Institute for Electron Microscopy and Nanoanalysis
Graz Centre for Electron Microscopy

Micromechanics

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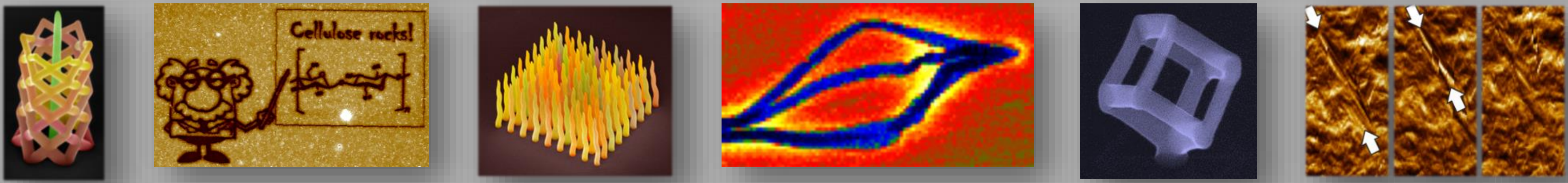
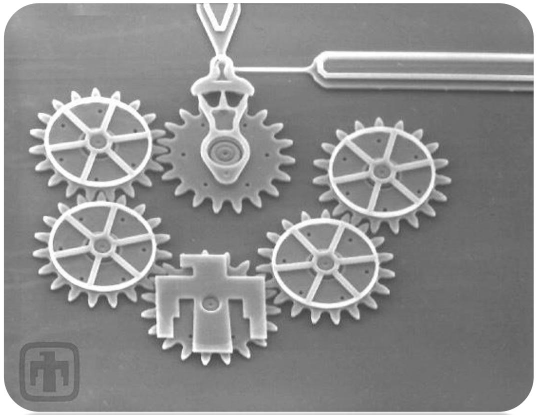
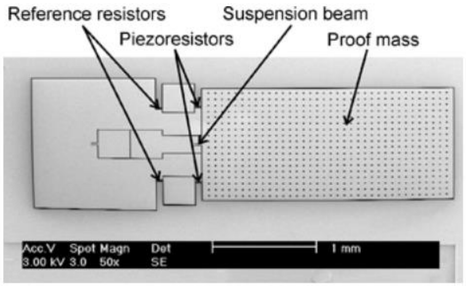


16 May 2017

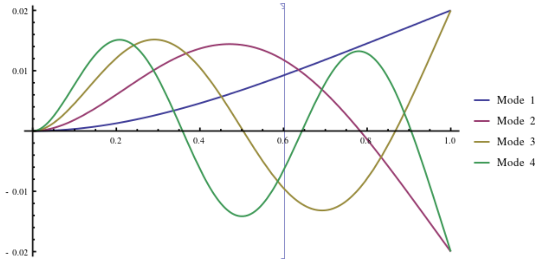
Outline

- In this part so called Micro Electro Mechanical Systems (**MEMS**) are in the main focus
- We start with the definition what MEMS actually are
- Then we briefly discuss the main fabrication routes
- We then discuss a series of different MEMS applications by means of their operation principle
- Finally, we have a look on micromechanics itself to see possibilities and limitations

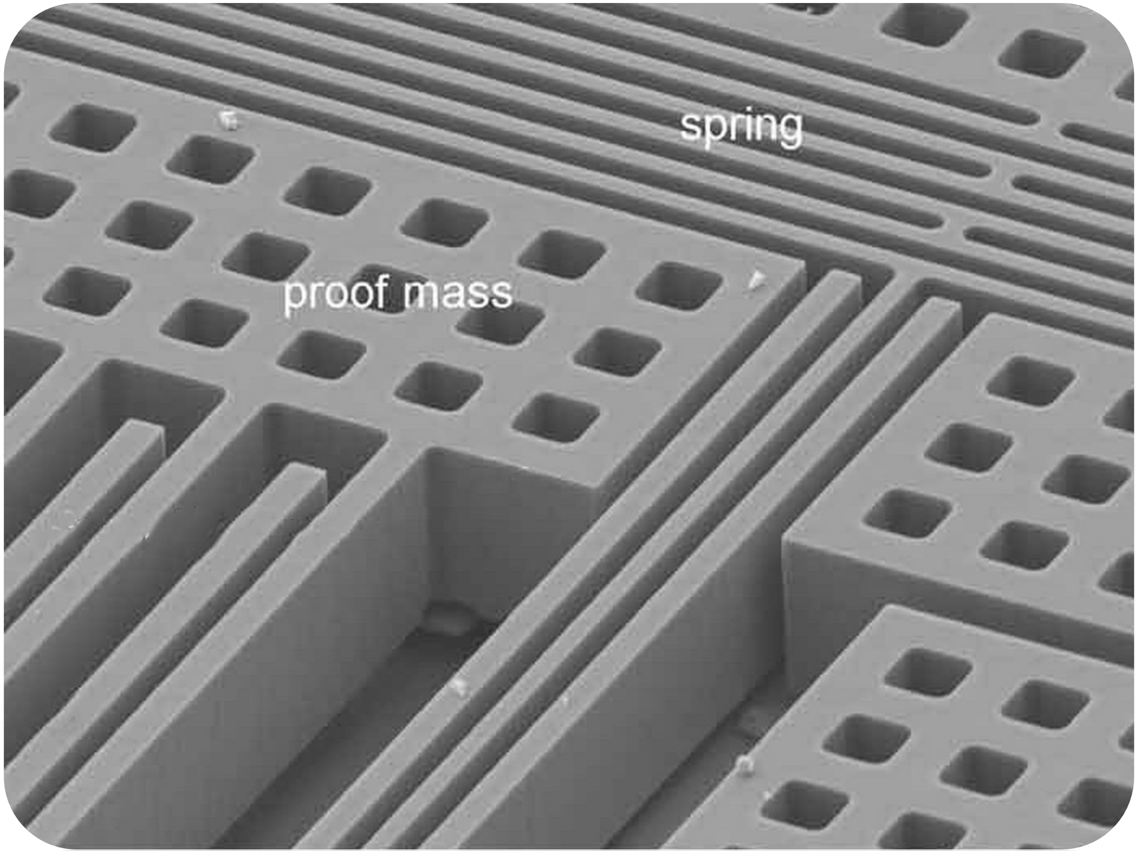




Scanning electron micrograph of an SOI-based piezoresistive accelerometer, fabricated in a single fabrication step.



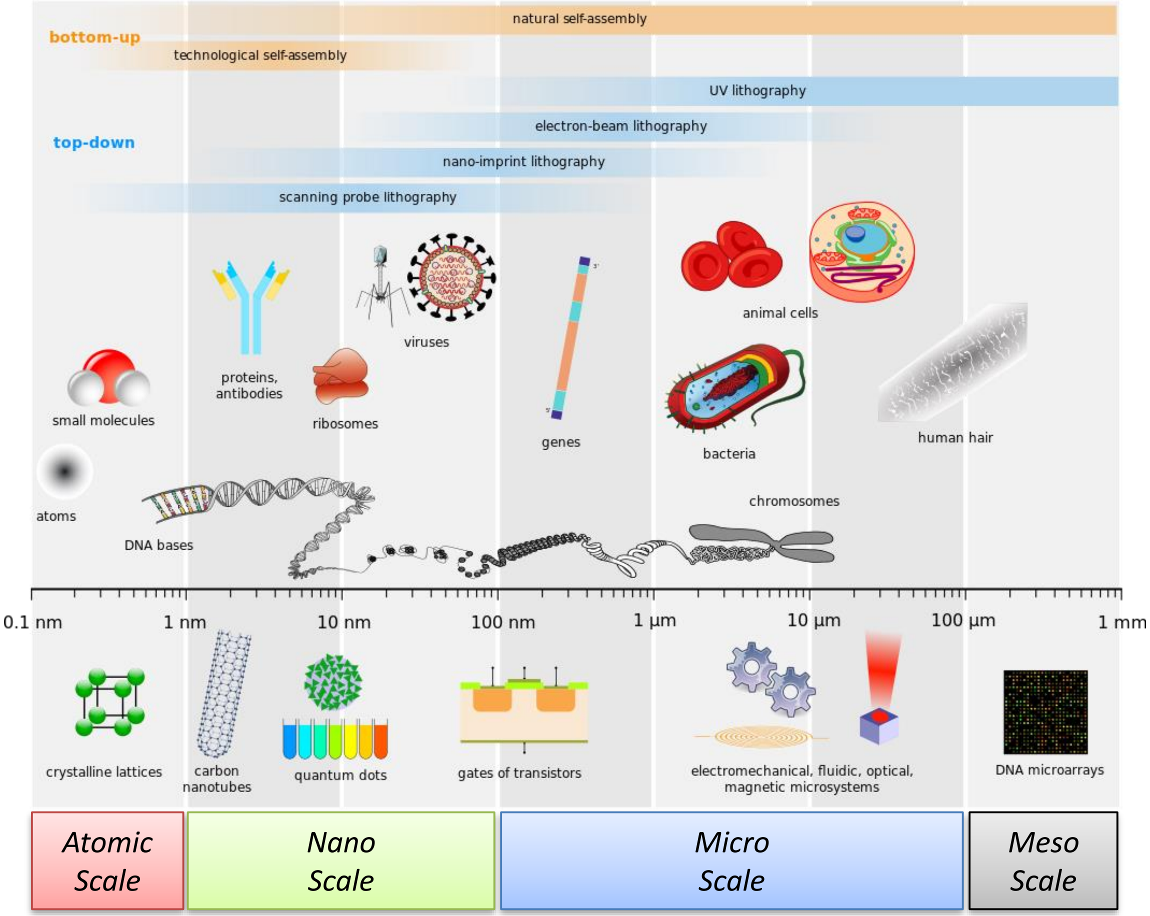
WHAT IS A MEMS?



MEMS Definition

- Although the definition slightly varies, a system is called **M**icro-**E**lectro-**M**echanical-**S**ystem if

  1. the relevant part have at least one dimension *D* in the range → 100 µm ≤ D ≤ 0.1 µm

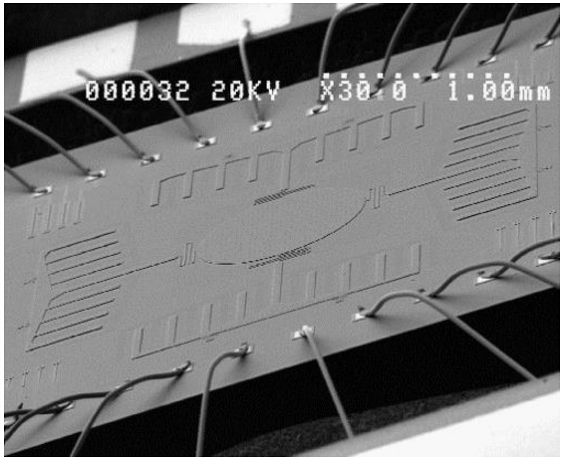


MEMS Definition

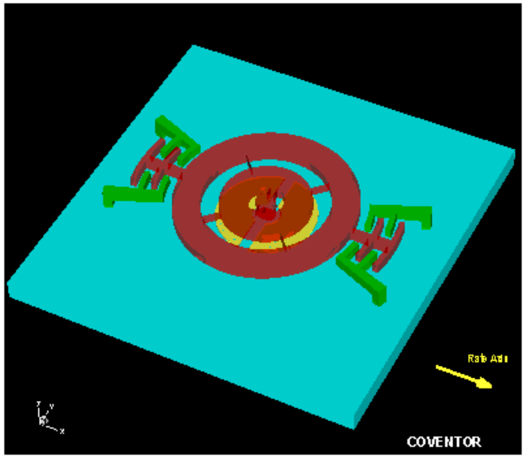
- Although the definition varies a little, a system is called **M**icro-**E**lectro-**M**echanical-**S**ystem if

  1. the relevant part have at least one dimension *D* in the range → 1000 µm ≤ D ≤ 0.1 µm
  2. they contains actuators → something IS moved by an electrical signal

piezoelectric movement



electrostatically driven movement



2013 Edition

MEMS Definition

ITRS International Technology Roadmap for Semiconductors

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  1. the relevant part have at least one dimension *D* in the range → 1000 µm ≤ D ≤ 0.1 µm
  2. they contains actuators → something IS moved by an electrical signal
  3. they contains mechanical sensors → something MOVES which is then detected electrically

Mechanical

Thermal

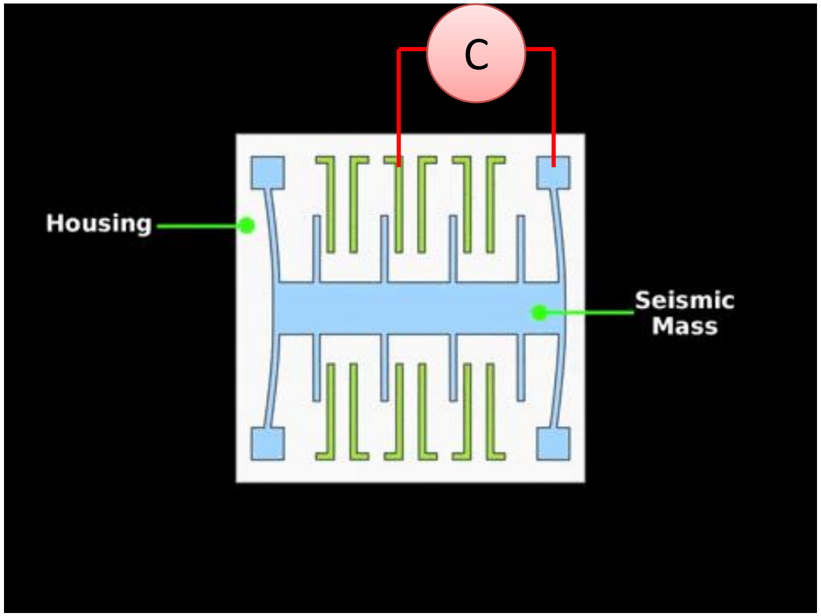
Chemical

Magnetic

Optical

Electrical

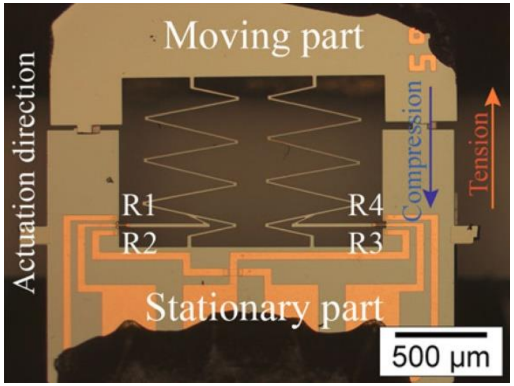
sensors



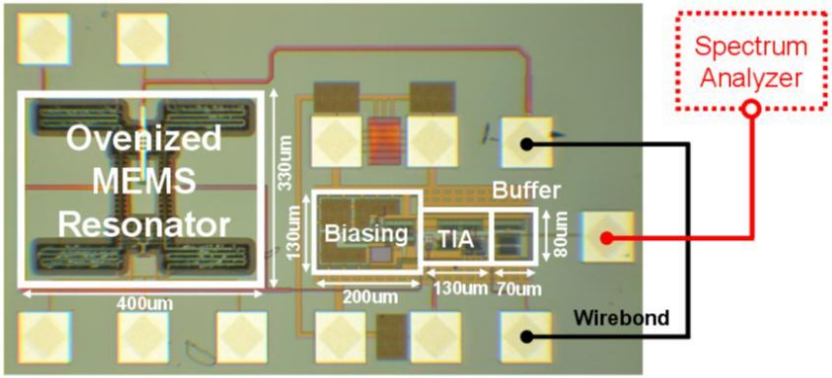
MEMS Definition

- Typically, a MEMS device can not operate on its own but is mostly packaged together with an integrated circuit (**IC**)
- The IC provides an electronic interface to the sensor or actuator, signal processing / compensation, and analog and or digital output
- The MEMS can be integrated in two different ways
  1. Monolithic integration → full integration in the relevant IC chip
  2. Co-integrated → MEMS system is on a separate chip and packaged together with the IC

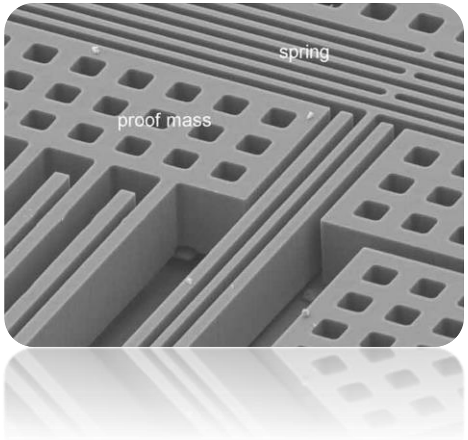
sensor and relevant electronics are fully integrated



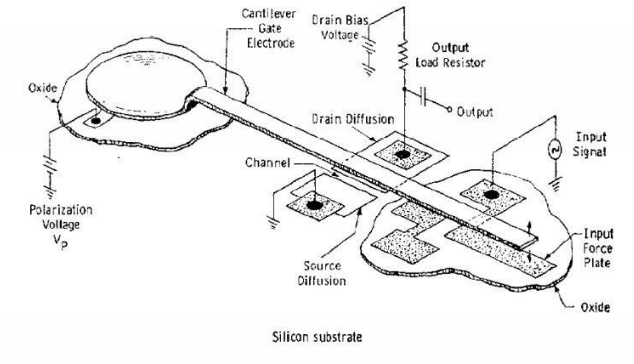
sensor and relevant electronics are separated



NICE … BUT IS THAT RELEVANT?

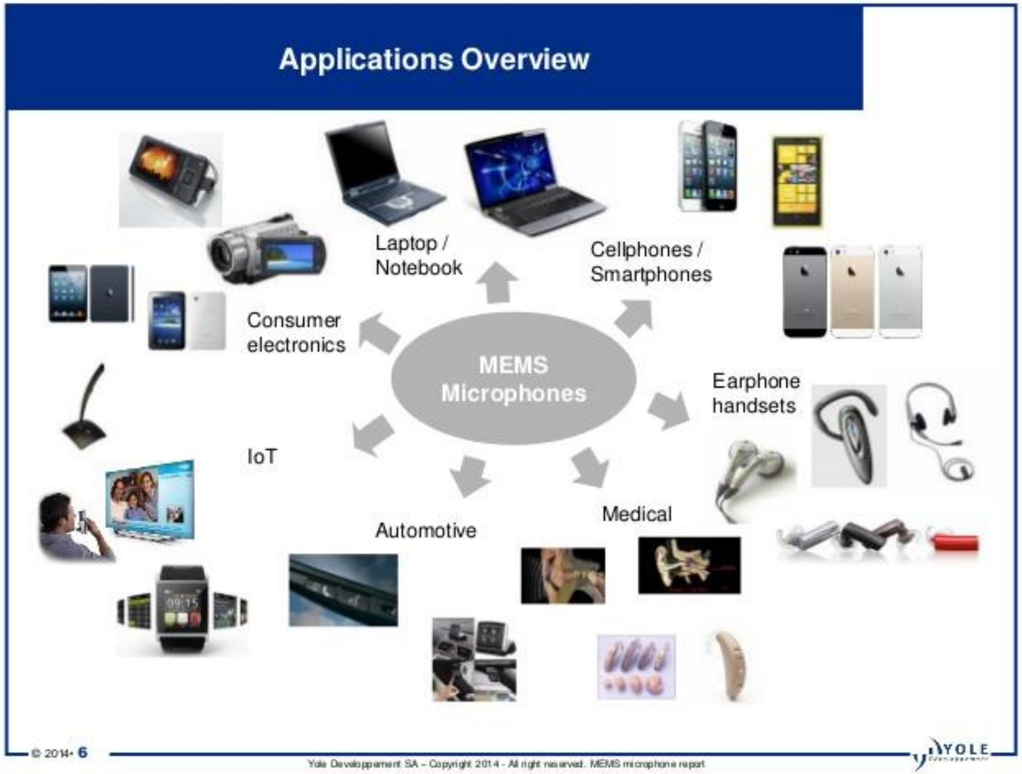


Relevance

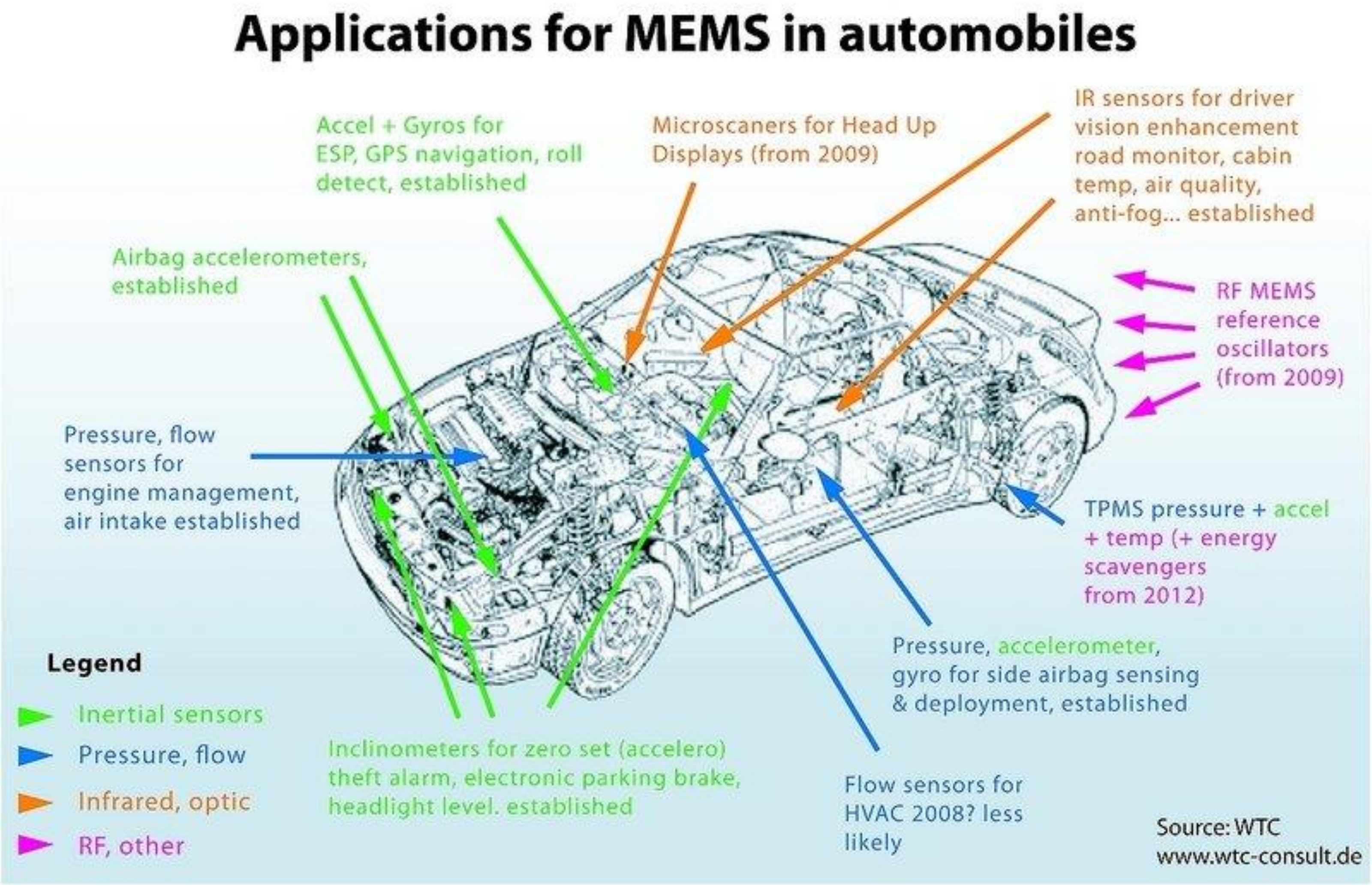


- This area is very matured as it started about 55 years ago
  - 1961 → first silicon pressure sensor (Kurz et-al)
  - 1967 → resonant gate transistor (Nathanson, et-al)

- Beside the highly important application as nano-probe for Atomic Force Microscopy (AFM), MEMS can be found in many commercial everyday products:
  - pressure sensors
  - gas sensors
  - microphones
  - accelerometers
  - gyroscopes
  - digital light projectors
  - ink jet printer cartridges
  - micro-motor systems
  - communication devices
  - ... and many more …


Applications Overview

An Intensive Example - Automotive



Applications for MEMS in automobiles

Accel + Gyros for ESP, GPS navigation, roll detect, established

Microscaners for Head Up Displays (from 2009)

IR sensors for driver vision enhancement road monitor, cabin temp, air quality, anti-fog... established

Airbag accelerometers, established

RF MEMS reference oscillators (from 2009)

Pressure, flow sensors for engine management, air intake established

TPMS pressure + accel + temp (+ energy scavengers from 2012)

Pressure, accelerometer, gyro for side airbag sensing & deployment, established

Legend

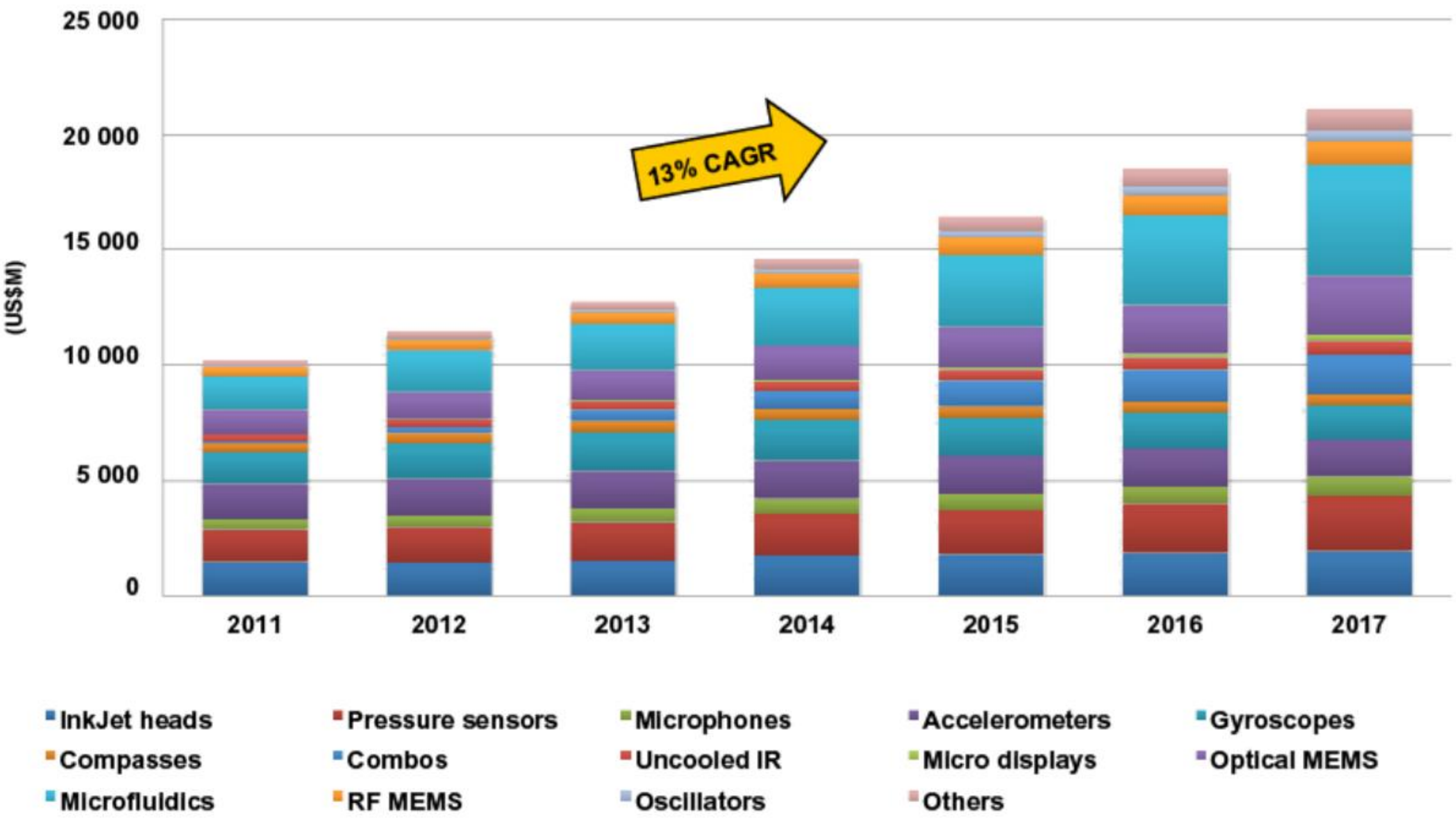
- ▶ Inertial sensors
- ▶ Pressure, flow
- ▶ Infrared, optic
- ▶ RF, other

Inclinometers for zero set (accelero) theft alarm, electronic parking brake, headlight level. established

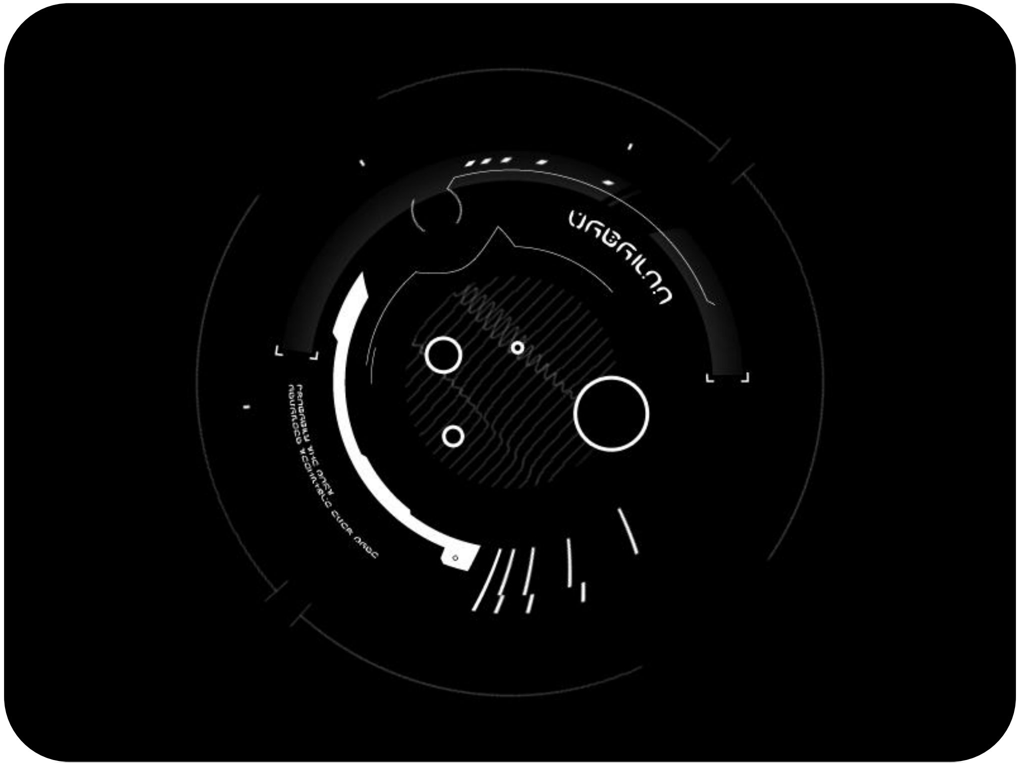
Flow sensors for HVAC 2008? less likely

Source: WTC
www.wtc-consult.de

MEMS Market


25 000
20 000
15 000
10 000
5 000
0
(US$M)
13% CAGR
2011
2012
2013
2014
2015
2016
2017
InkJet heads
Pressure sensors
Microphones
Accelerometers
Gyroscopes
Compasses
Combos
Uncooled IR
Micro displays
Optical MEMS
Microfluidics
RF MEMS
Oscillators
Others

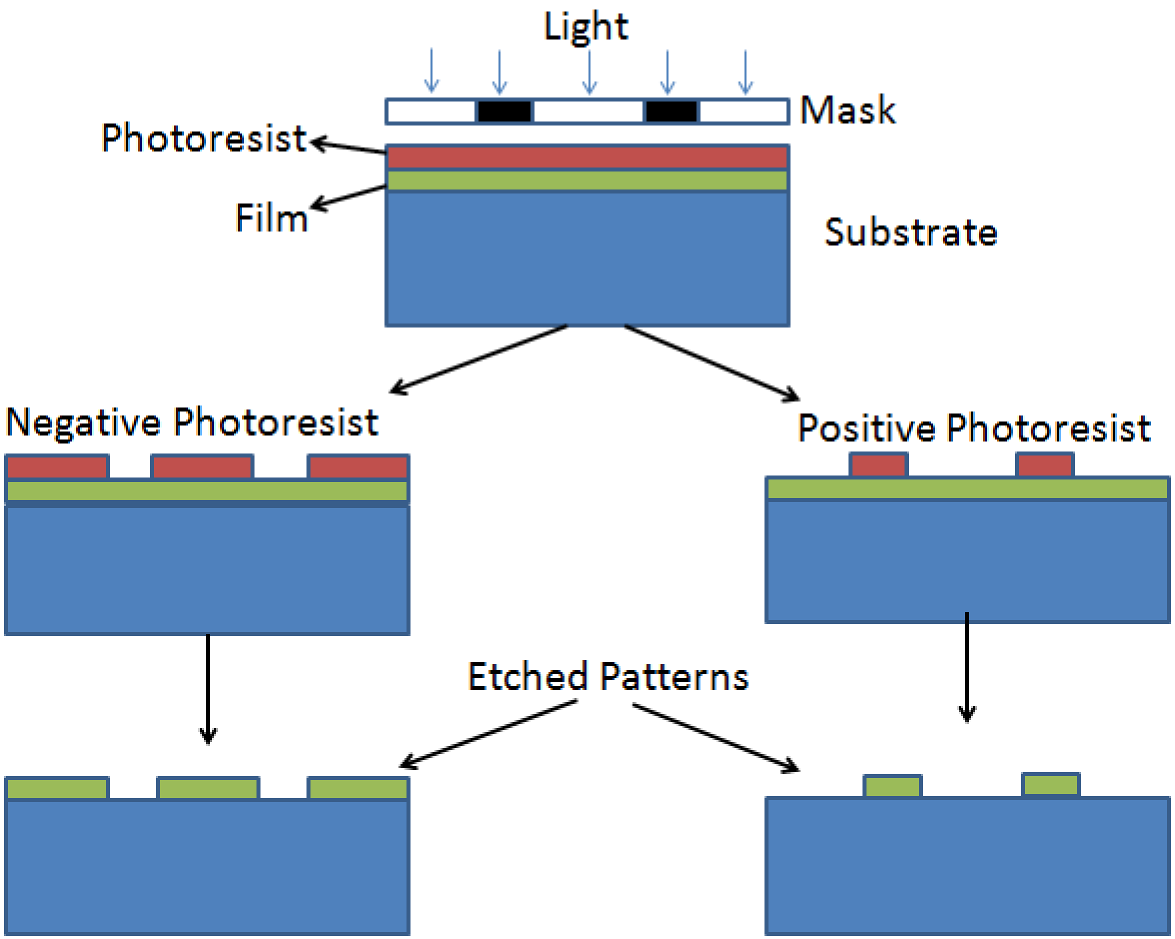
HOW TO FABRICATE MEMS?



Fabrication Approaches

MEMS processing iteratively uses three main processes

1. Patterning → usually resist based to define the selected area fabrication of subsequent layers

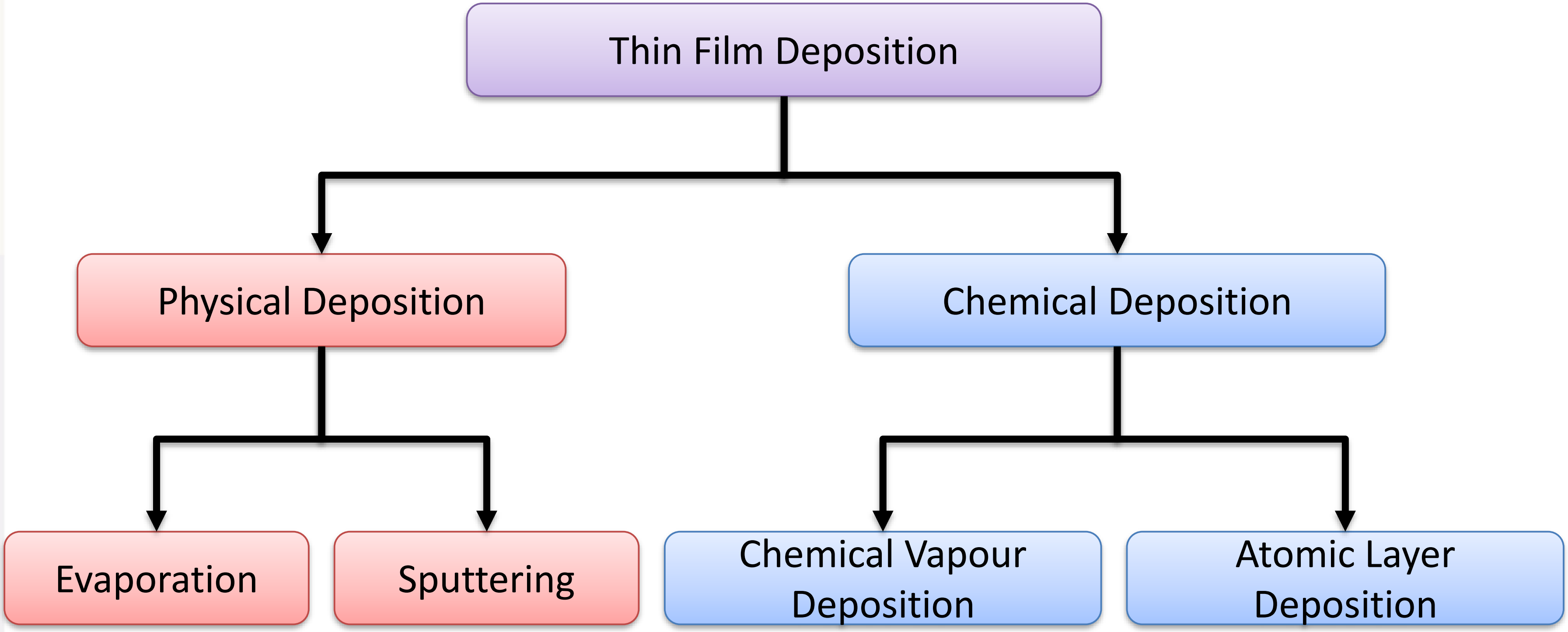


Fabrication Approaches

MEMS processing iteratively uses three main processes

1. Patterning → usually resist based to define the selected area fabrication of subsequent layers

2. Deposition → creation of a material film from Å up to about 100 µm
   - Chemical → gas stream reacts (condenses) on the surface
   - Physical → direct material condensation (reaction) on the surface



Thin Film Deposition

Physical Deposition

Chemical Deposition

Evaporation

Sputtering

Chemical Vapour Deposition

Atomic Layer Deposition

Fabrication Approaches

MEMS processing iteratively uses three main processes

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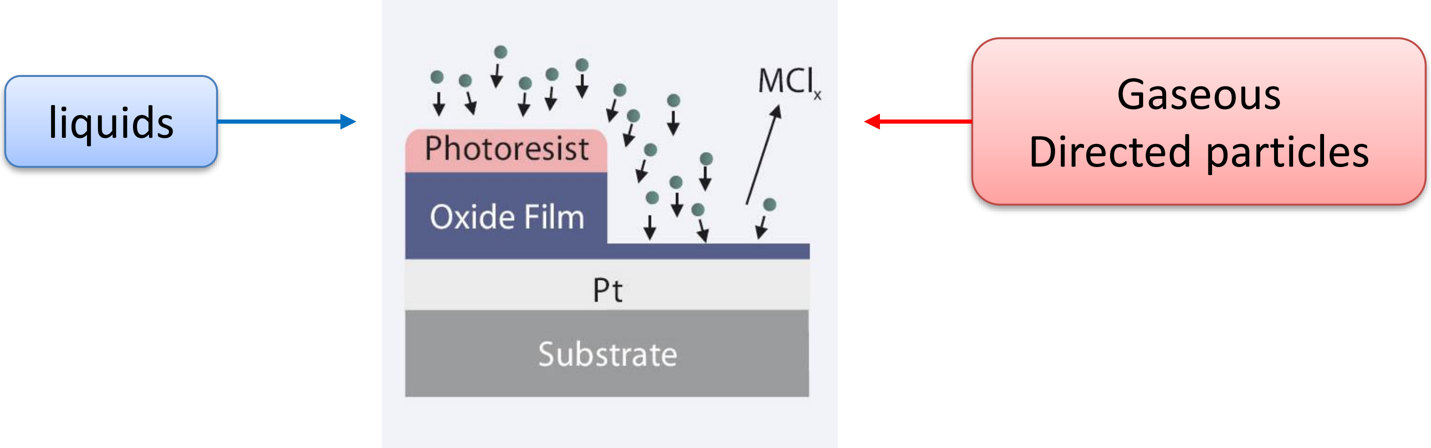
2. Deposition → creation of a material film from Å up to about 100 µm
   - Chemical → gas stream reacts (condenses) on the surface
   - Physical → direct material condensation (reaction) on the surface

3. Etching → removing materials on selected (patterning) or non-selected areas
   - Wet etching → solution based with high chemical selectivity
   - Dry etching → sputtering (material implantation) and / or plasma / gas approaches



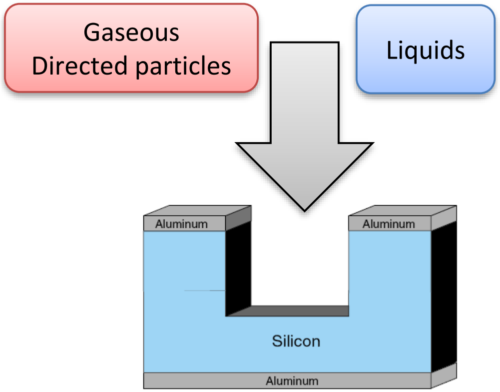
liquids

Gaseous
Directed particles

Fabrication Methods

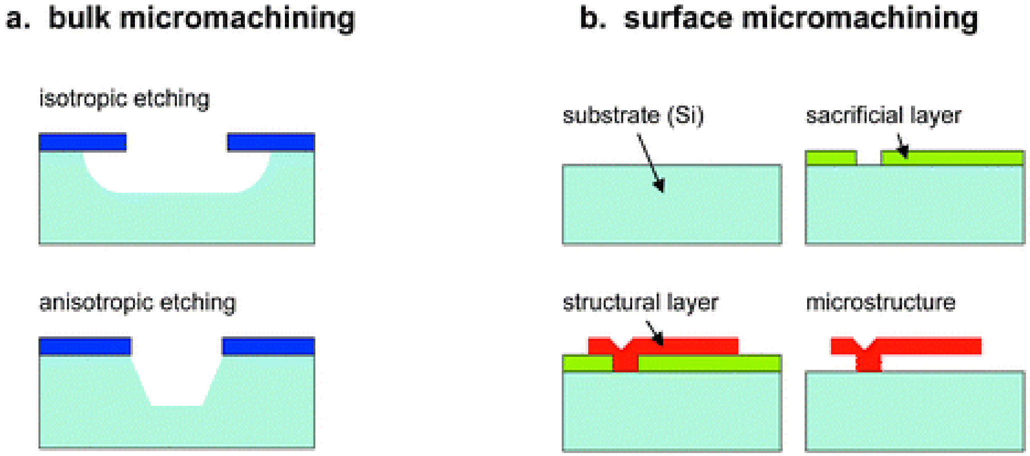
In MEMS microfabrication there are typical two different basic approaches

1. Bulk machining for the “straightforward” material removal
   - Selective or non-selective material removal (patterning dependent)
   - Both, physical and chemical material removing is used
   - The latter, however, is more often used as it allows two different types
     - Isotropic → spatially homogeneous independent on the materials crystallographic structure
     - Anisotropic → different etch rates in different crystallographic orientations
2. Surface machining
   - This process is different as it allows the fabrication of free-standing surface layers
   - *Lets have a closer look on that*



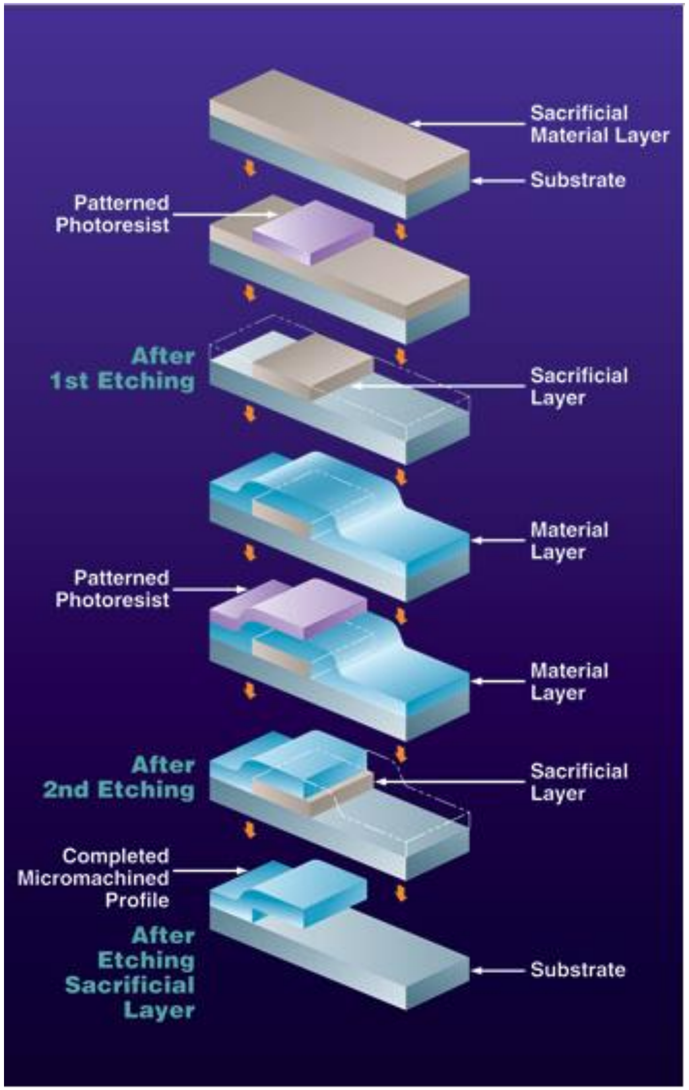
Gaseous
Directed particles

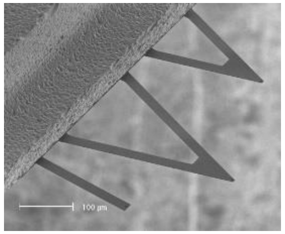
Liquids

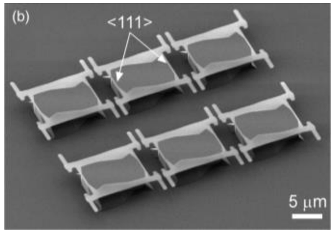


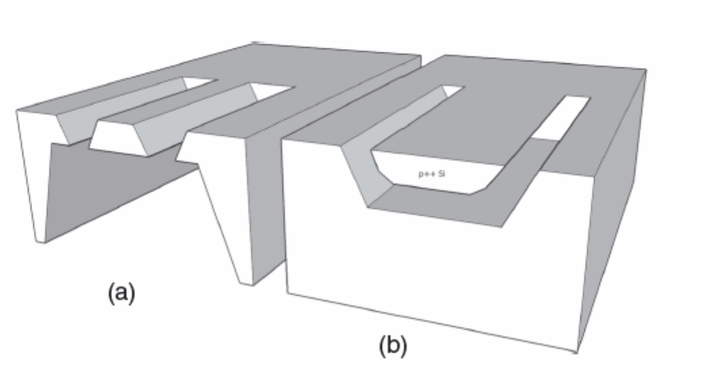
Surface Micromachining for Freestanding Structures

- The key to fabricate free-standing regions is the introduction of a sacrificial layer, smart patterning design and a multistep fabrication procedure
- It starts with the introduction of the sacrificial layer
- This is followed by the resist layer and its patterning
- And is finalized by the removal of the sacrificial layer



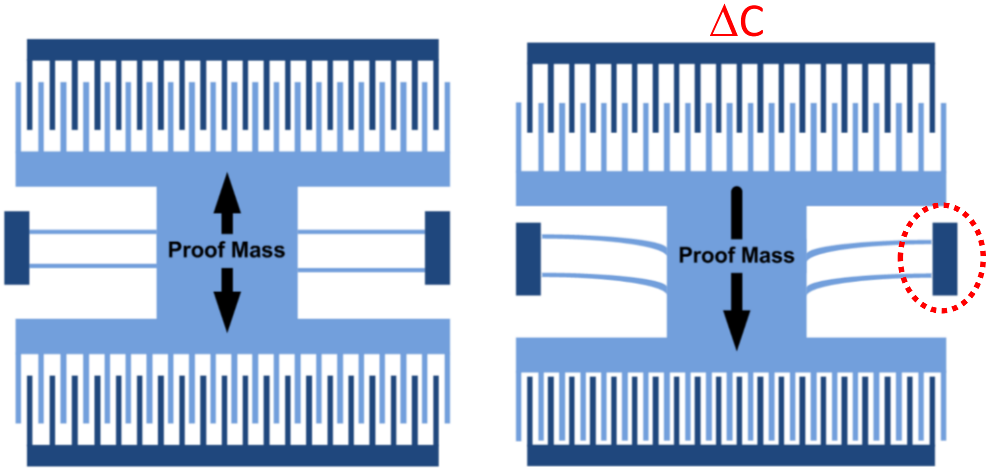


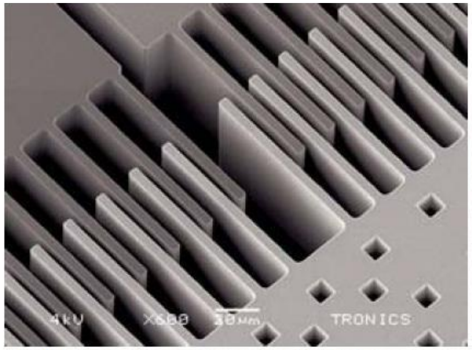




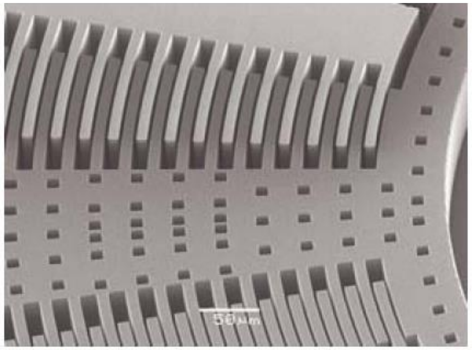
Advanced Freestanding Structures

- Challenge: how to “free” only SOME parts why the others should be fixed with the substrate?
- While the first two steps remain the same, the buried oxide layer (lower red region) can then be removed in a second step to vertically release large structures (again the accelerometer)



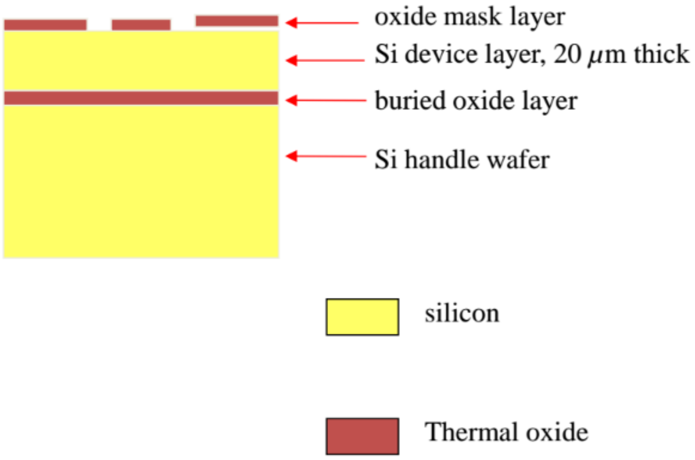


a) High performance capacitive accelerometer
DRIE etched on 100 µm thick SOI

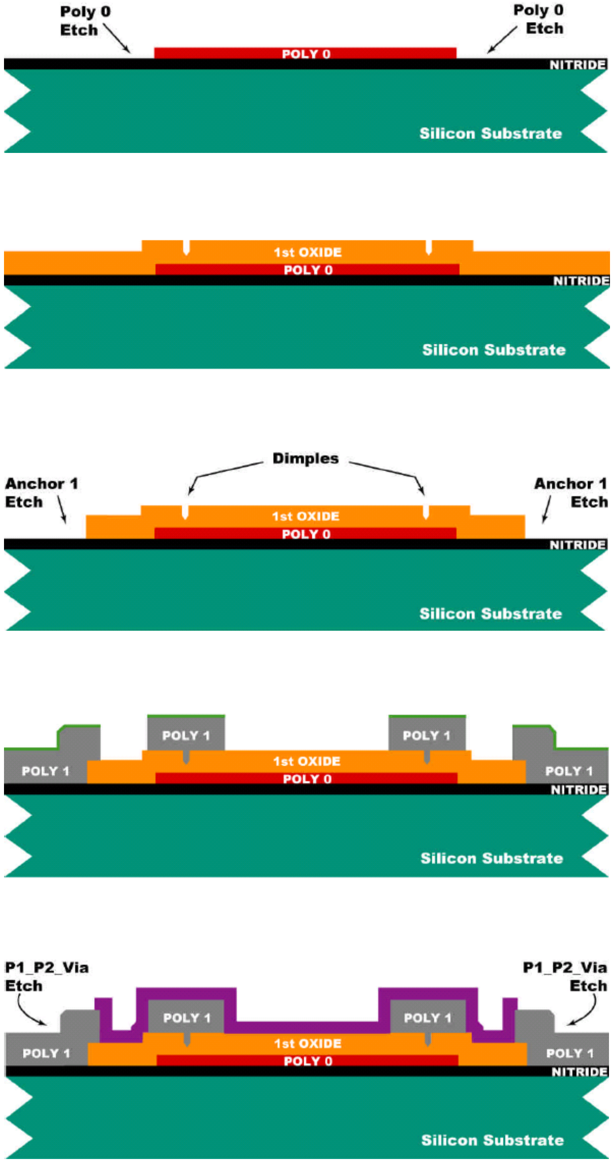


d) Capacitive gyro
DRIE etched on 60 µm SOI

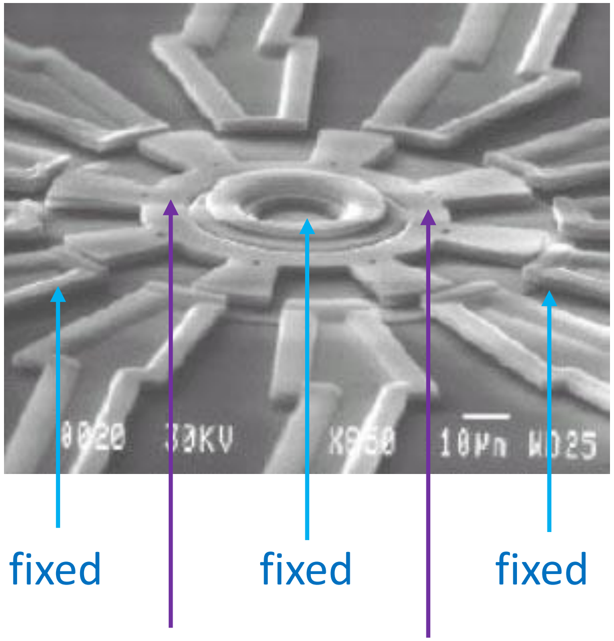
(Source: Alcatel Micro Machining Systems)



Multi Level Processing – A Close Look



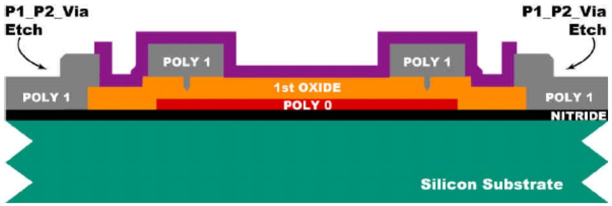
micro rotation device

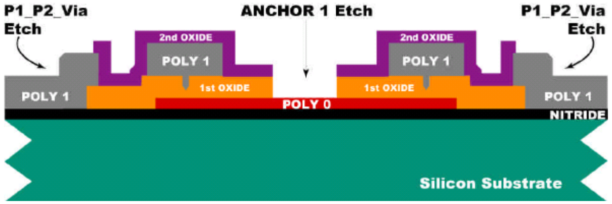


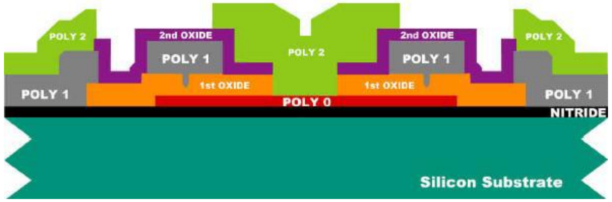
fixed fixed fixed

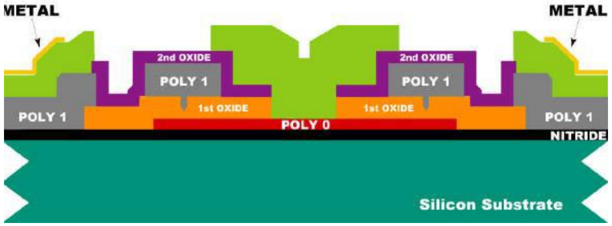
movable movable

Multi Level Processing – A Close Look

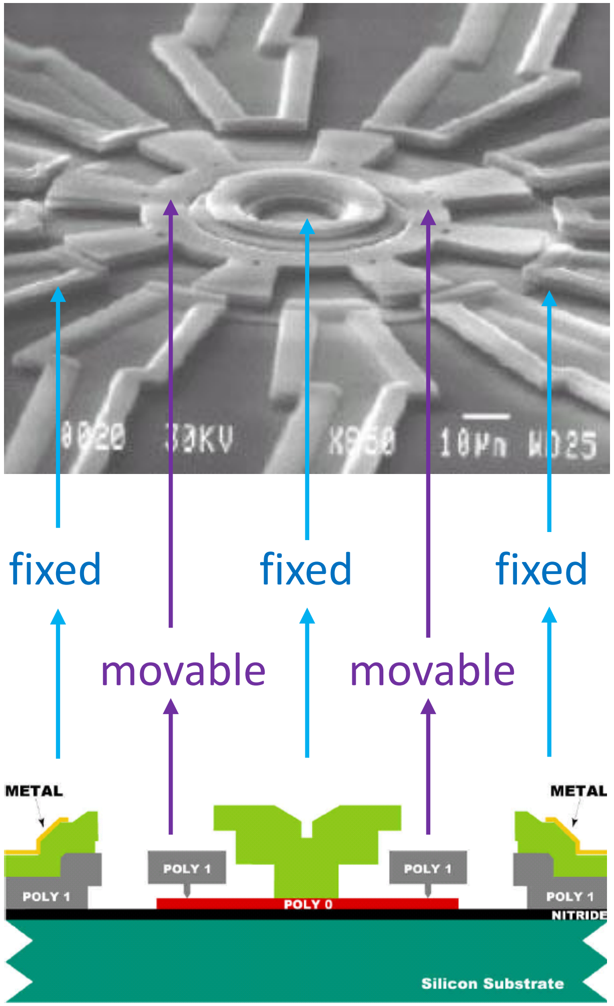






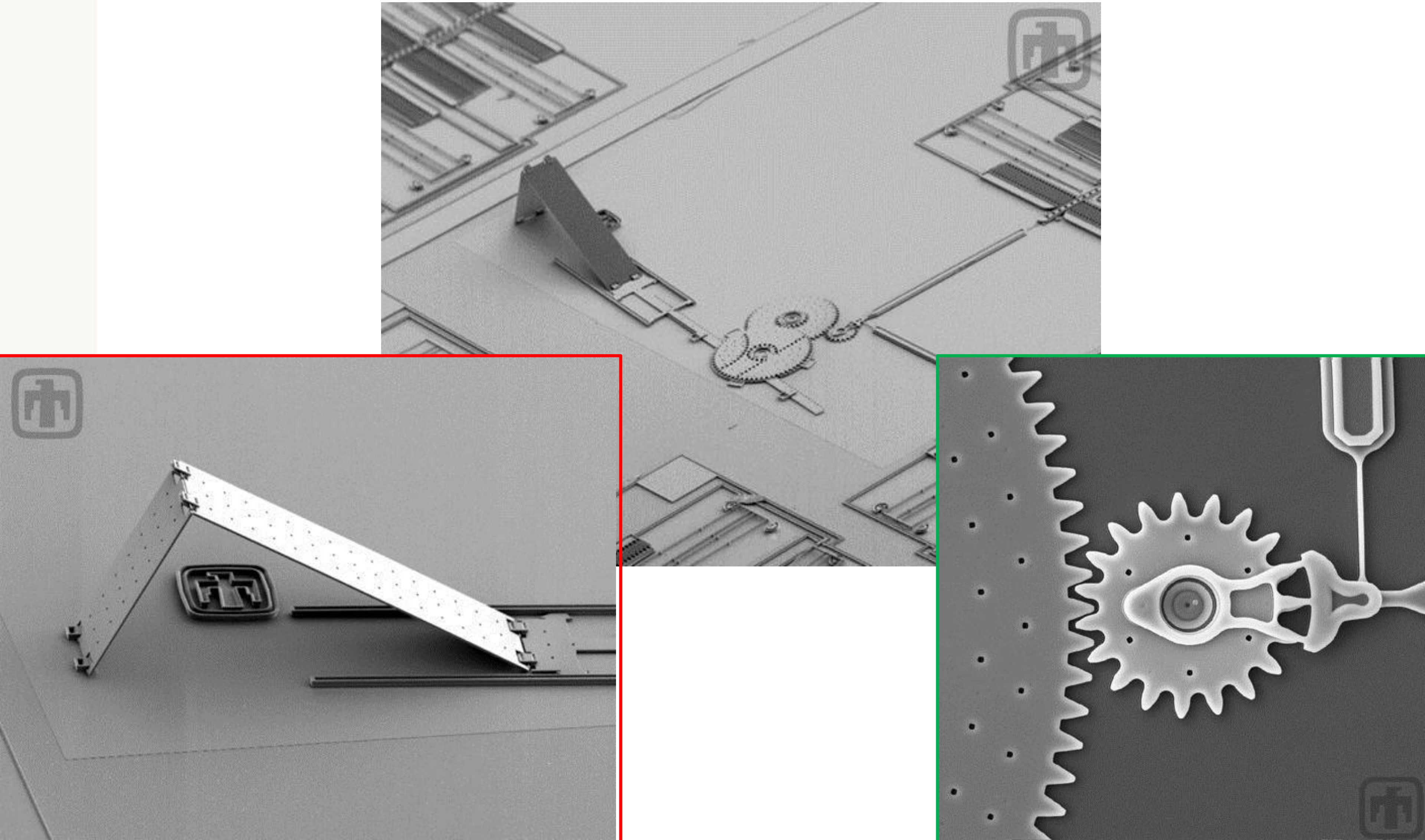


micro rotation device

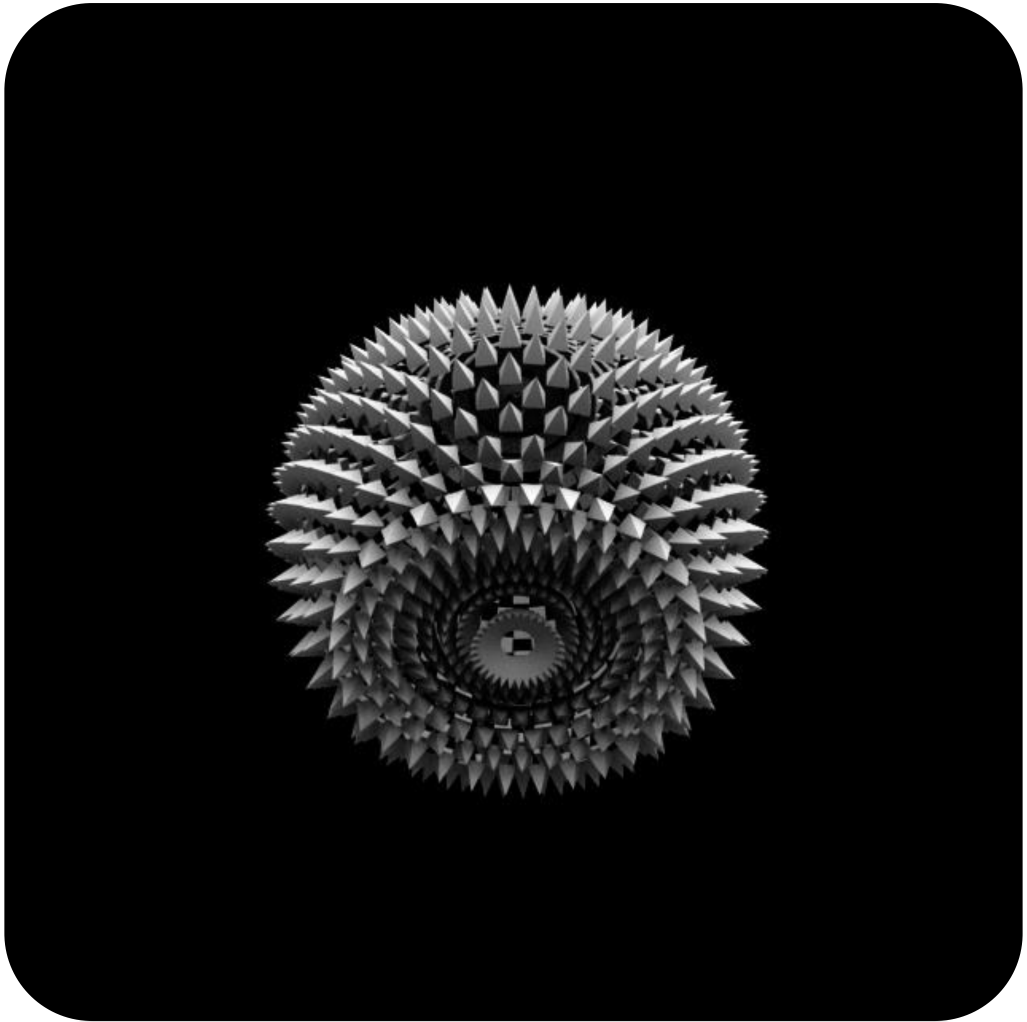


Multi Level Processing

- With this approach even highly complex MEMS concept can be realized (~ 10k€ per 5x5 mm chip)

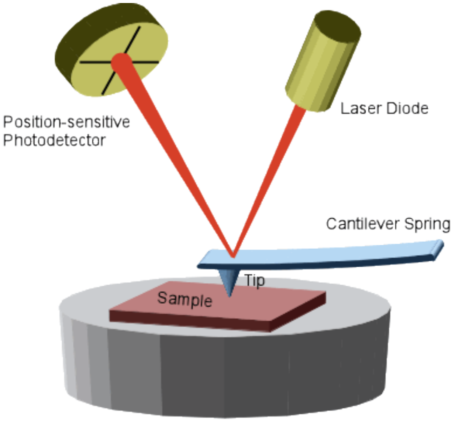


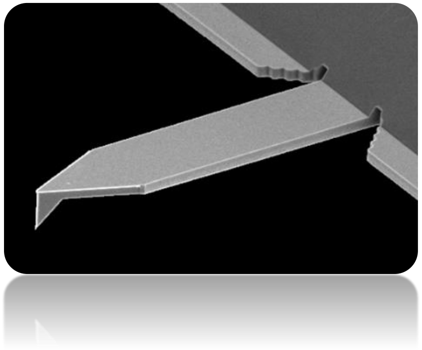
APPLICATIONS – PART I

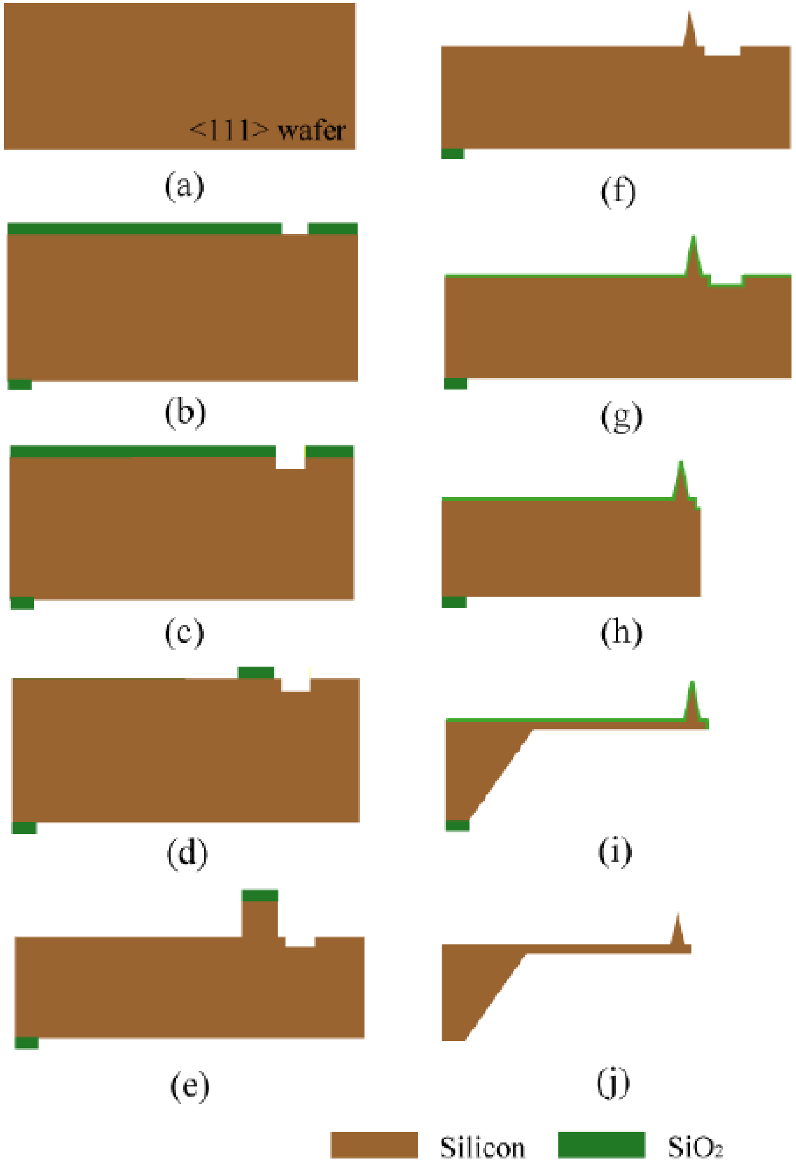


Atomic Force Microscopy – Bulk Machining

- Atomic Force Microscopy (AFM) has been evolved into a standard surface analyses tool to access 3D morphology and material properties on the nanoscale
- The essential element, however, is the cantilever with a nanoscale tip
- How to fabricate that?

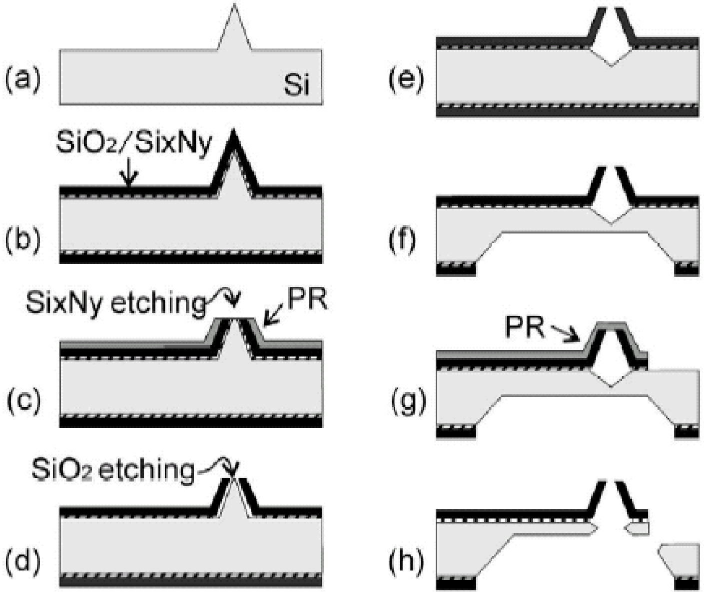




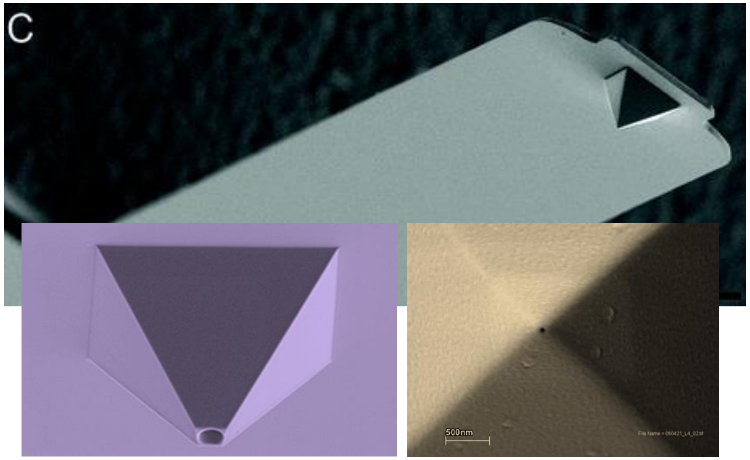


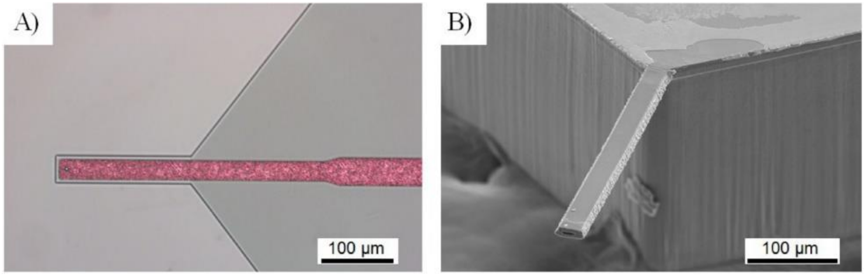
AFM - Adding Further Functionalities

- A smart combination of these multi-step application procedures allows integration of additional functionalities in AFM cantilever
- For instance, so called “hollow cantilever / tips” have been demonstrated for dynamic nano-fluidic applications



(A)





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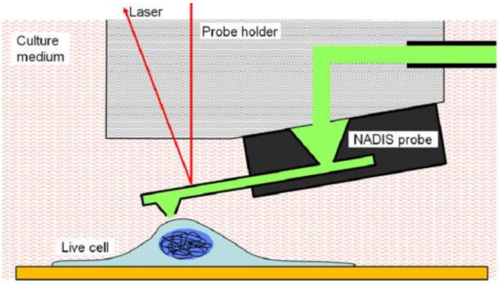
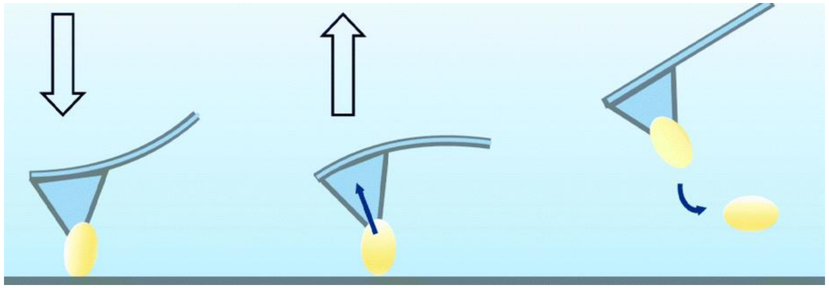
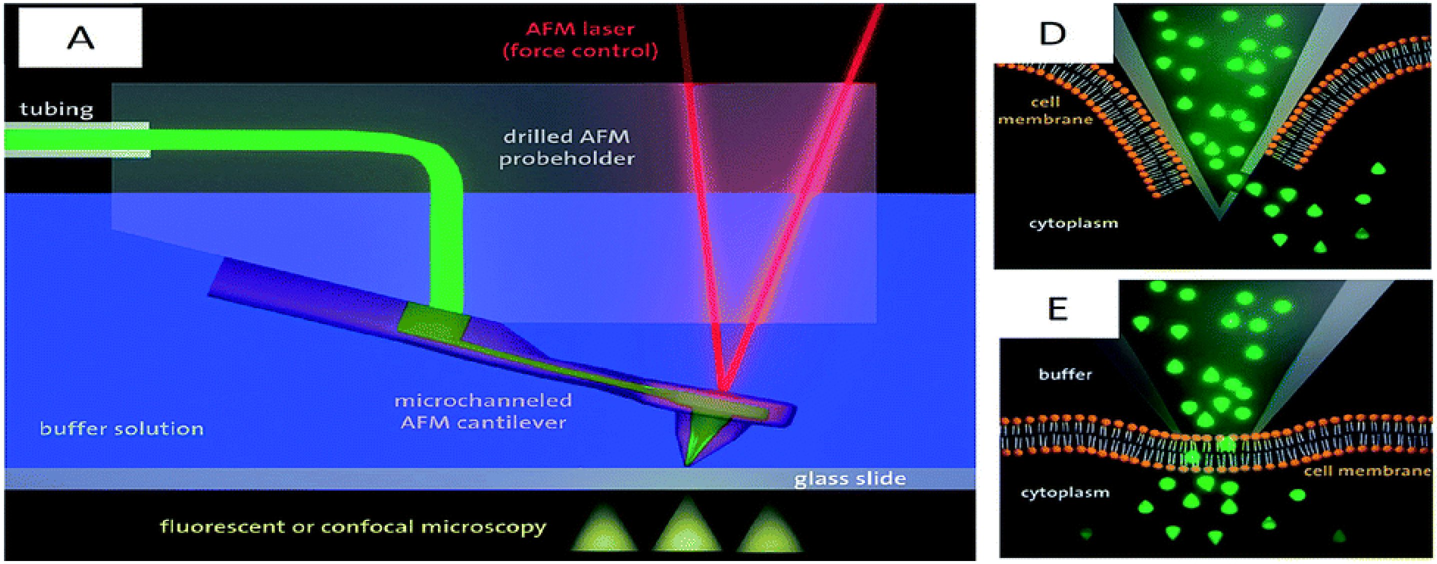
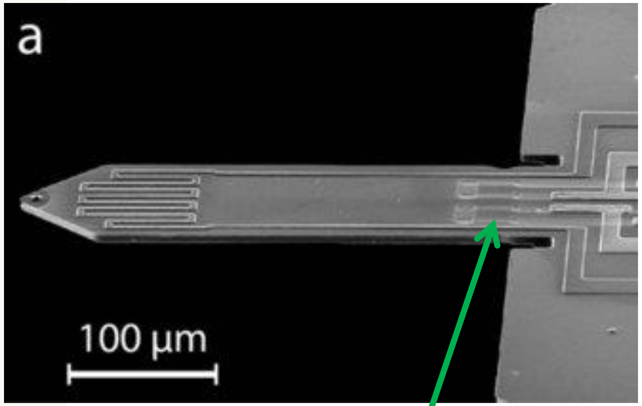




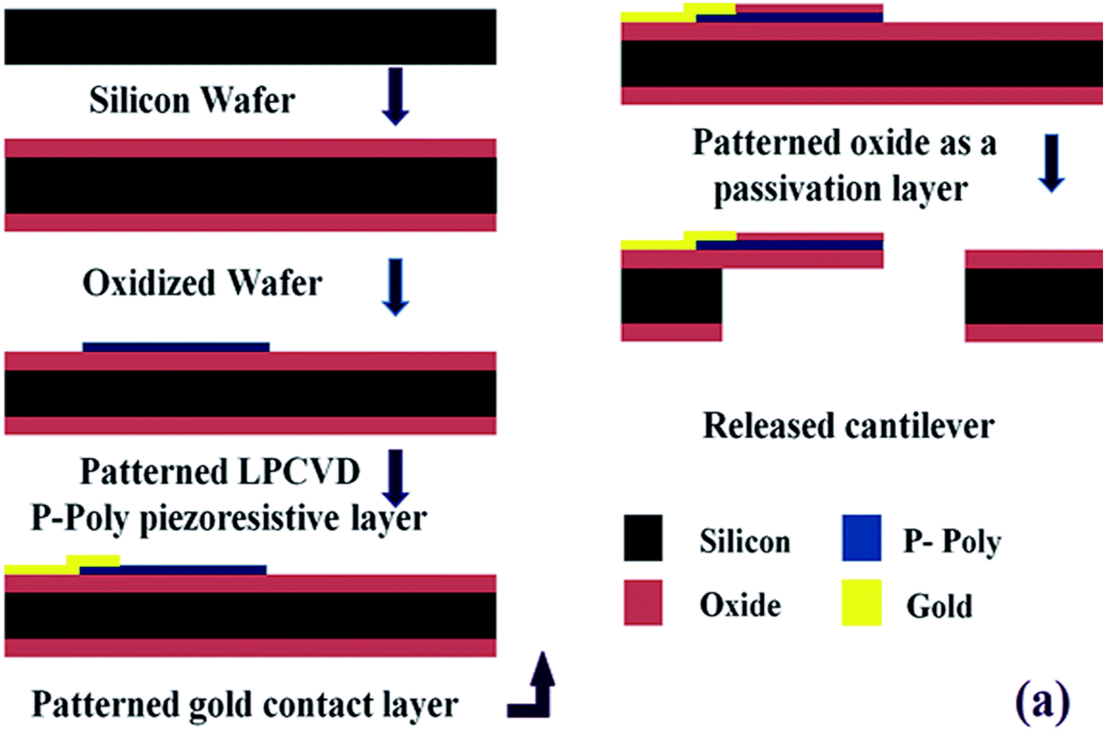


AFM - Adding MEMS Elements

- However, such systems only become MEMS if actuating and / or sensing elements are added
- As example, adding a thin, piezo-resistive layer enables the monolithic integration of a detection element



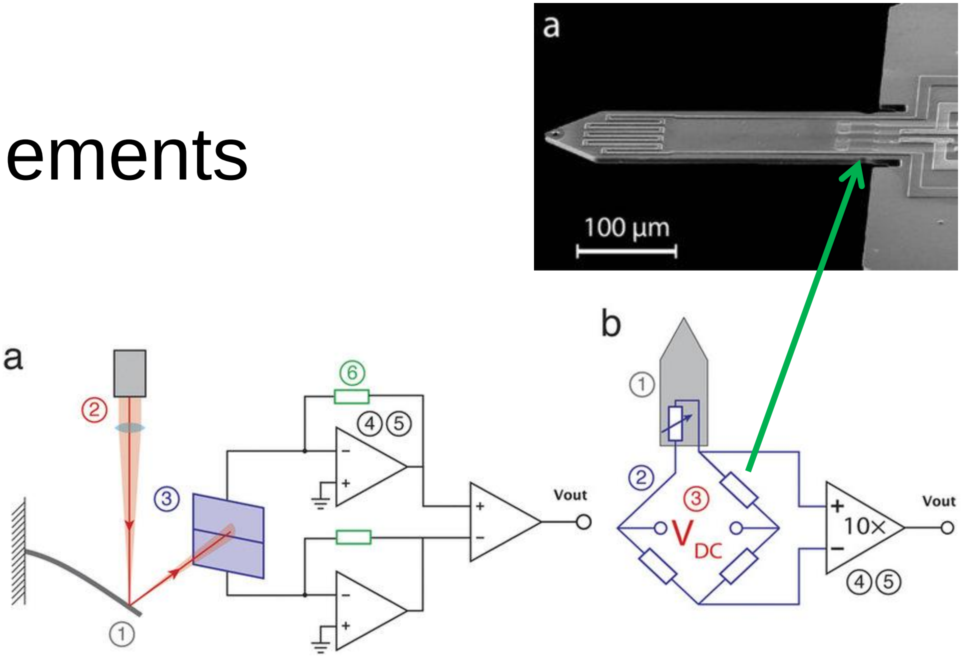
self-sensing elements give information about the cantilever movement

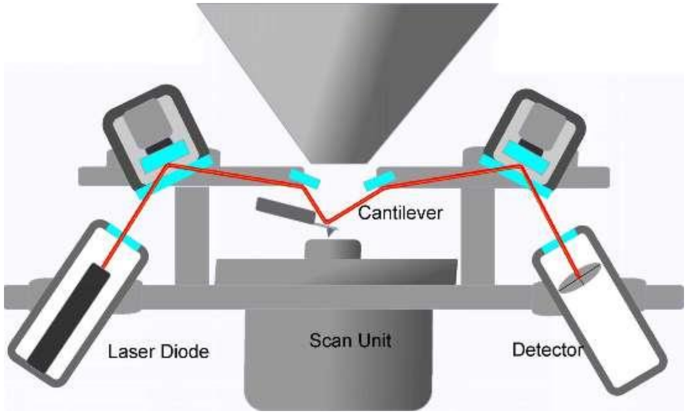


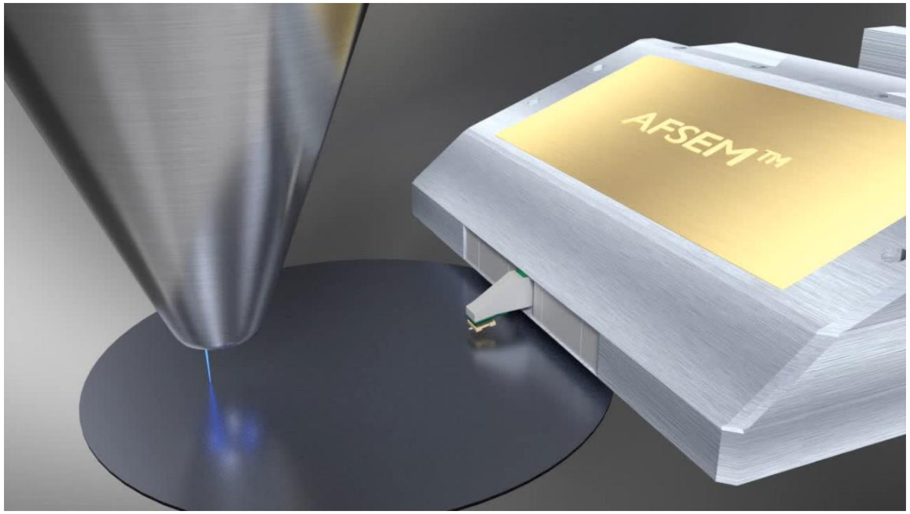
AFM - Adding MEMS Elements

- In this special case, this eliminates the space consuming optical detection system

- Advantages are the
  - Much more simple handling
  - Integratability in highly space confined systems



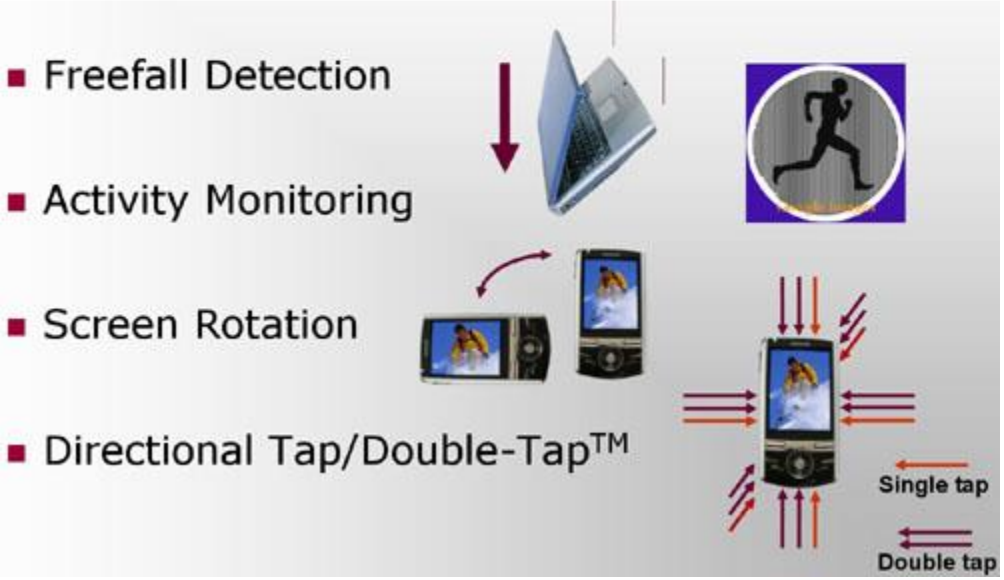




Accelerometers

As the name says, this type measures acceleration for application in

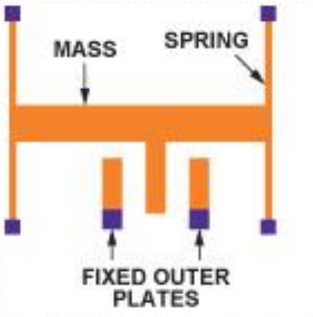
- Phones
- Game controllers
- Airbag sensors
- Machine vibrations
- Seismic activity
- Pedometers
- Inertial navigation systems
- RC flight components

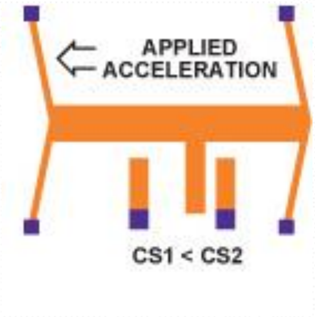


- Freefall Detection
- Activity Monitoring
- Screen Rotation
- Directional Tap/Double-Tap™

Accelerometers – Capacitive Basic Principle

It bases on the an accelerated mass which is changes the capacity relative to neighbored electrodes → easy electric detection

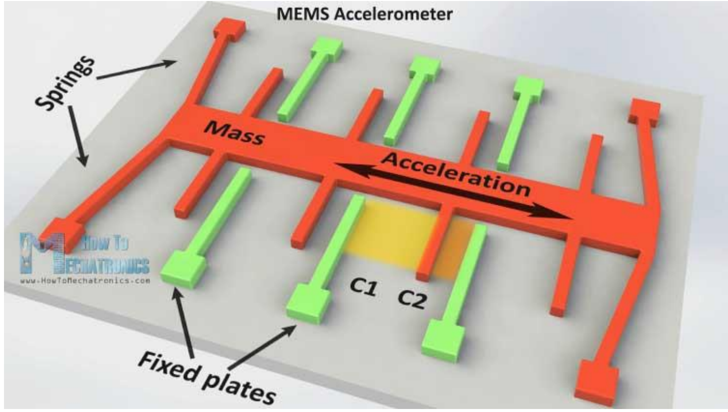


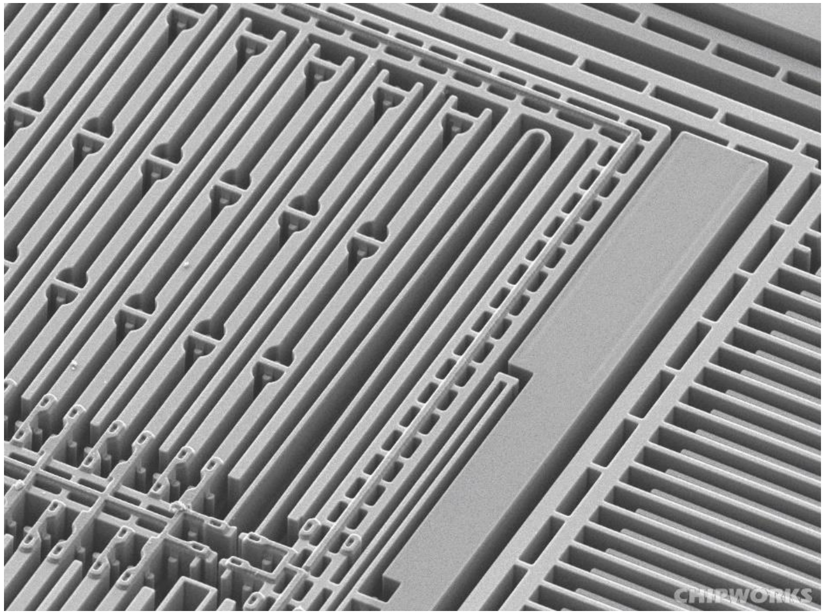


Accelerometers – Capacitive Basic Principle

- The sensor responses 1) on the displacement x and 2) on the entailed change in the capacity C
- These quantities, in turn, depend on
  - $x = -m.a/k$ → m … mass; k … spring constant; a … acceleration
  - $C = \varepsilon.A/d$ → ε … dielectric constanct; A … capacitance area; d … separation distance ($f_{(x)}$)

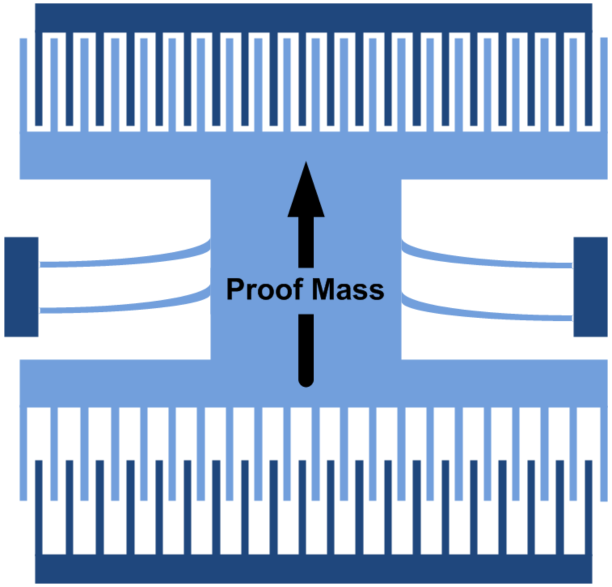
- From that it is obvious that the design can be adapted to maximize the sensitivity via
  - Increasing the mass m (larger proof mass body)
  - Reducing the spring constant m (reducing the spring cross sections)
  - Increasing the capacitance area (many, high electrodes)

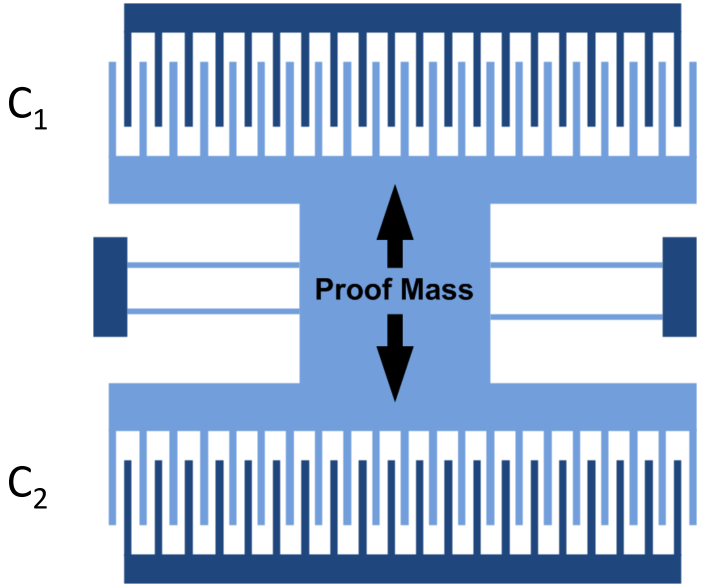


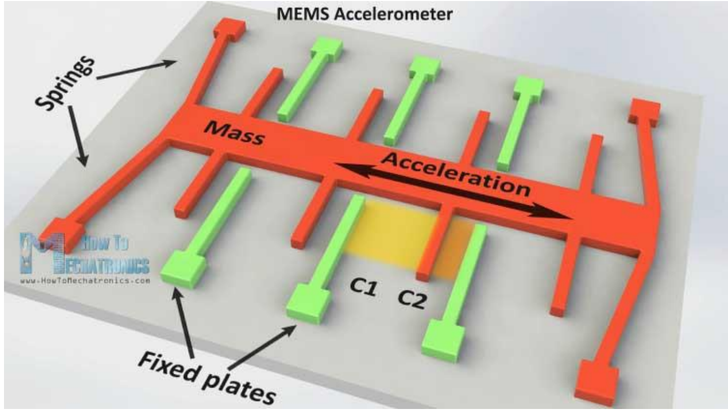


Multi-Axis Accelerometers

- If the movement is now perpendicular to the before discussed direction the capacity is homogenously in- / decreasing for both C1 and C2
- This can be used to enable a two axis accelerometer!

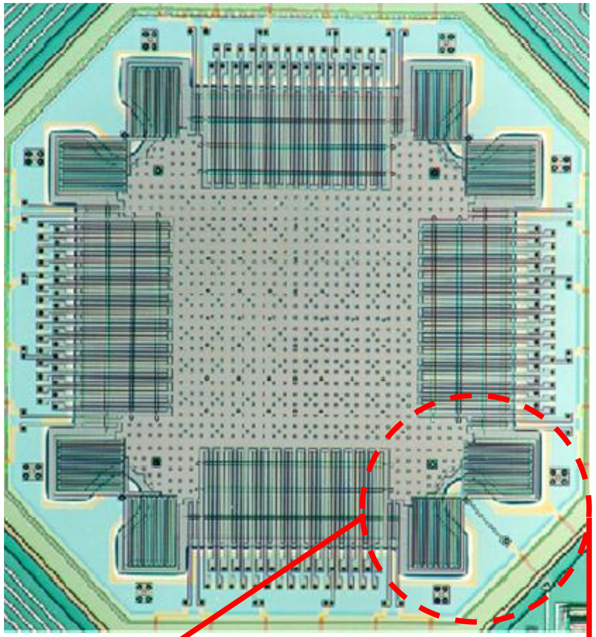

$C_1 \neq C_2$

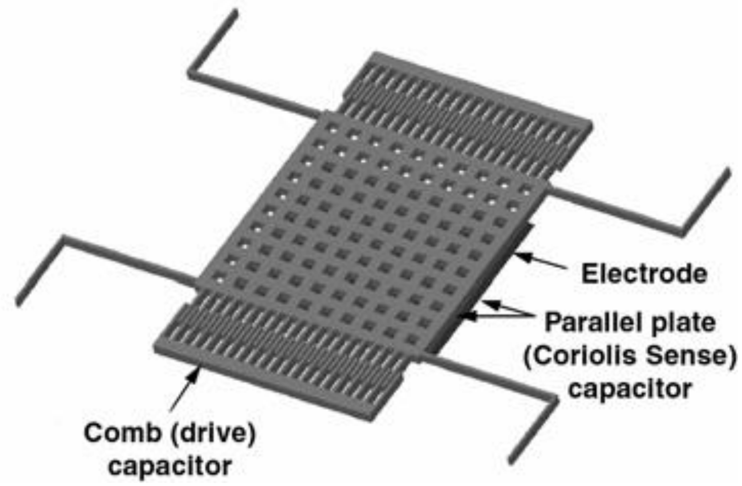

$C_1 = C_2$

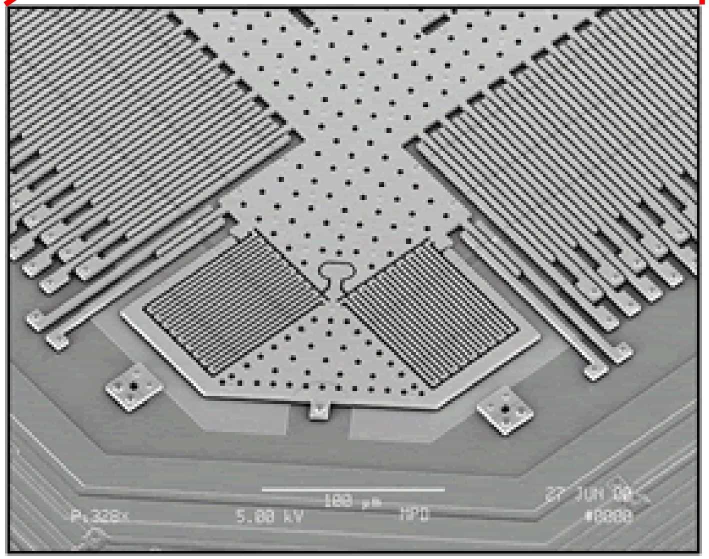


Multi-Axis Accelerometers

- If the movement is now perpendicular to the before discussed direction the capacity is homogenously in- / decreasing for both C1 and C2
- This can be used to enable a two axis accelerometer!
- By adding a third electrode in vertical direction, a 3-axes device can be realized
- Real devices use large comb structures in X and Y to clearly differentiate between the X and Y

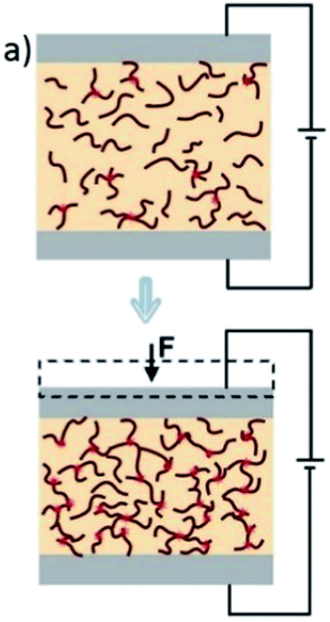




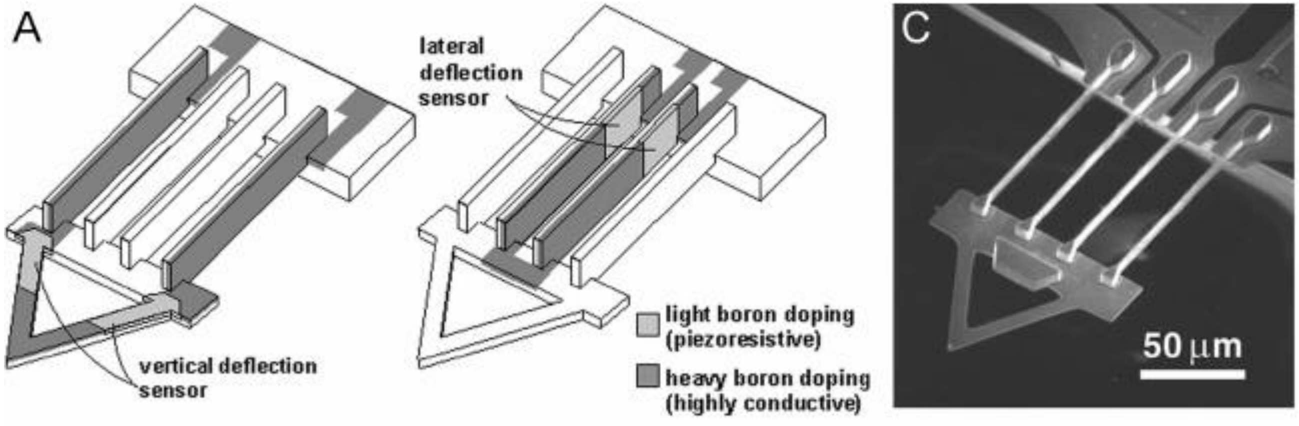


Accelerometers – Piezoresistive Basic Principle

- Instead of a capacitive detection the sensing mechanism can also use the piezoelectric effect
- This effect bases on low concentration dopants (mostly conductive species)
- If the material is stressed or strained it changes its conductivity
- When such materials or doping zones are fabricated the right way it gives high flexibility

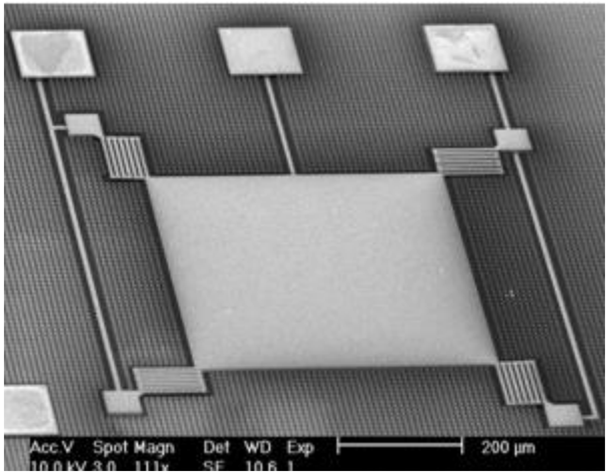


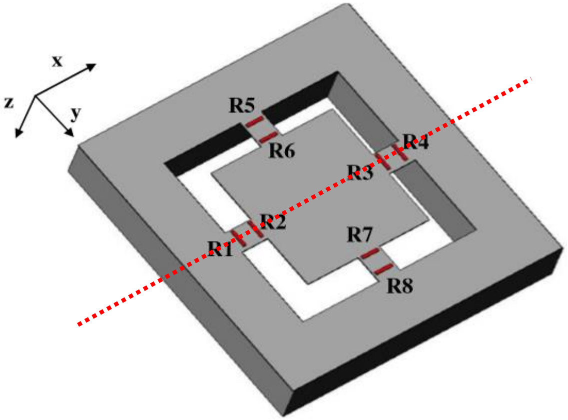
Piezoresistivity

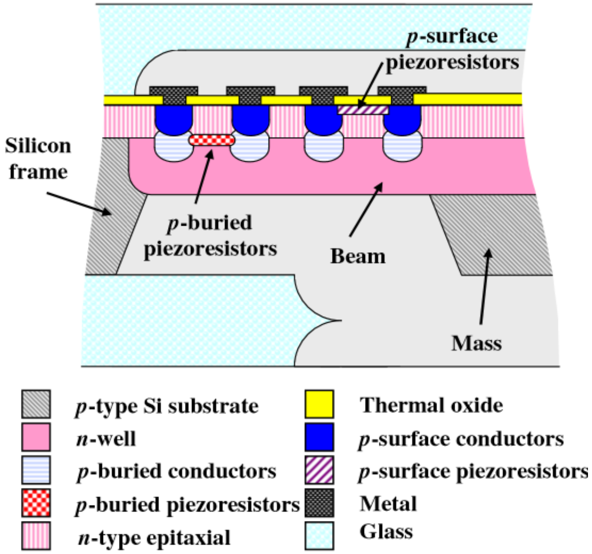


Accelerometers – Piezoresistive Basic Principle

- Basic setup is simpler in geometry but more complex by its layer sequence

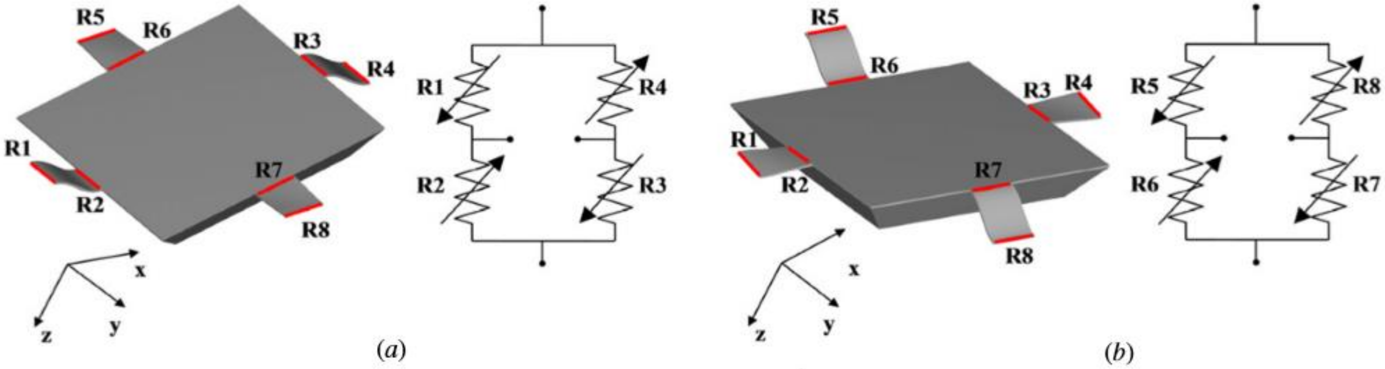






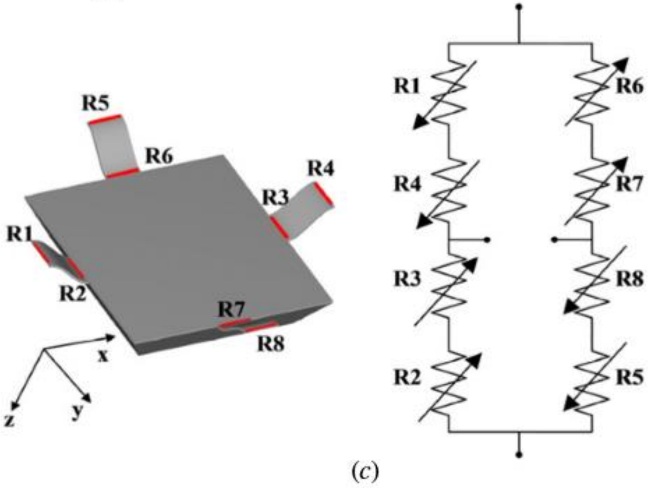
Accelerometers – Piezoresistive Basic Principle

- Electric operation requires complex models

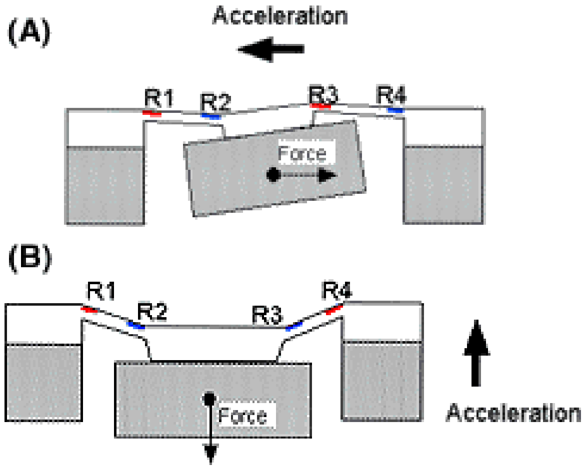


(a)

(b)



(c)



Accelerometers – Piezoresistive Basic Principle

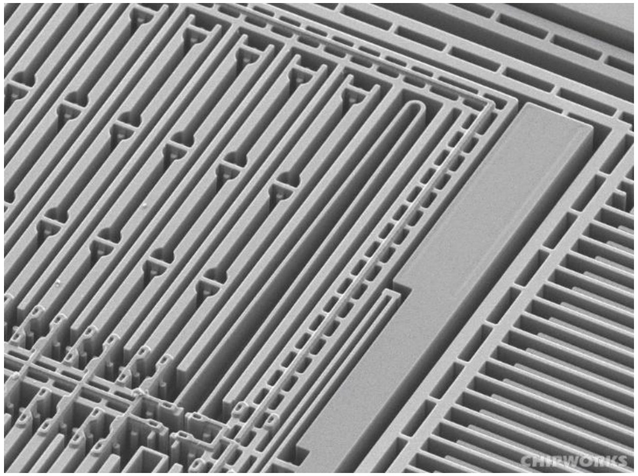
Advantages:

- The overall structure is usually much simpler and smaller than for capacitive sensors
- The sensors usually allow high frequency sensing
- As the design can be done more rigid higher accelerations can be measured (up to 6000 g)
- Low hysteresis (compared to piezoelectric MEMS – see later)

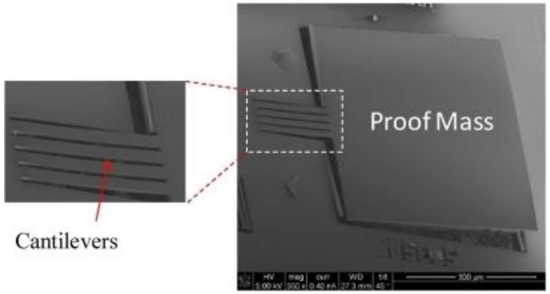
Disadvantages

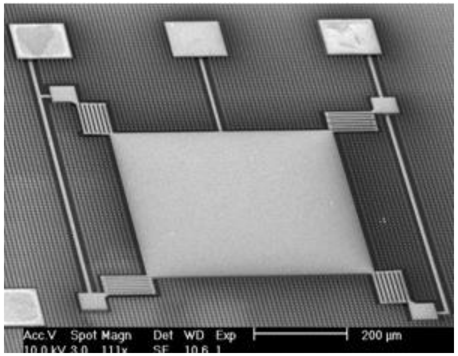
- Much more complex operation w.r.t. electric readout
- Environmental sensitive (T, humidity, …)
- Not long time stable

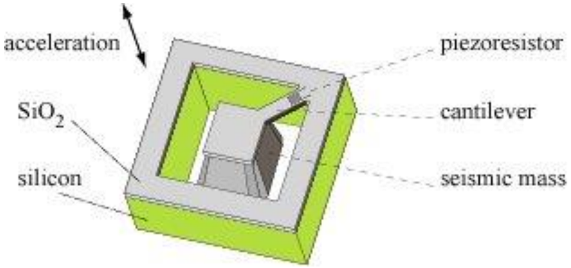
capacitive



piezoresistive

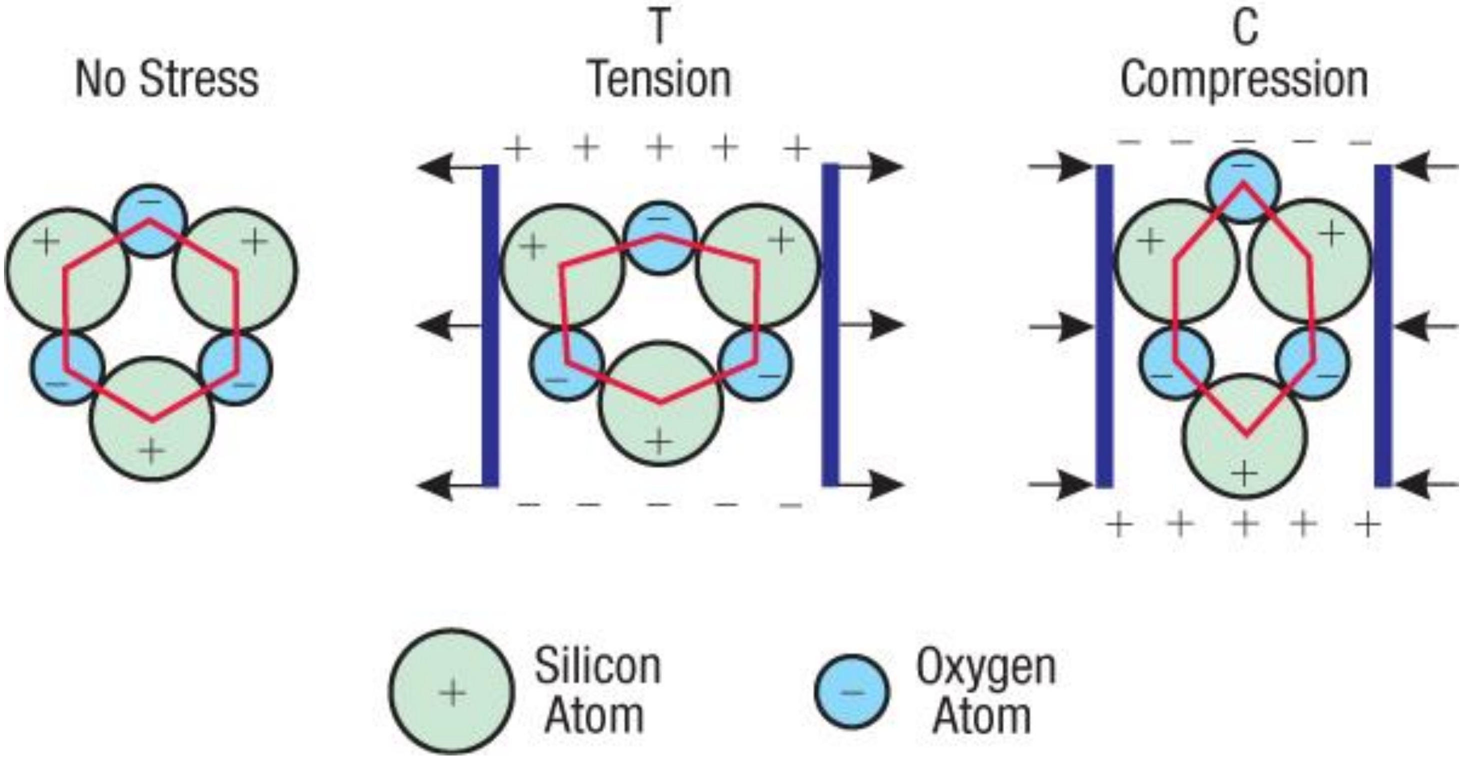






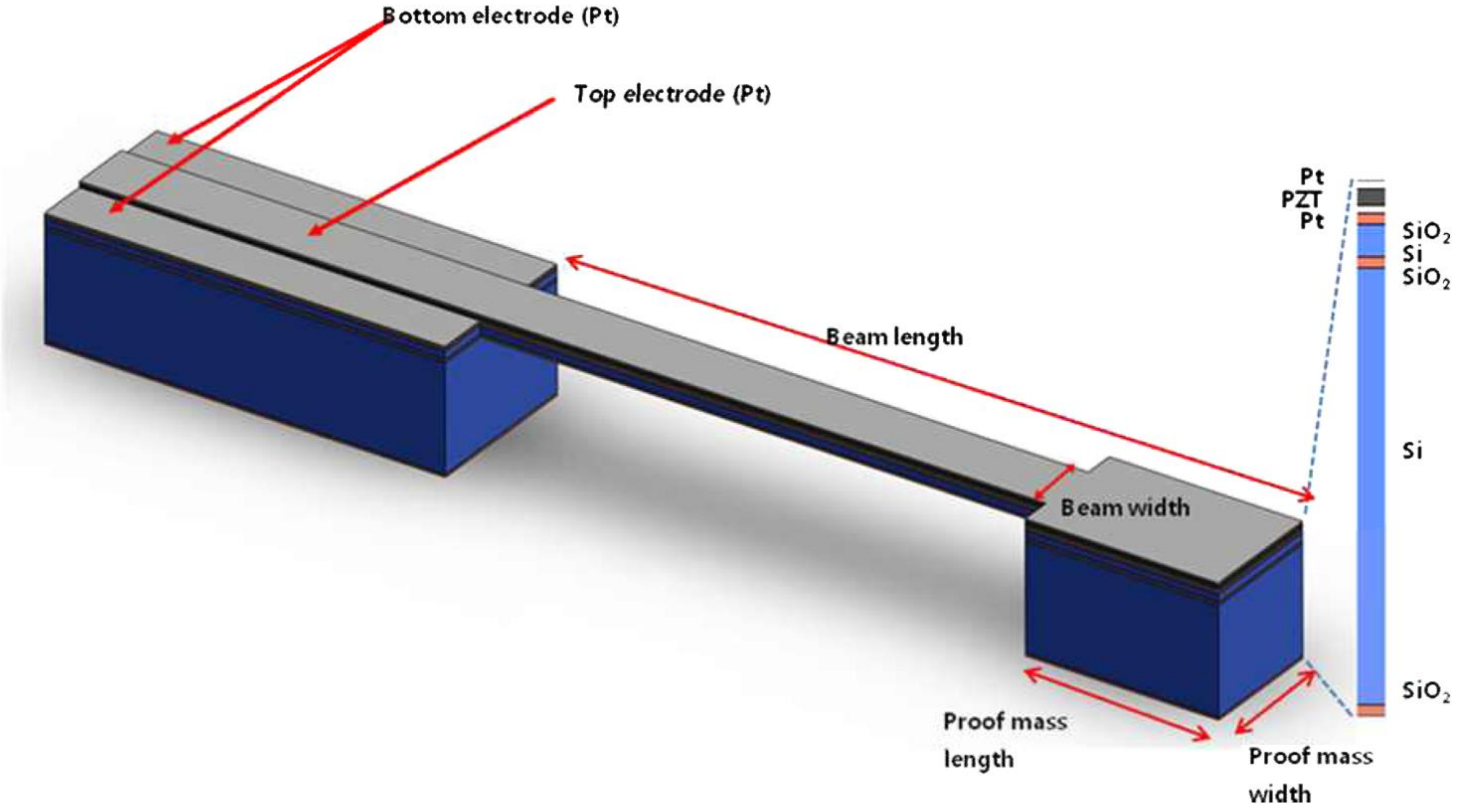
Accelerometers – Piezoelectric Basic Principle

- In contrast to piezoresistivity, the piezoelectric effect is more dedicated to the crystal structures
- When attaching an electrode on top and on bottom, the mechanical deformation induces a voltage which can be measured (materials could be quartz, Zinc-Oxide (ZnO), Lead-Titanate ($PbTiO_3$) or Lead-free Bariumtitanate ($BaTiO_3$).
- The essential part, however, is that this effect can be TURNED AROUND, meaning that applying a voltage leads to mechanical deformation with sub-nanometer accuracy (very important later on)



Accelerometers – Piezoelectric Basic Principle

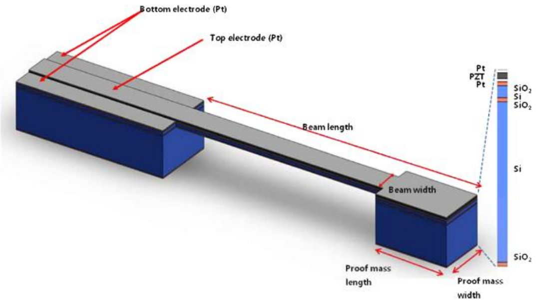
- These sensors consist of a multi-layer structure with top and bottom electrodes and the piezoelectric material in the center

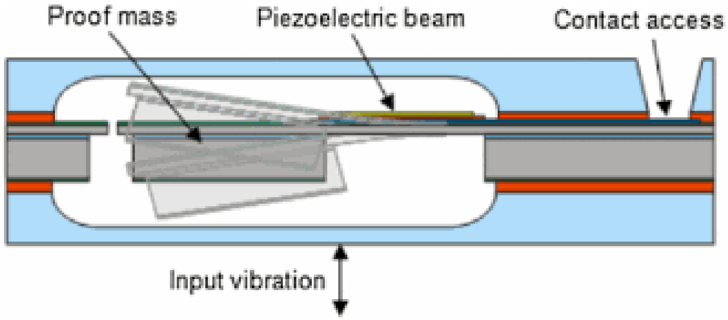


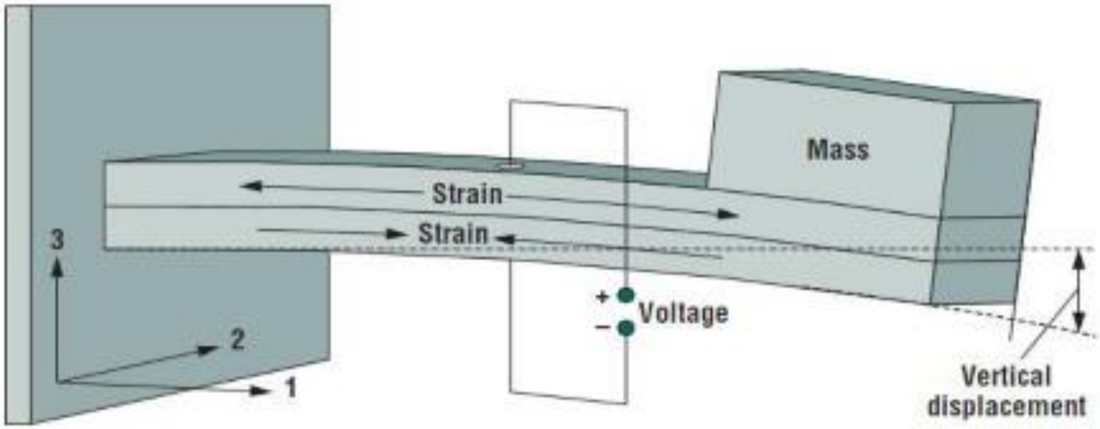
Accelerometers – Piezoelectric Basic Principle

- These sensors consist of a multi-layer structure with top and bottom electrodes and the piezoelectric material in the center

- Once the proof mass bends the beam the piezoelectric effect causes the desired voltage
- However, the spatial position of the sensor is absolutely essential!







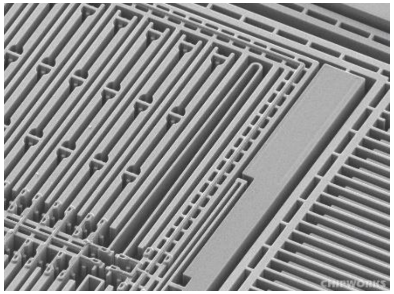
Accelerometers – Piezoelectric Basic Principle

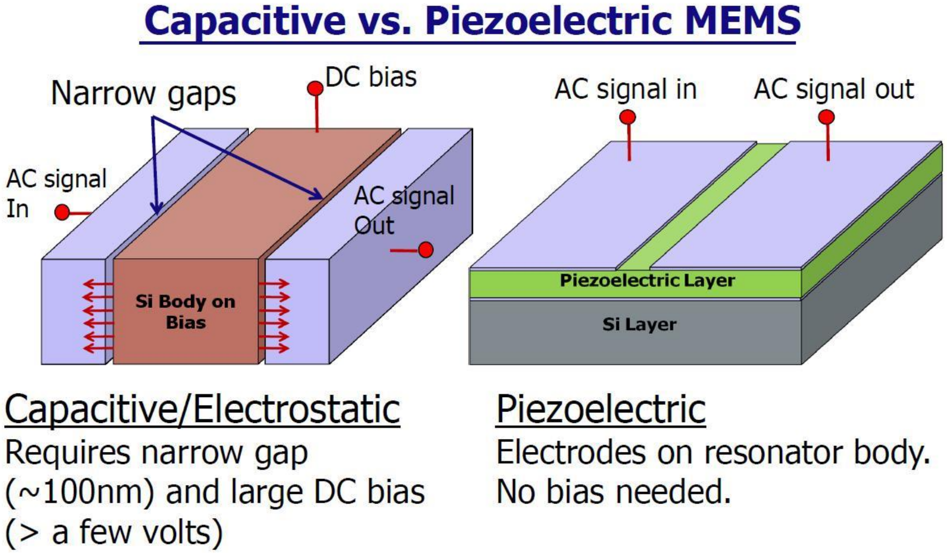
Advantages:

- The design is simple and robust which minimizes fabrication efforts
- The sensors usually allow high frequency sensing
- As the design can be done more rigid higher accelerations can be measured (up to 6000 g)

Disadvantages

- Much more complex operation w.r.t. electric readout
- No static measurements!
- Environmental sensitive (T, humidity, …)
- Not long time stable
- Hysteresis effects

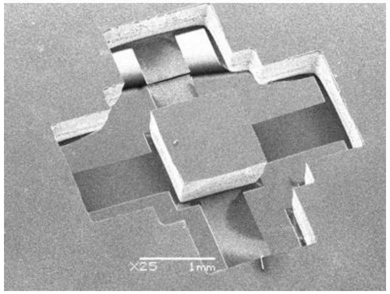




Capacitive vs. Piezoelectric MEMS

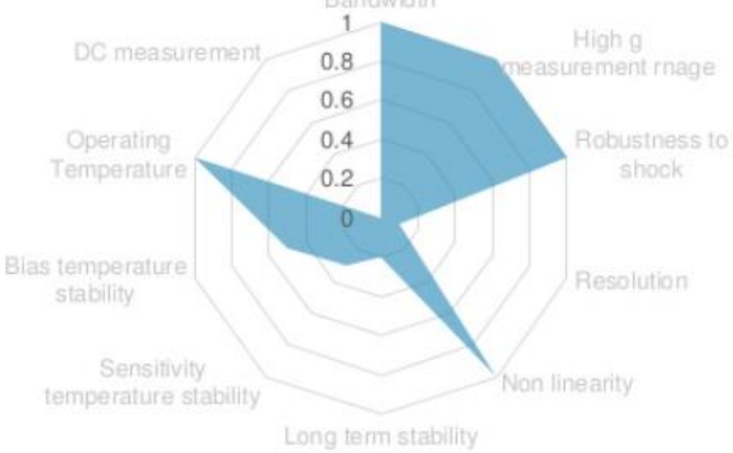
Capacitive/Electrostatic
Requires narrow gap (~100nm) and large DC bias (> a few volts)

Piezoelectric
Electrodes on resonator body. No bias needed.

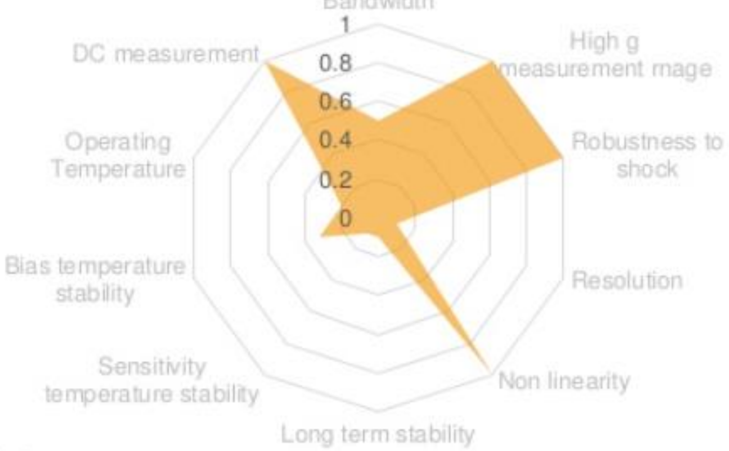


Accelerometers – Principle Comparison

Piezoelectric



Piezoresistive



Capacitive MEMs