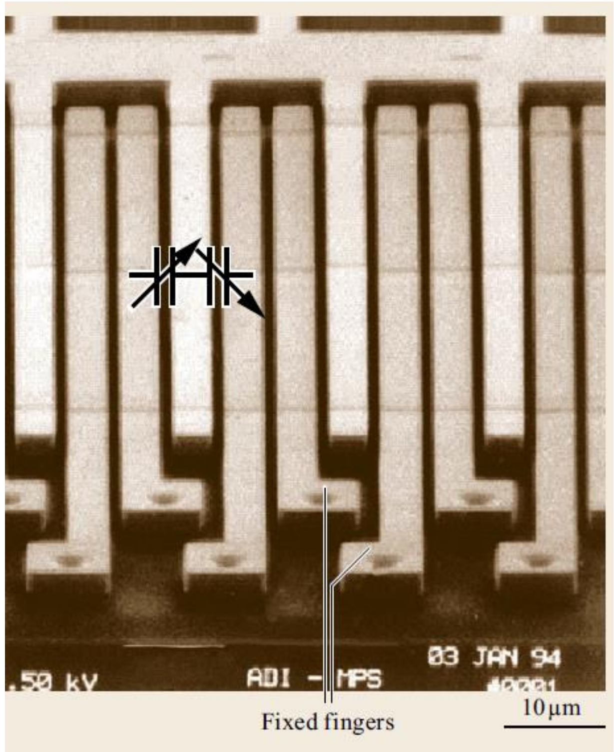
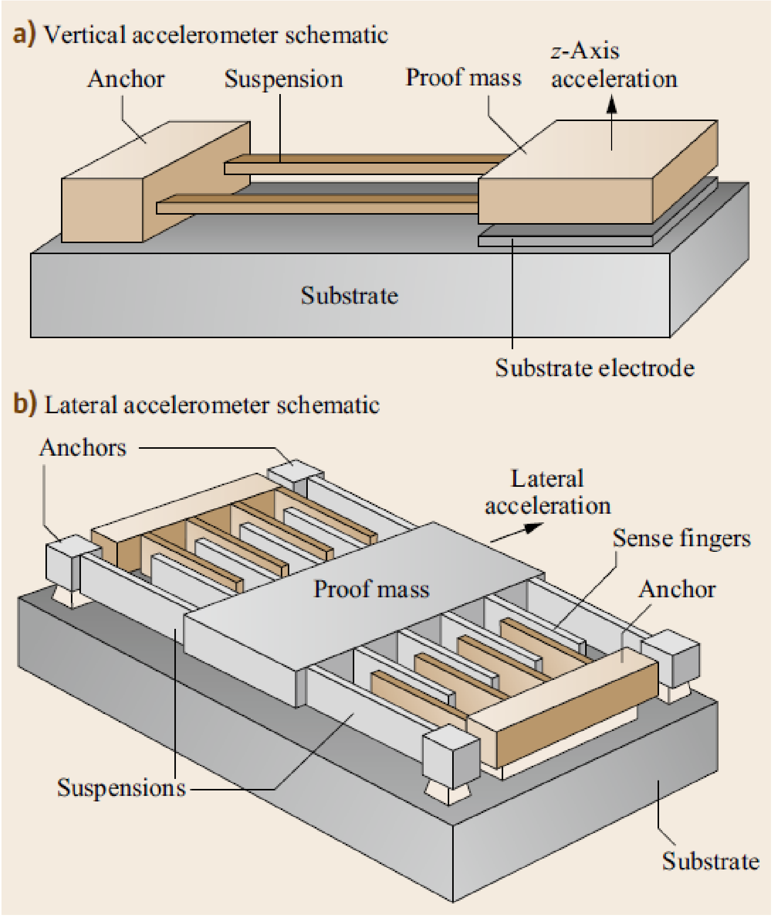
MEMS Devices – Accelerometer

- Airbags, vibration sensors, tilt angle...





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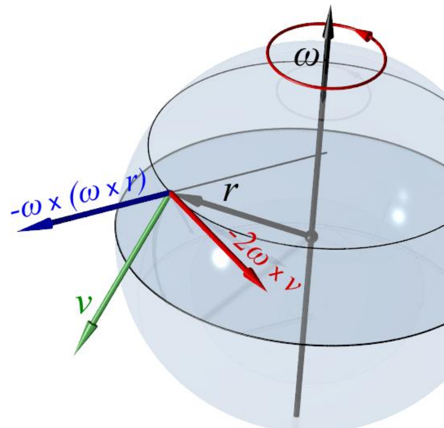
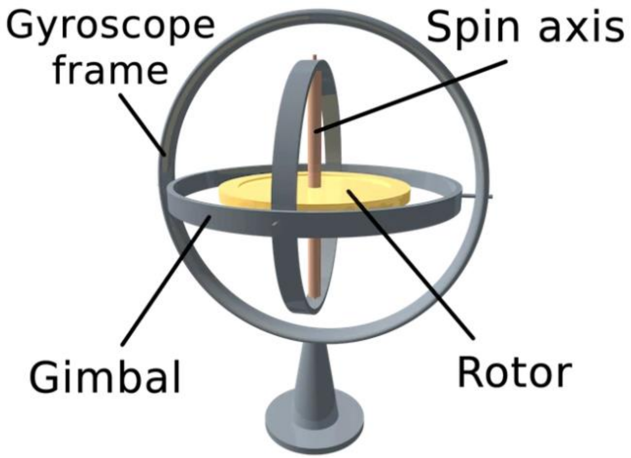
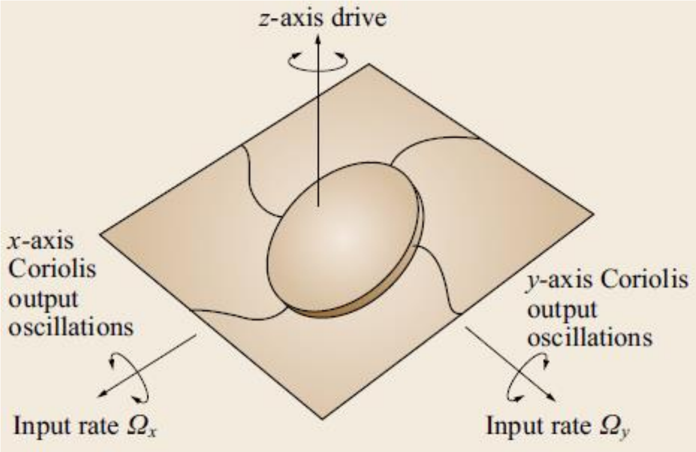
MEMS Devices – Gyroscope

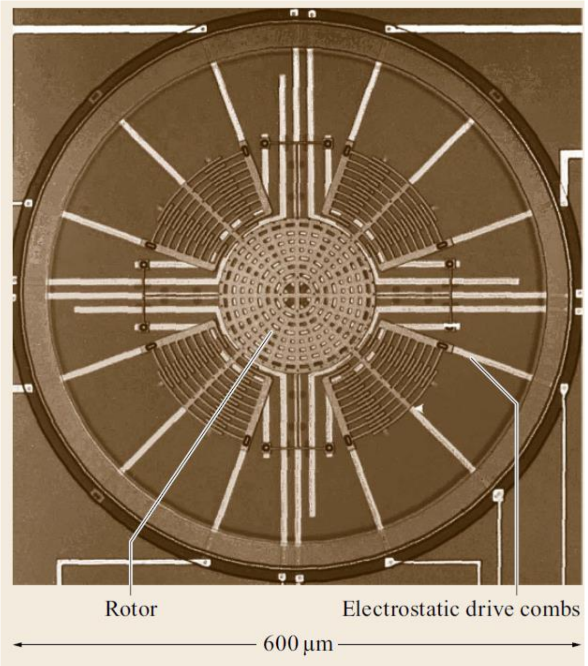


- Flywheel that maintains the position of its axis of rotation in inertial space



- Instead of a flywheel, MEMS gyroscope uses the effect of the Coriolis force on the direction of vibration when the gyroscope changes position – measures angular acceleration





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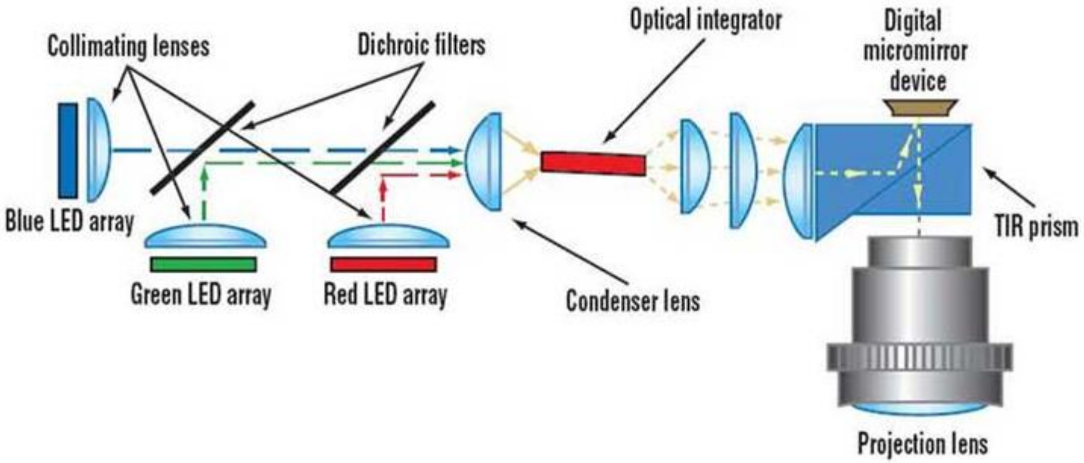
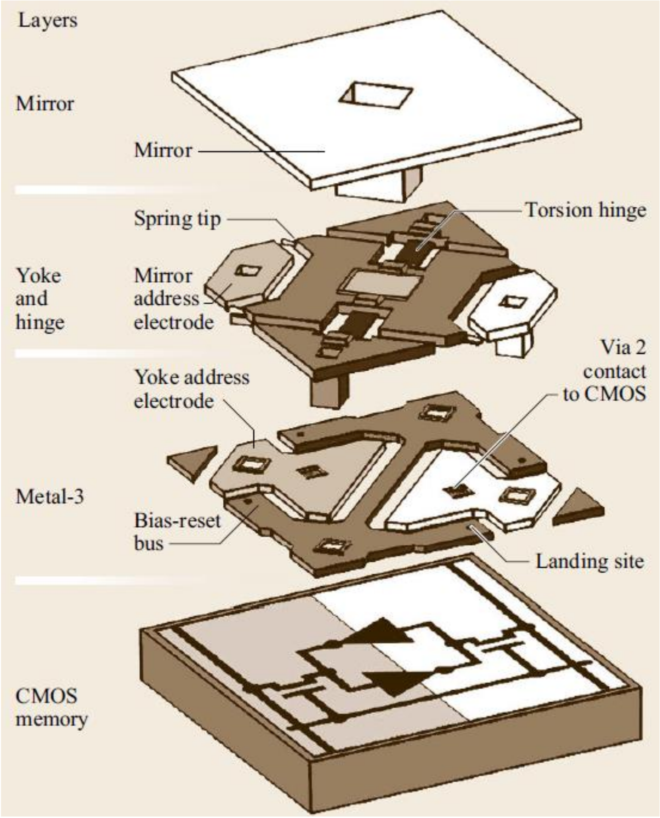
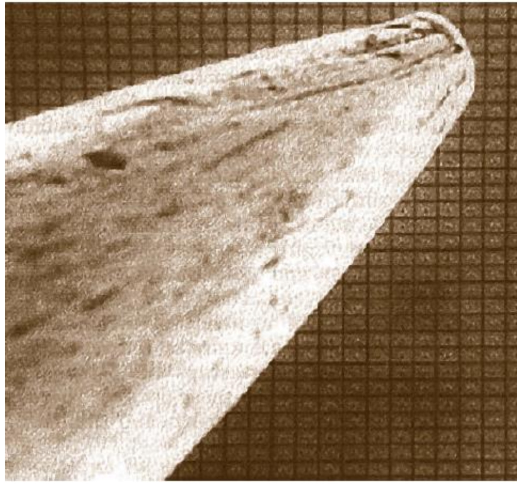
https://www.letemsvetemapplem.eu/2014/01/23/jak-funguje-digitalni-gyroskop-princip-toho-proc-iphone-dokaze-urcit-v-jake-je-poloze/
https://steemit.com/steemstem/@aximot/how-does-the-coriolis-force-determine-the-spin-of-a-cyclone

MEMS Devices – Digital Micromirror Device

- Millions of 14 x 14 μm mirrors. The basic component of a DLP projector.



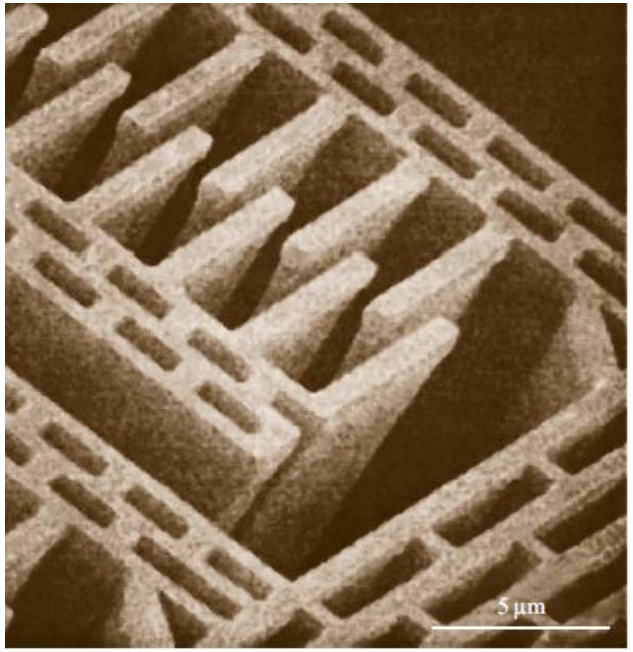




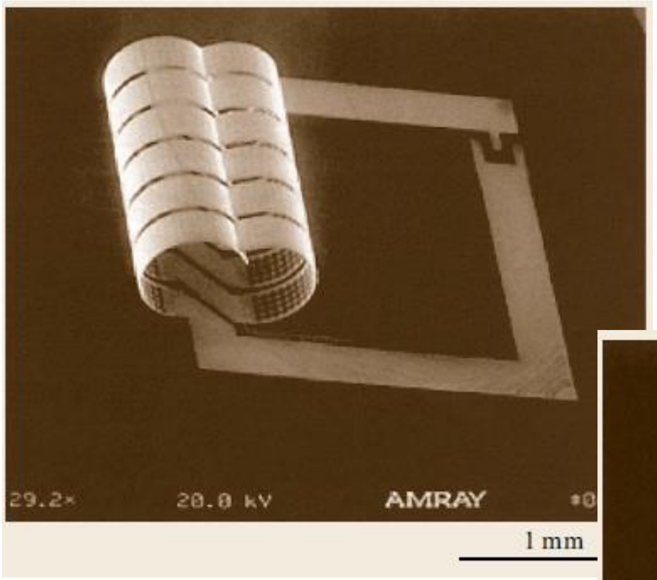
B. Bhushan (Ed.), Springer Handbook of Nanotechnology, 2017
https://www.projectorreviews.com/terms/dlp/

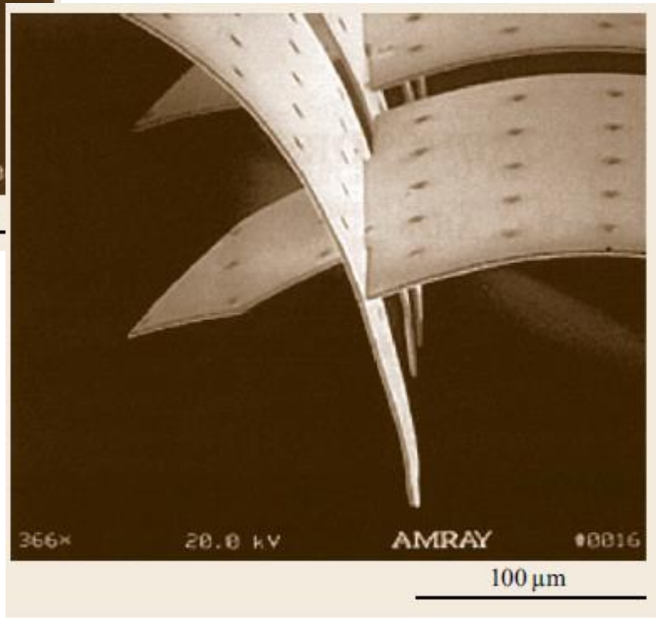
MEMS Devices – Electrical Components

- Variable capacitor



- Coil





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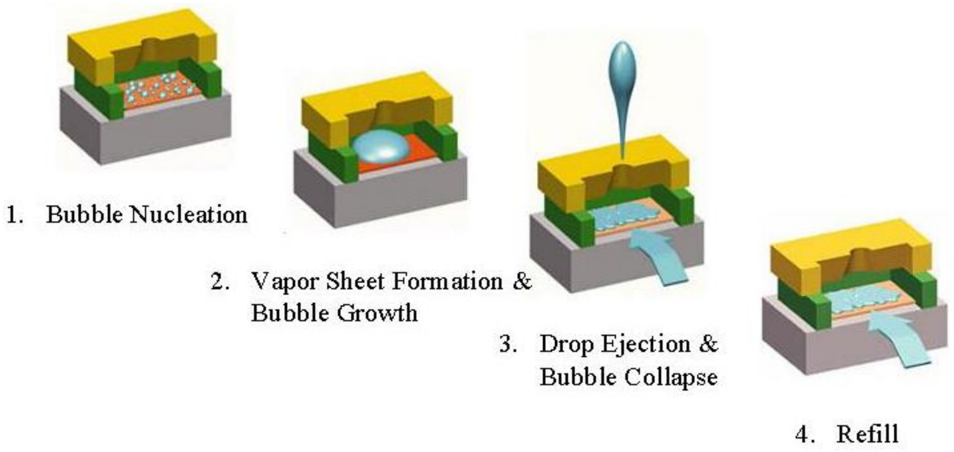
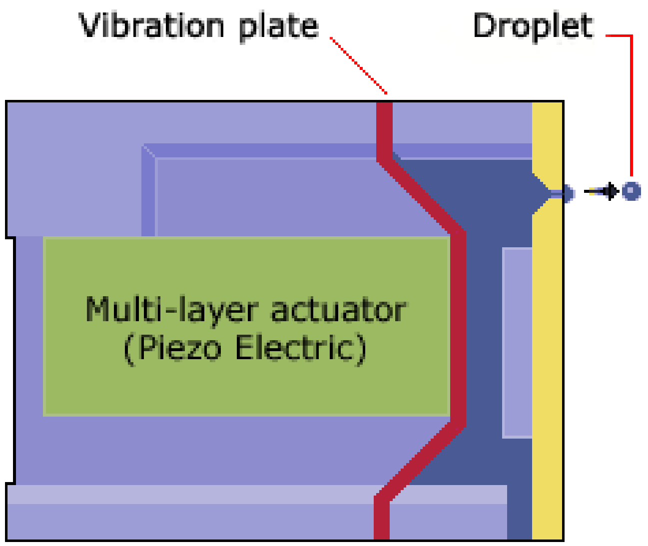
MEMS Devices – Printhead

- Thermal printing



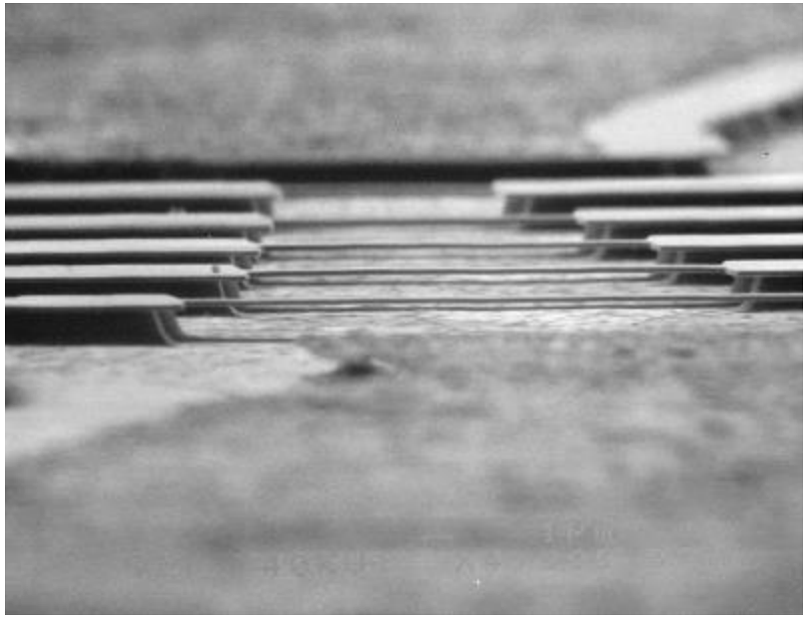
- Piezo printing

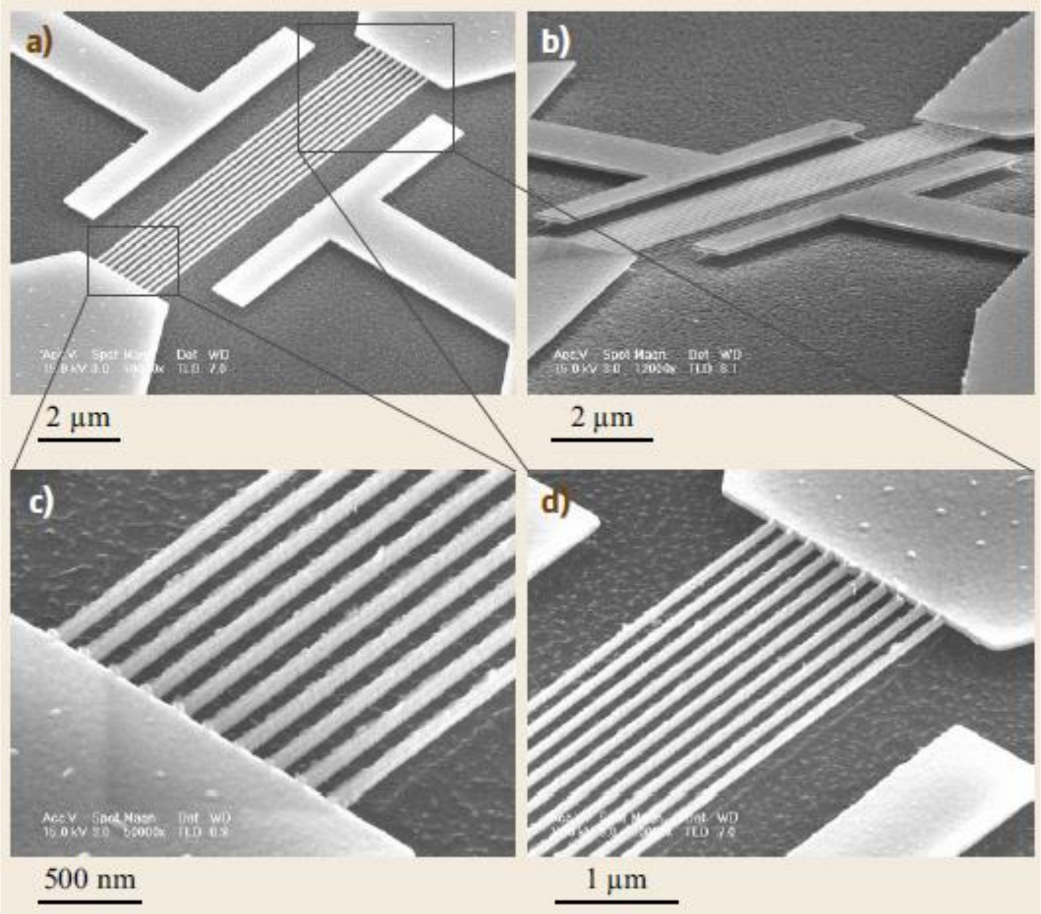


https://www.eetimes.com/little-squirts-make-big-impact-in-printing/7
http://www2.mie.utoronto.ca/labs/MUSSL/gallery1.htm

NEMS – Resonators

- RF signal transmission and conditioning
- Sensors - change in frequency of oscillation (measurement of the molecule mass)





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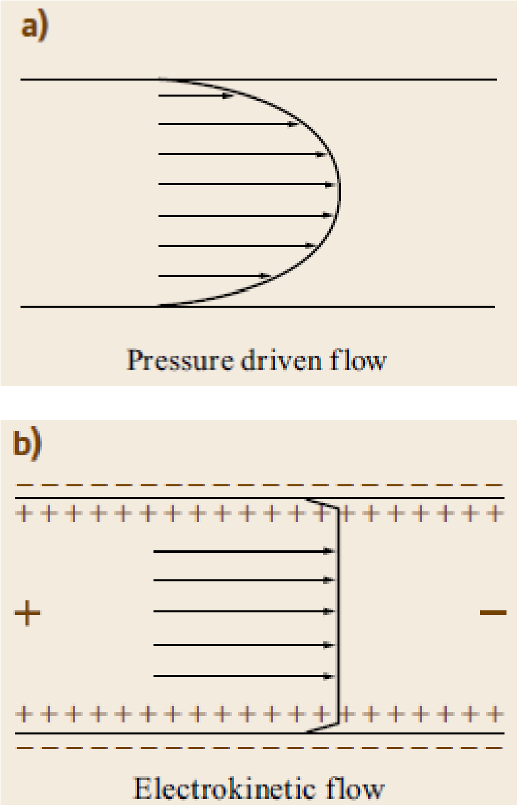
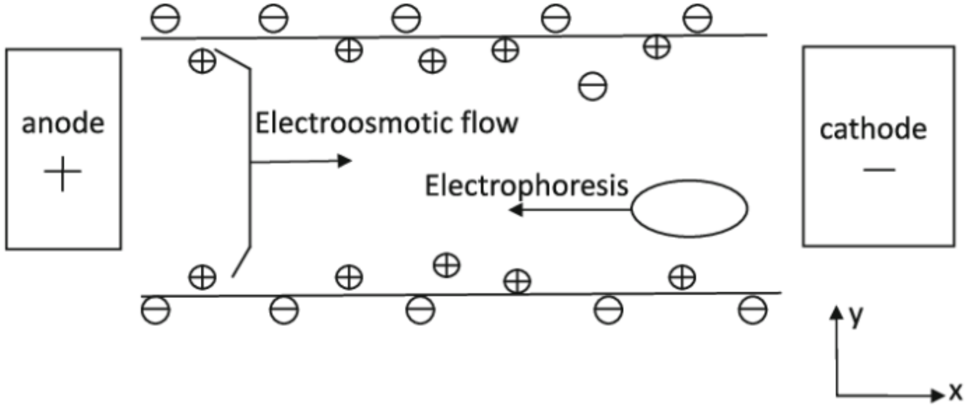
Microfluidics

- Handling small volumes of liquids (< 1 μl) in small geometric dimensions
- Analysis of biological and chemical samples, synthesis and dosing of drugs, mixing, flow direction control,...
- 3 basic pumping methods:
  - Pressure
  - Electroosmotic – an electric field drives ions in the wall bilayer, causing the entire volume of liquid to move
  - Electrophoretic – ions with opposite polarity move in the opposite direction





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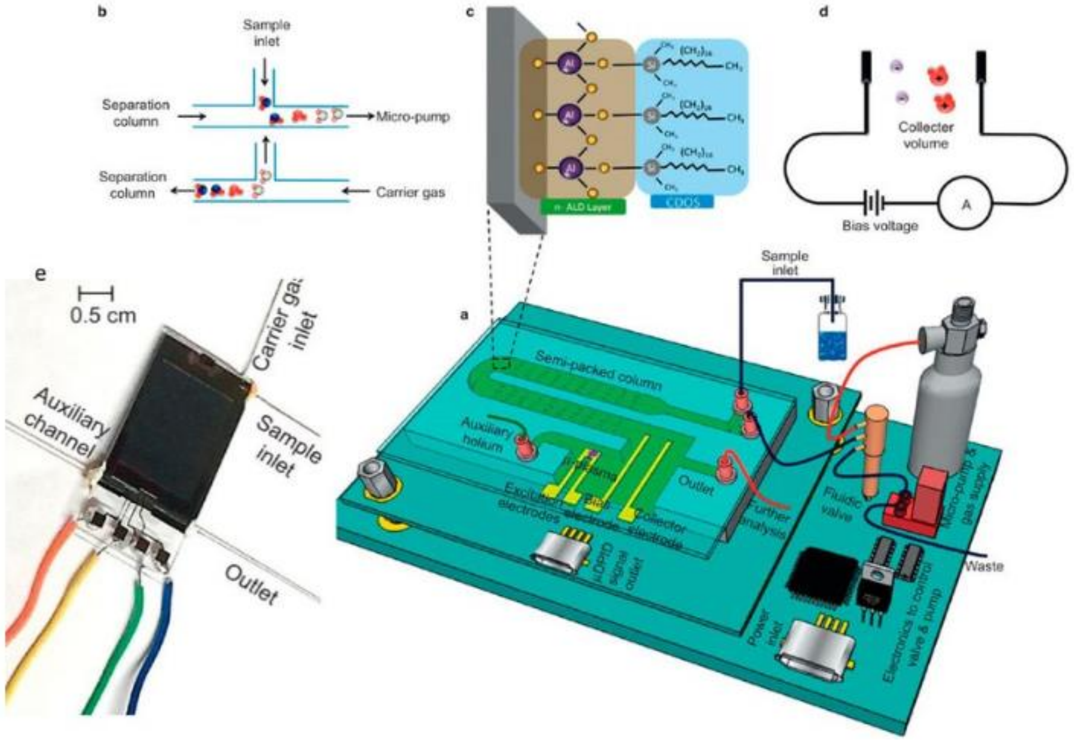
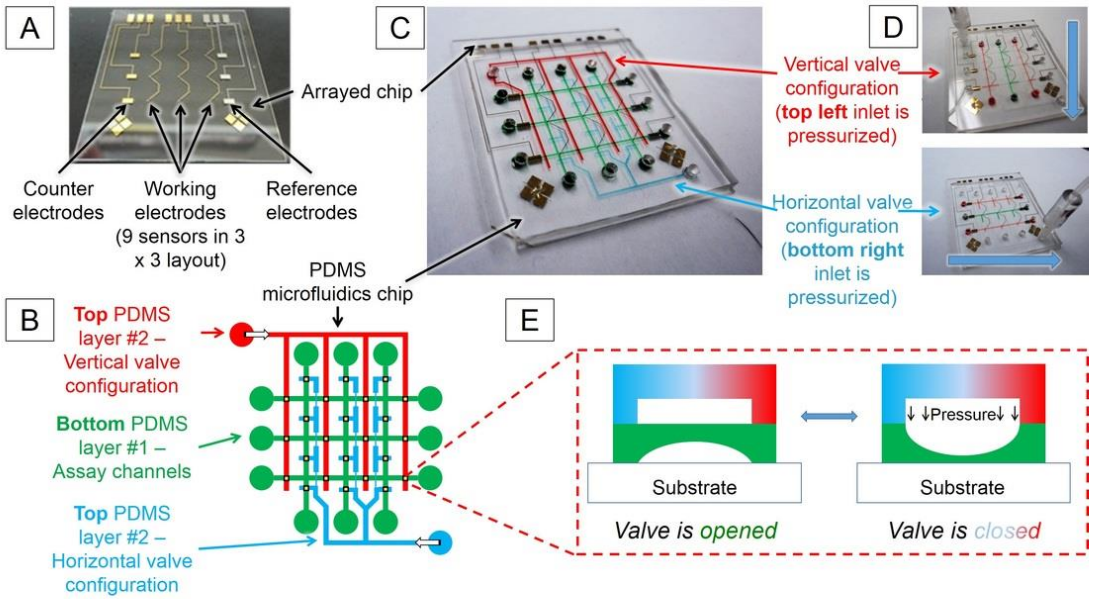
https://www.researchgate.net/publication/230839624_Dissipative_particle_dynamics_simulation_of_field-dependent_DNA_mobility_in_nanoslits

Lab-on-a-Chip





https://www.benyoav.com/bio-mems.html
https://www.researchgate.net/figure/Block-diagram-of-the-chip-scale-GC-platform-developed-by-VT-MEMS-Lab-a-setup_fig11_328518747

Conclusion

- Basic micro- and nanomachining methods
- Principles of operation of some MEMS and NEMS components
- MEMS in everyday electronics, NEMS still in development