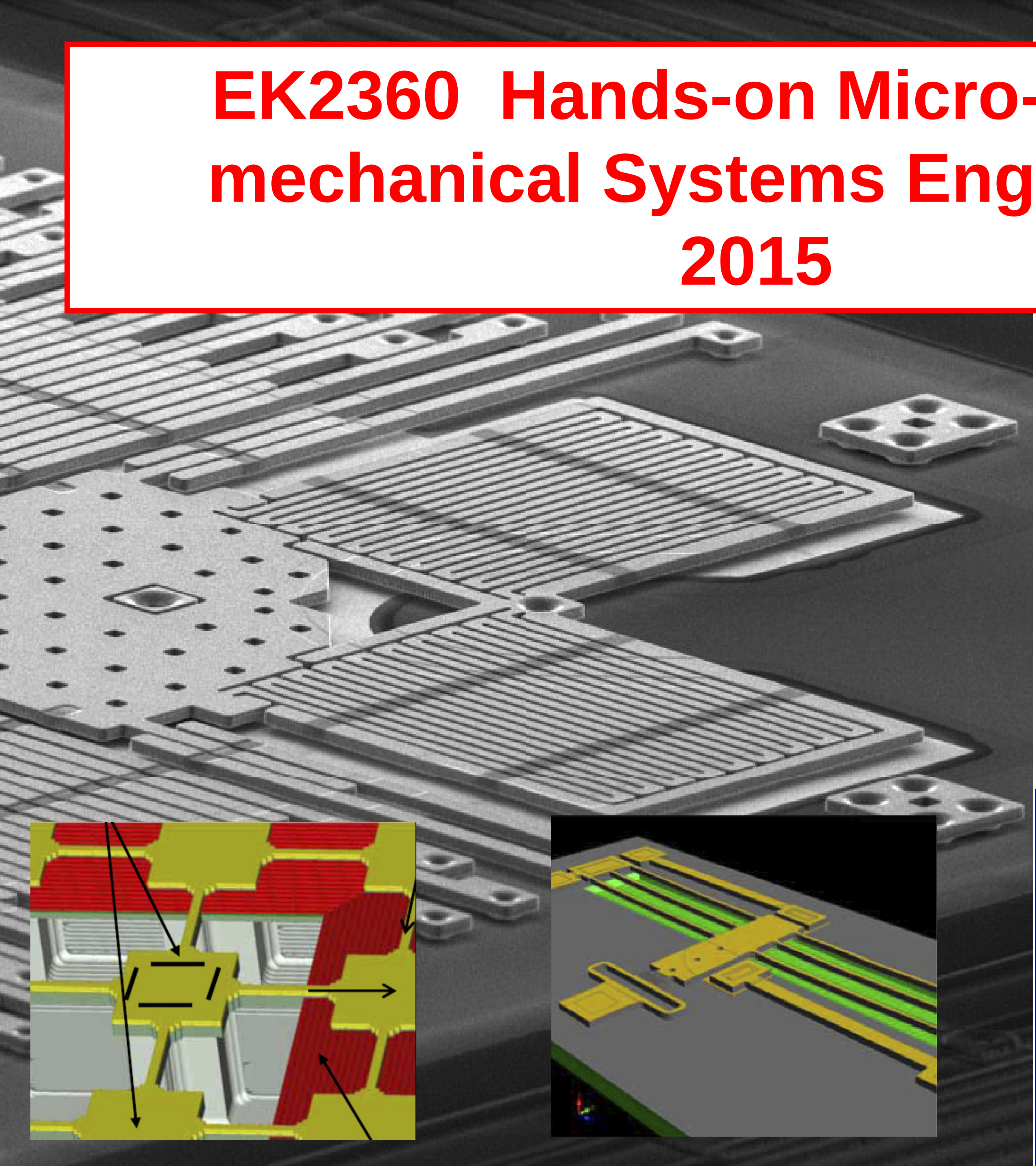
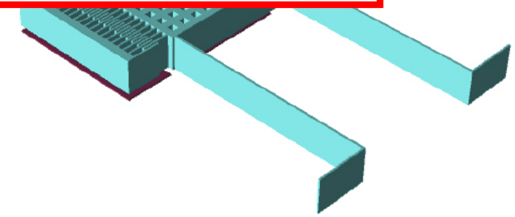
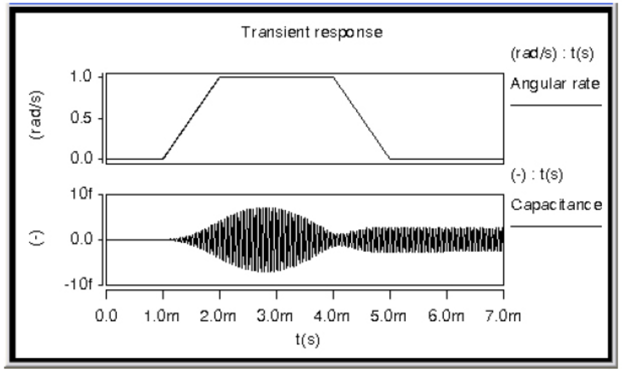
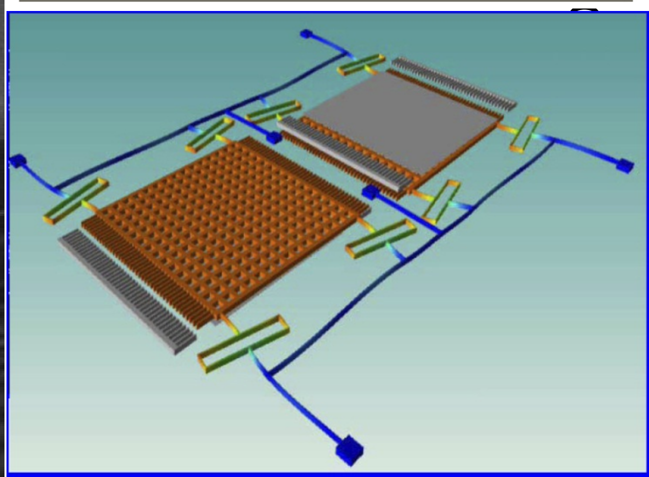
EK2360 Hands-on Micro-Electro-mechanical Systems Engineering 2015

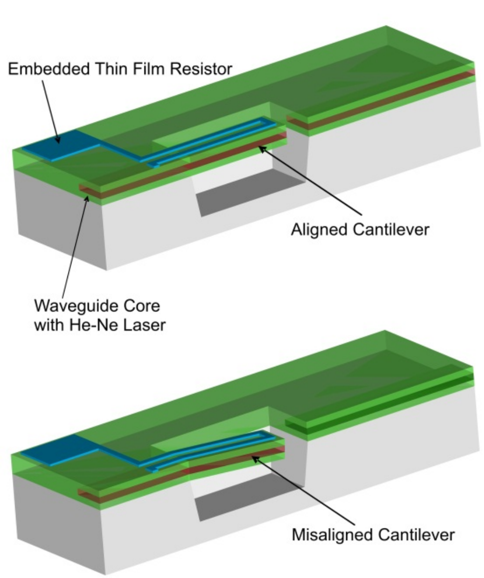


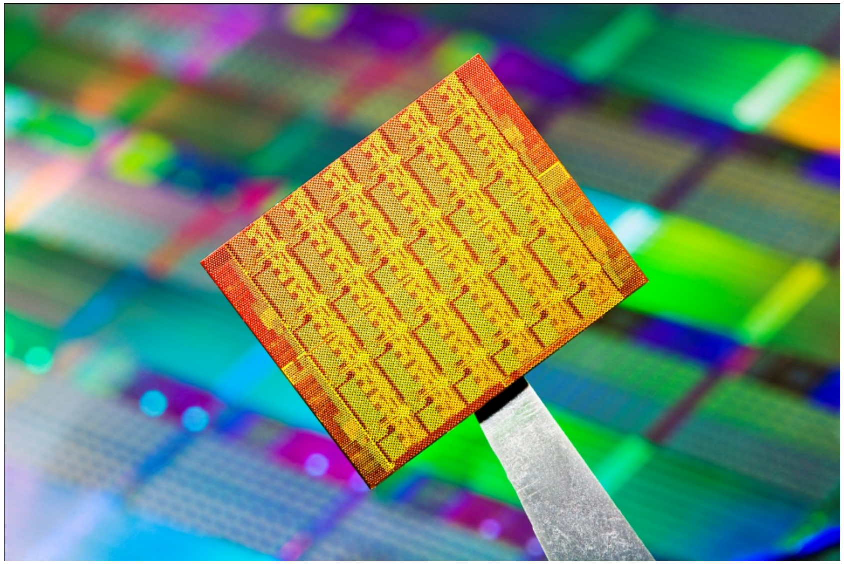


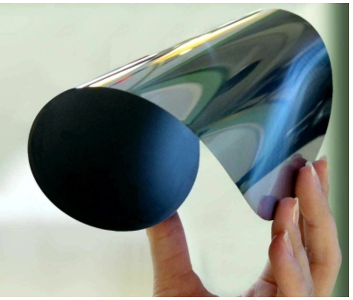


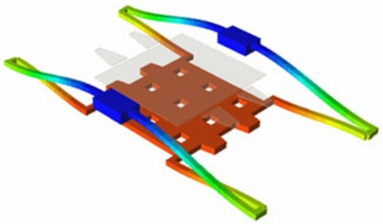


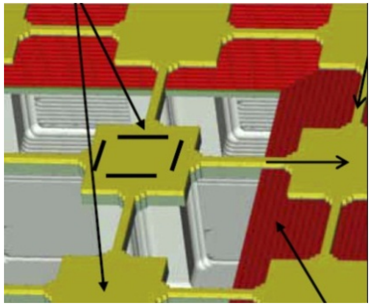
MEMS and Basics of MEMS Actuator Design

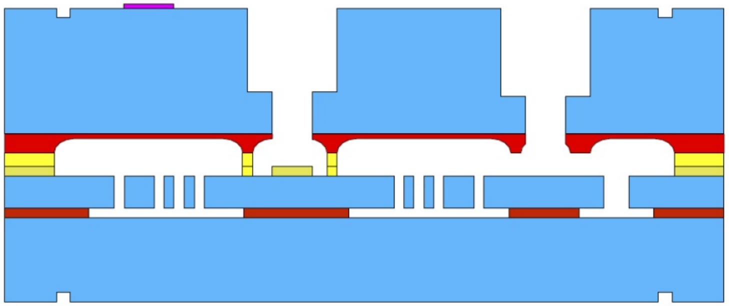


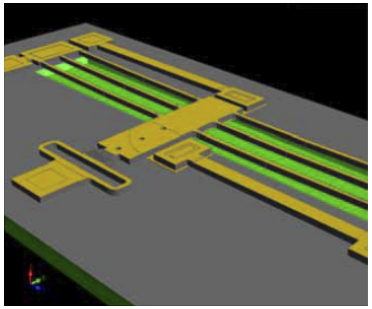












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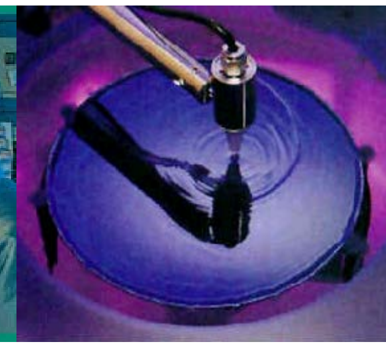
Contents

1. Short introduction to MEMS

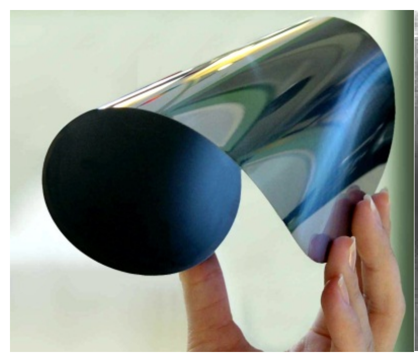
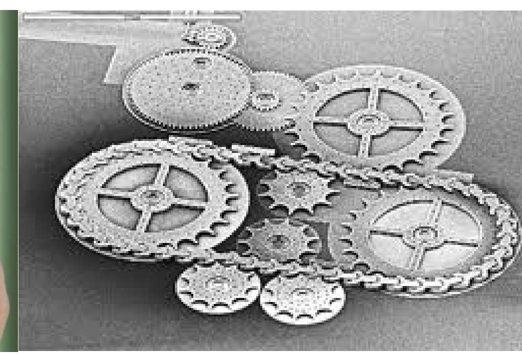
(micro-electromechanical systems)

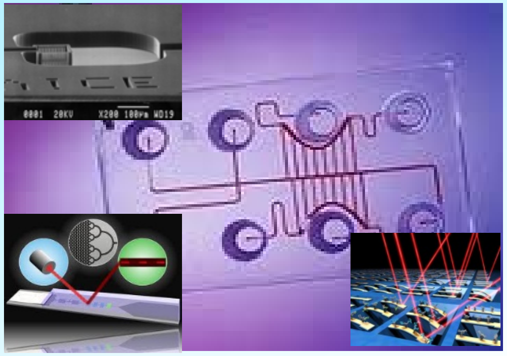
MEMS = micro-electromechanical systems

- **synonyms:** microsystem technology, micromachining
- **origins:** fabrication of microelectronics

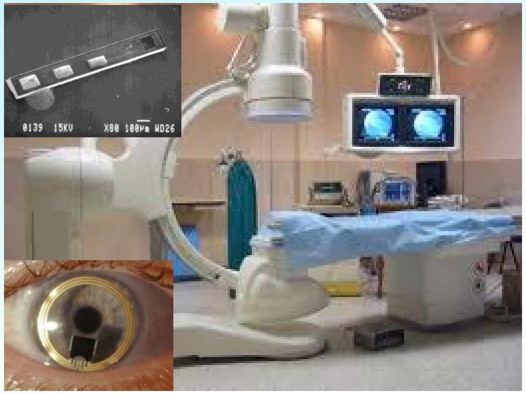




- ”**mechanical**” devices based on semiconductor fabrication processes,
- adding psysical interaction (sensing and actuating) to microelectronics

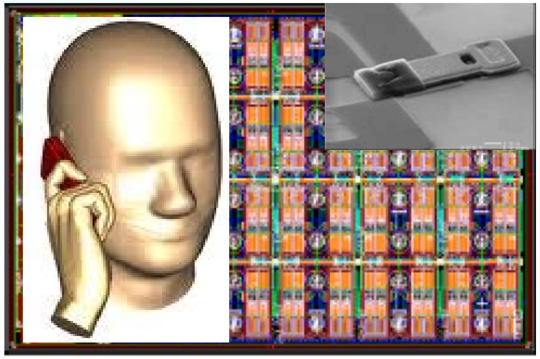





biotechnology (bioMEMS)



medical diagnosis (medical MEMS)



telecom (RF MEMS)

Applications of MEMS

IT-MEMS

microphones

optical MEMS

inertial sensors

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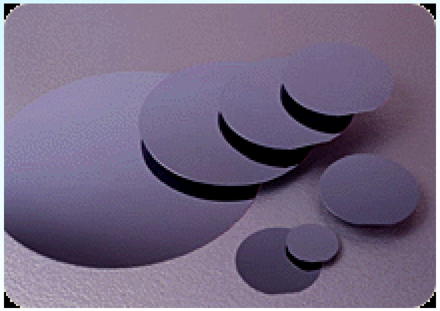
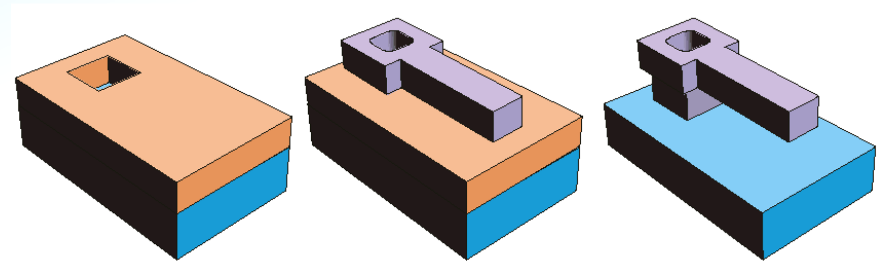
MEMS fabrication methods



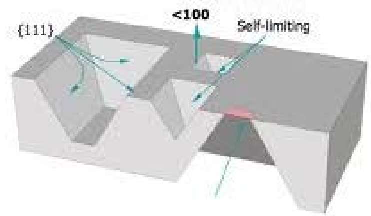
silicon wafers

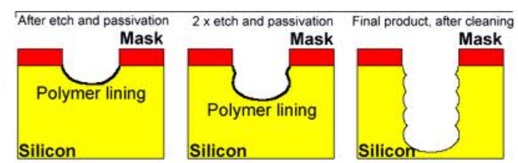
photolithography (sub-mm features!)

- Surface micromachining



- Bulk micromachining

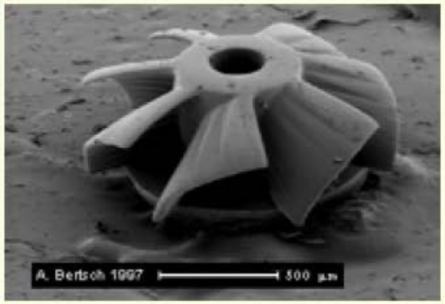




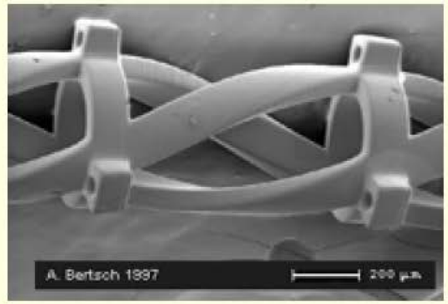
- Packaging/integration (bonding)

- (polymer microfabrication)

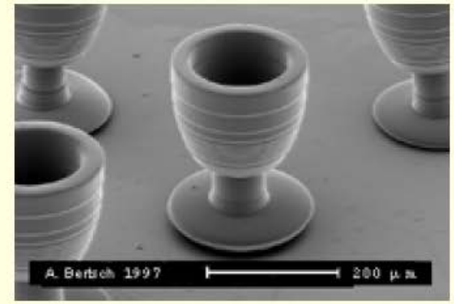
Faszinating (useless?) MEMS



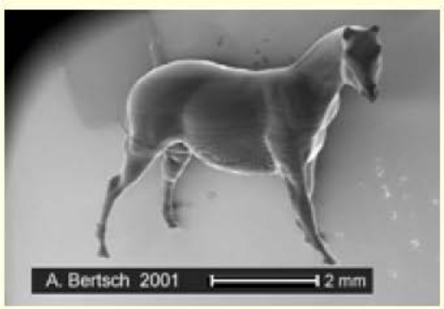
Turbine



Small spring



Small cup

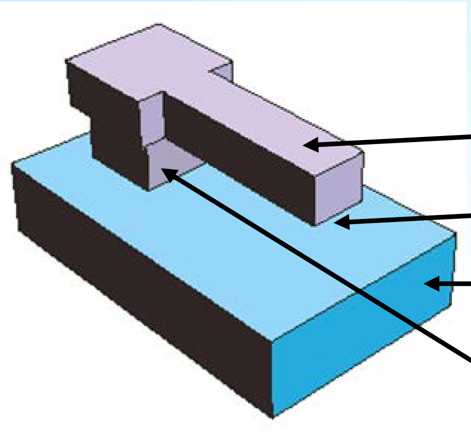


Small horse

Miniature Porsche

Miniature statue of liberity

Which MEMS can we do in this course?

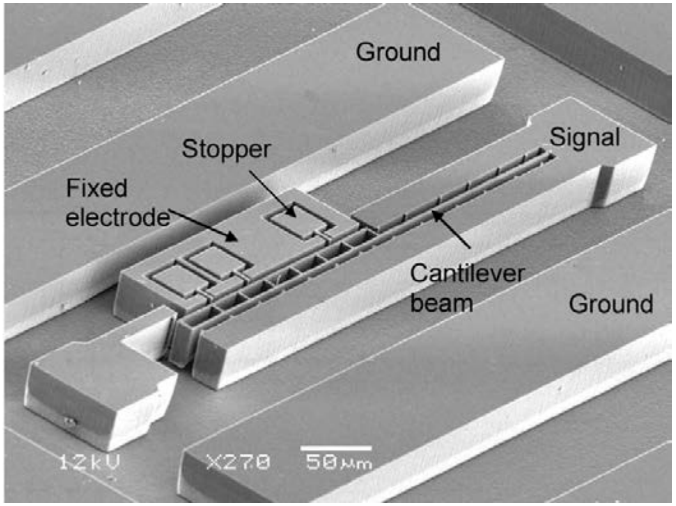


Moveable structure in device layer
Underetched sacrificial layer
Silicon handle wafer (stable base)
Anchor point (connection of moveable structures with handle wafer)

Silicon device layer (30µm)
Oxide sacrificial layer (2µm)
Silicon handle wafer (500µm)

Cross-section of SOI
(silicon-on-insulator) wafer

Underetching silicon structures
in the device layer => free-etched,
laterally moveable structures



2. Introduction to MEMS actuators

Transducers
interacting with environment

Sensors
measuring environment

Actuators
changing environment

measuring physical / chemical / biological properties:

- accelerometers, gyros
- pressure sensors, microphones
- flow sensors
- stress&strain sensors
- biosensors, chemical sensors
- bolometric infrared sensors

active interaction with environment on a micro scale:

- micromirrors
- MEMS switches, tuneable capacitors
- micropumps, microvalces
- HD read/write heads
- microgrippers
- force-feedback sensors

in this course, we do MEMS actuators

MEMS Actuators

- typically consist of:

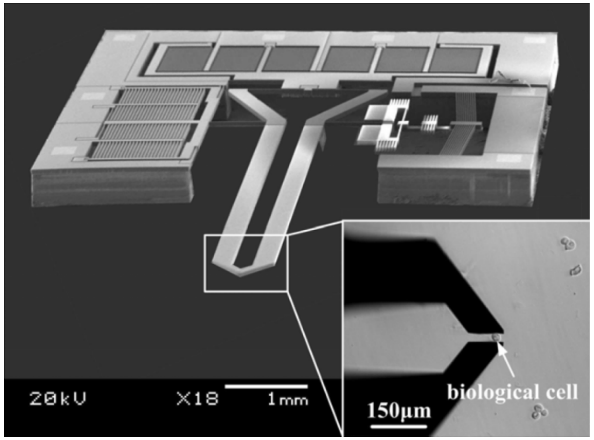
actuation mechanism | **restoring mechanism** | [**feedback mechanism**]

active movement by external energy

usually passive (mechanical spring); latching mechanisms

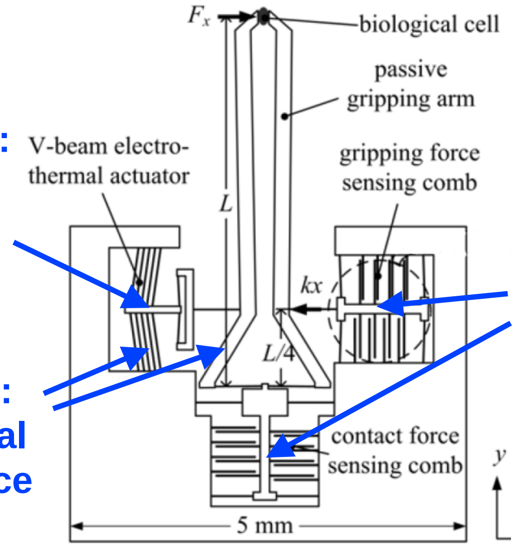
sensing displacement, force, ...

- example: microgripper for manipulation of cells



actuation: thermal actuator (close)

restoring: mechanical spring force (open)

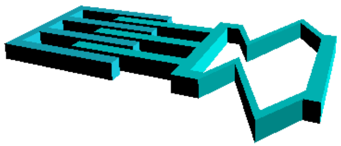


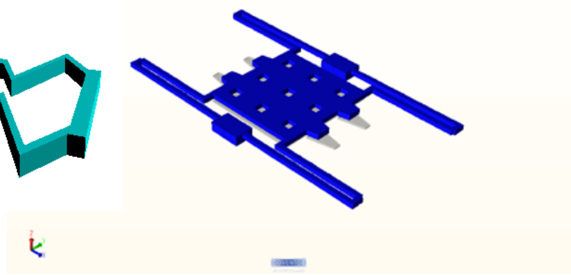
feedback: contact force, gripping force (sense)

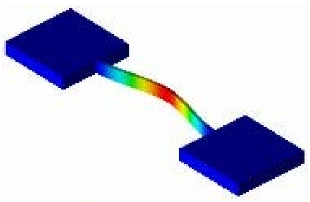
Actuation Principles

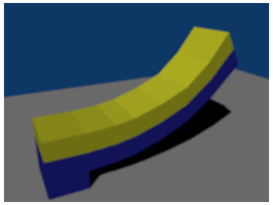
Most common actuation principles:

- electrostatic: Coulomb forces
- electrothermal: thermal expansion
- piezoelectric: charge-induced expansion









Less common actuation principles:
magnetostatic, Lorentz-force, optical forces

All principles have different advantages/disadvantages.

in this course, we'll work with electrostatic actuators

Electrostatic vs. electrothermal

ELECTROSTATIC	ELECTROTHERMAL
small displacement (<5µm)	large displacement possible
very fast (µs)	very slow (ms)
largest force at max. displacement	largest force at no displacement
very low power consumption	very high power consumption
close 100% efficiency	very low efficiency
typically very high voltage needed (20-100V)	low voltage (1-2V) as tradeoff to high current possible
based on Coulomb forces (electrostatic charging)	based on thermal expansion of different materials or temperature differences of same material

3. Electrostatic actuators

Electrostatic force

- **<u>Principle:</u>** Coulomb force:
  A charge in an electric potential gradient experiences a force. => electrodes of different potential are attractive.

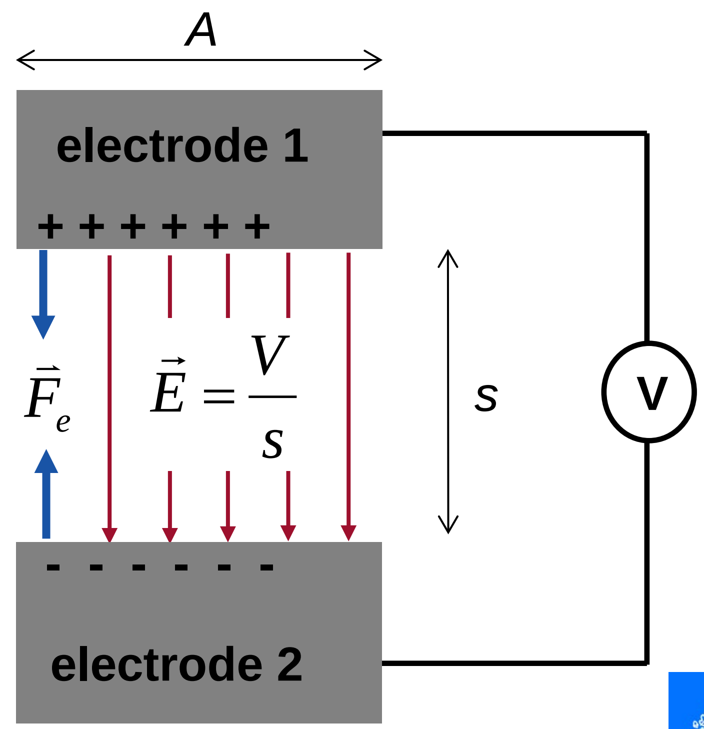
Coulomb force: $$\vec{F} = \vec{E}Q$$

Capacitance: $$C = \varepsilon \frac{A}{s}$$

Electrostatic energy: $$W = \frac{\varepsilon}{2}\left|\vec{E}\right|^2 = \frac{CV^2}{2}$$

Electrostatic force (general): $$\boxed{\vec{F}_{el} = -\frac{dW}{d\vec{s}} = -\frac{1}{2}V^2\frac{dC}{d\vec{s}}}$$

Electrostatic force (specific force (parallel plates): $$\vec{F}_{el} = \frac{1}{2}\varepsilon_0\varepsilon_r A\frac{V^2}{s^2}$$



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Electrostatic actuator concepts

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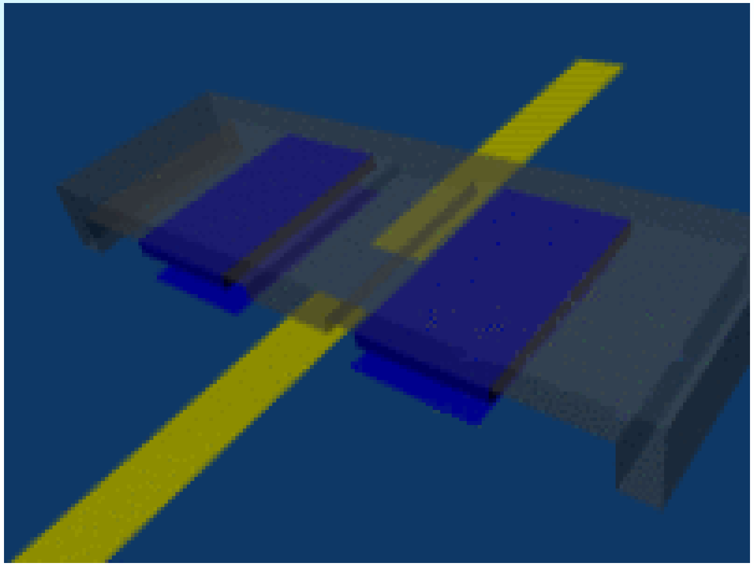
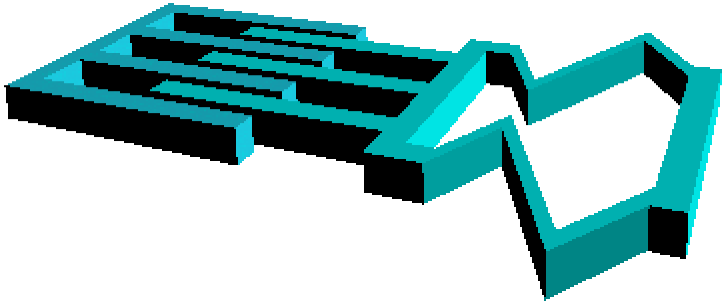


Parallel-plate actuators

typically:
- out-of plane movement
- surface-micromachined
- small displacements (<4µm)
- large forces/area

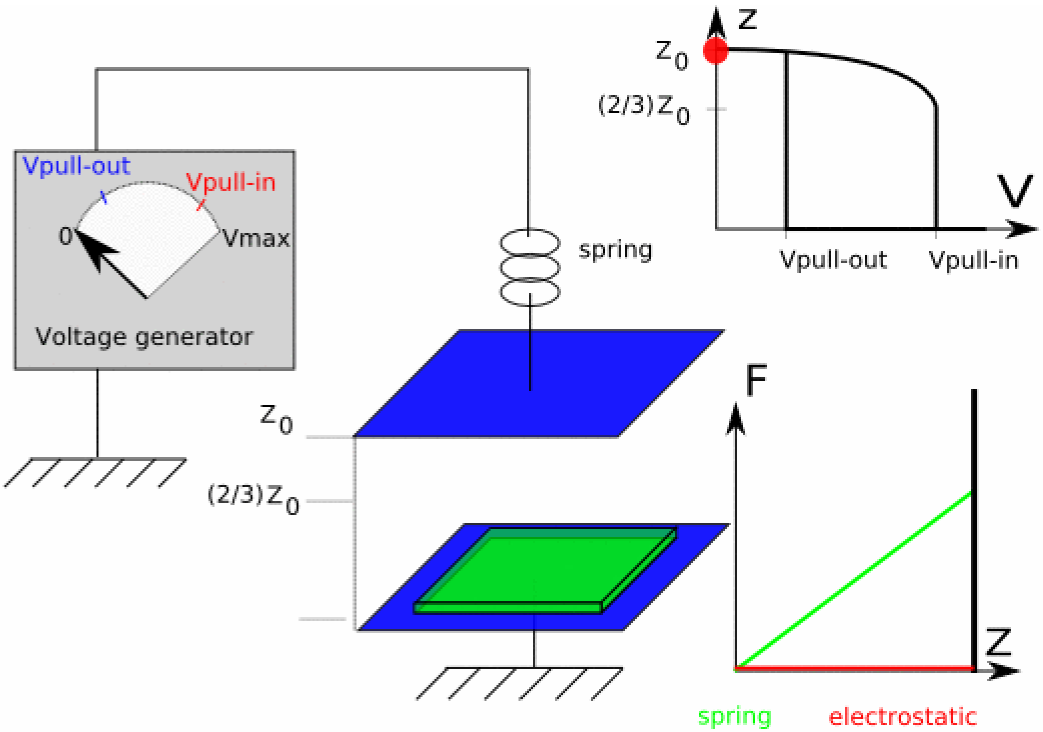


Comb-drive actuators

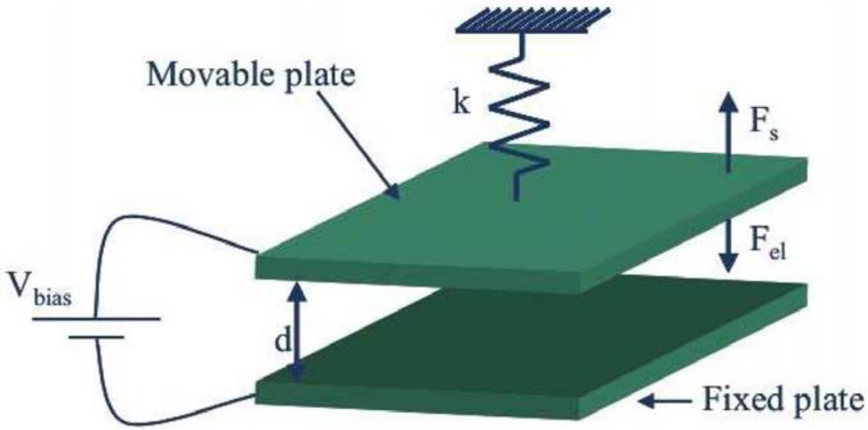
typically:
- in-plane movement
- bulk-micromachined
- large displacements (~30µm)
- small forces/area

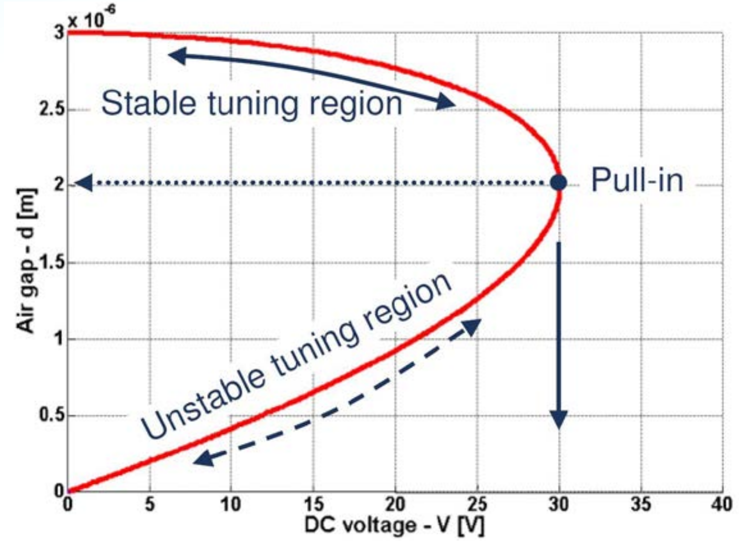
3A. Parallel plate actuators

- active and passive forces detemining the deflection:
  - electrostatic actuation force (active) $$\vec{F}_{el} = \frac{1}{2}\varepsilon_0\varepsilon_r A \frac{V^2}{(s_0 - s)^2}$$
  - restoring spring force (passive) $$\vec{F}_s = -ks$$
- non-linearity => stable and unstable operation regions:



Analog-mode operation





- maximum tuning range with voltage control is 1.5:1, i.e. pull-in will occur if the plate is moved more than 1/3 of the initial gap
- 1/3 is independent on geometry, dielectric layer, voltage !

$$V_{pull-in} = \sqrt{\left(\frac{2}{3}\right)^3 \frac{kd^3}{\epsilon_0 \epsilon_r A}}$$

k...spring constant
d...initial distance
A...electrode area

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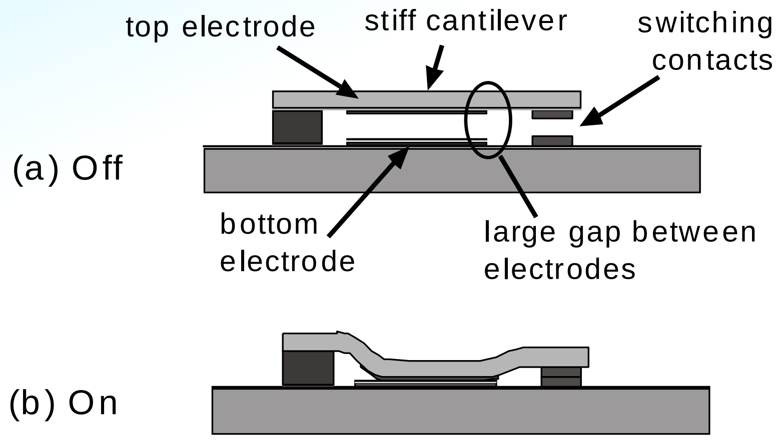
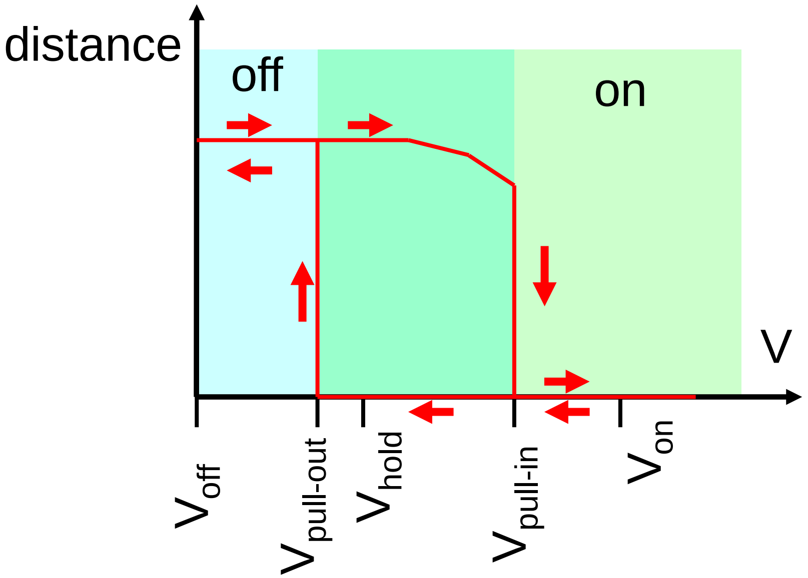
Digital-mode operation

- digital mode: either pulled-in or pulled-out





- $V_{pull\text{-}in} > V_{pull\text{-}out}$
  => hold voltage smaller than turn-on voltage
  => hysteresis effect which makes actuator very robust
  to voltage fluctuations

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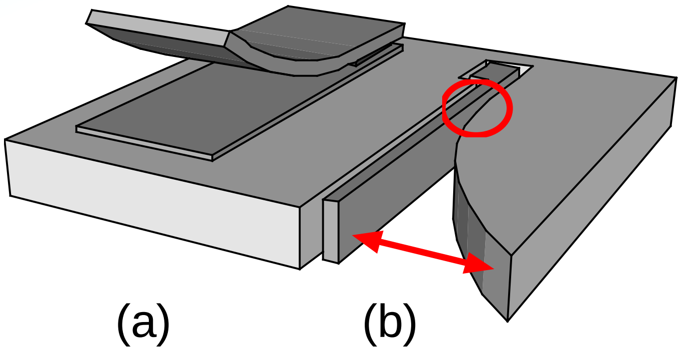
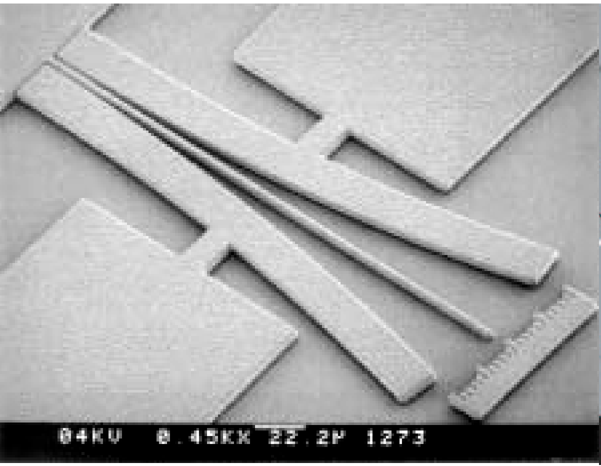
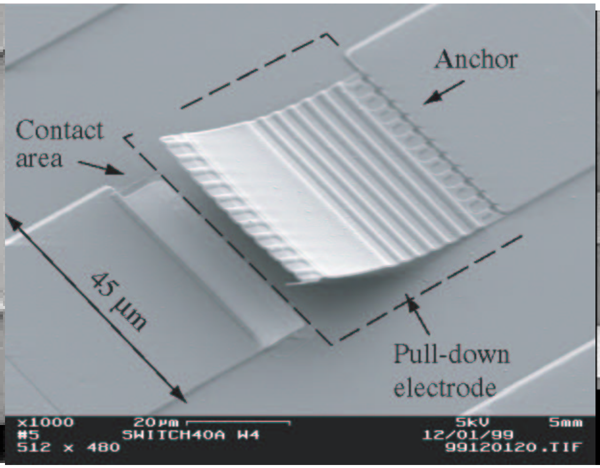
Special parallel-plate actuators: Curved-electrode actuators

- special design of parallel-plate actuator geometry
- other names: touch-mode, moving-wedge, zipper
- characteristics: moving low-distance region of high force
- performance: large displacement at low voltage

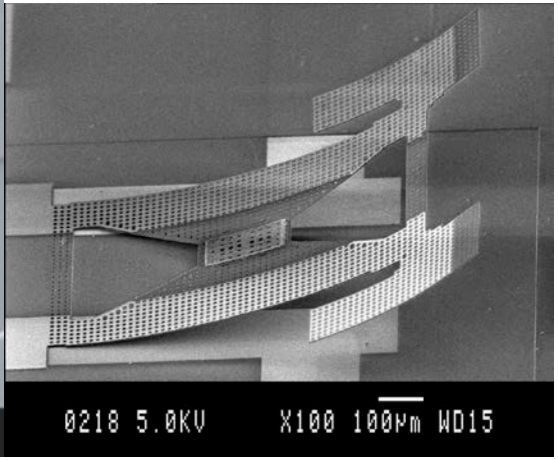




[Lengtenberg, 1997]



[Duffy, 2000]



[Oberhammer, 2003]

Stoppers vs. isolation layers

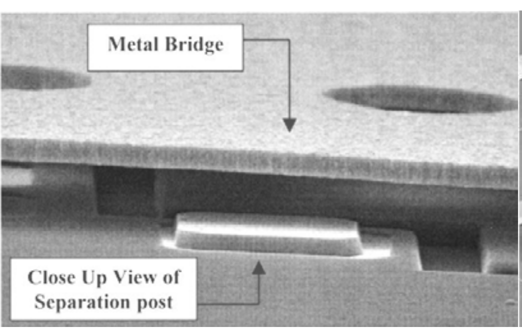
Purpose: preventing electrode short-circuit in pull-in

Stoppers:

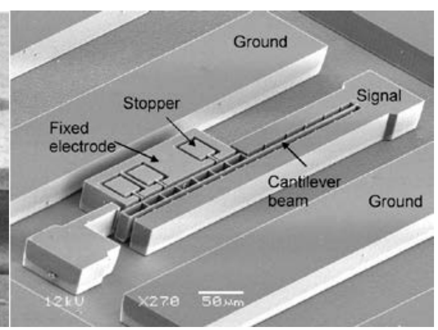
- no dielectric charging, all-metal MEMS devices
- smaller end force
- easy fabrication for in-plane, difficult for out-of-plane actuators

Isolation layers:

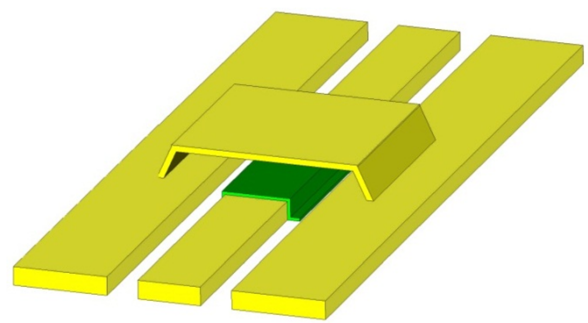
- reliability issues with dielectric charging
- larger end force
- easy fabrication for out-of-plane, difficult for in-plane actuators



stopper in vertical actuator

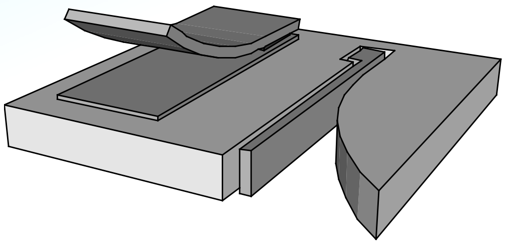


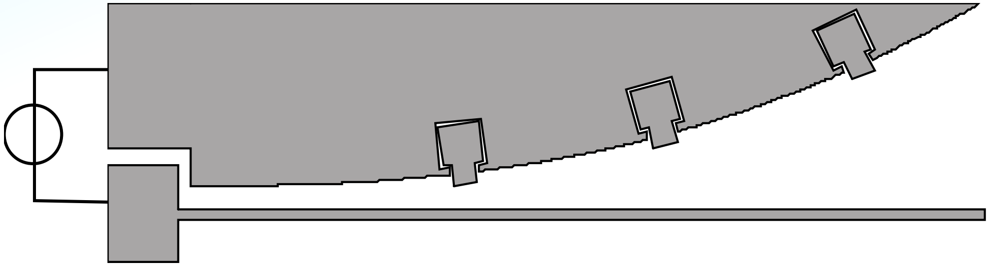
stoppers in lateral actuator

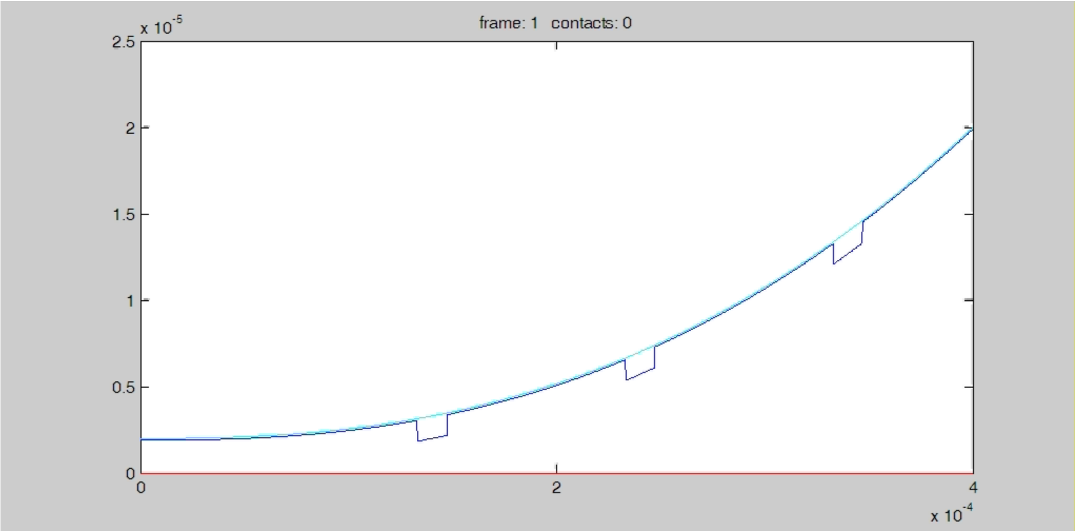


isolation layer in vertical actuator

Example:
Curved-electrode actuator with stoppers







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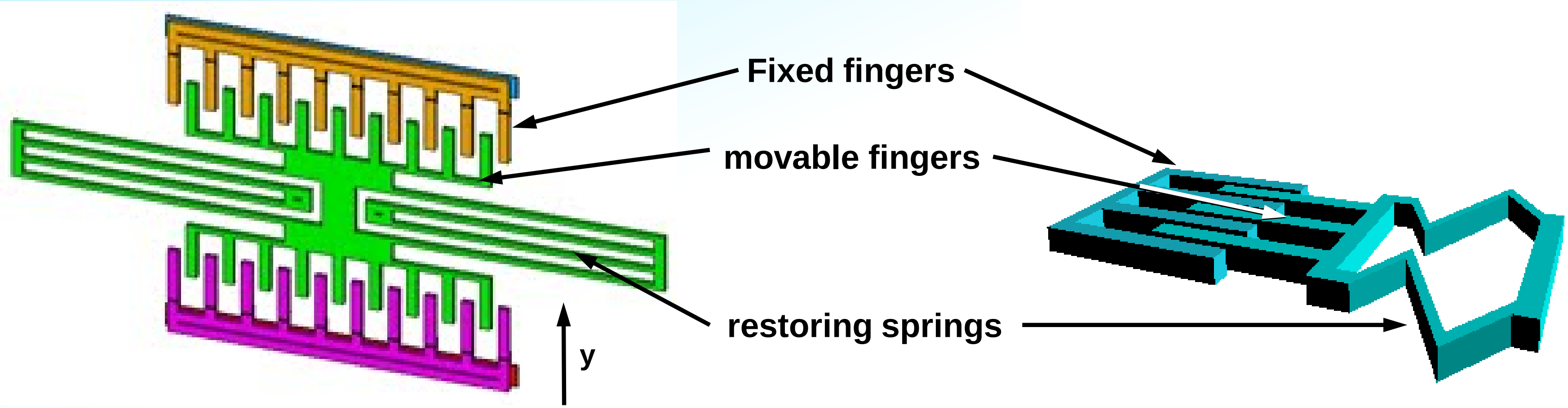
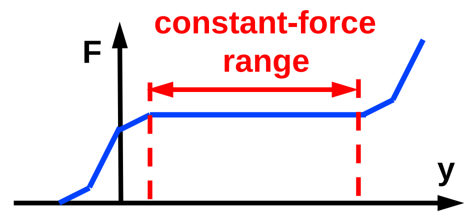
3B. Comb-drive Actuators



$$\boxed{dW = F ds} \quad W_{el-stat} = \frac{1}{2} C V^2 \quad \Rightarrow \quad F = \frac{dW}{ds} = \frac{1}{2} \frac{dC}{ds} V^2$$

- ΔC/Δs konstant over most of the range (even with fringing fields) => constant force actuator



- analytical formula for force estimation (no fringing fields):

$$F \approx \epsilon_0 N \frac{h V^2}{g}$$

F actuation force
N number of combs (1 side)
h height of combs
g distance between fingers
V actuation voltage

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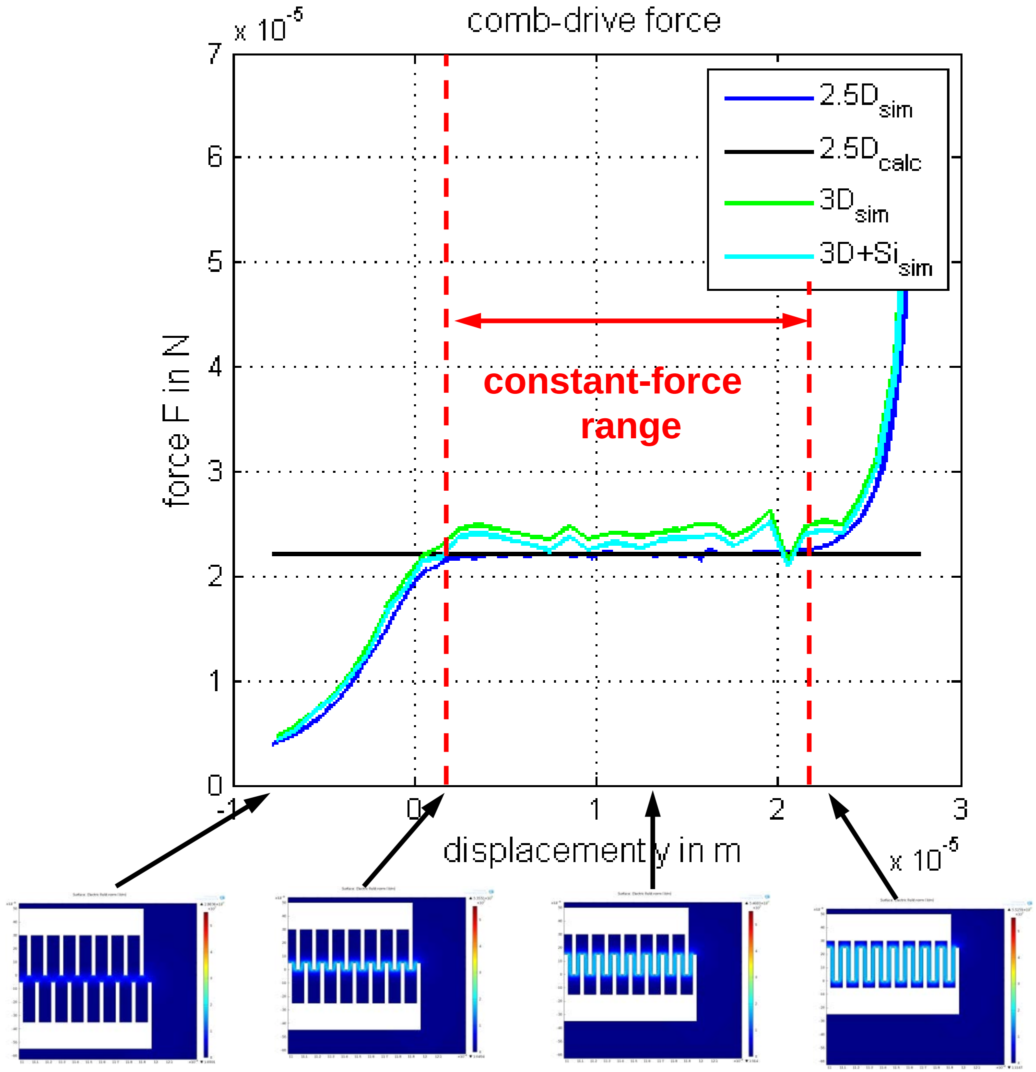
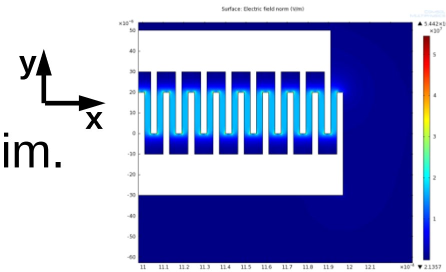
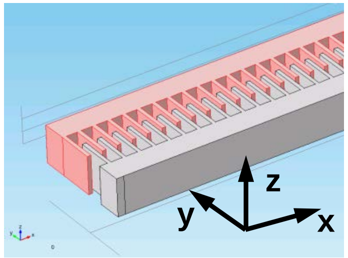
Simulated vs. calculated forces



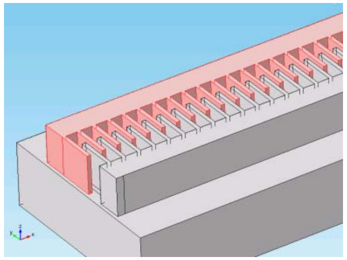
- calculation $F \approx \epsilon_0 N \frac{hV^2}{g}$
- 2.5D sim.



- 3D sim.



- 3D sim. with Si substrate



Parameters:

N=100 V=50V g=3µm h=30µm w=3µm (finger width) L=30µm (finger length)

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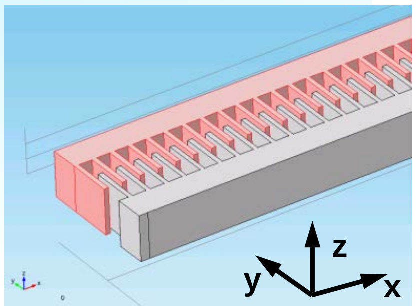
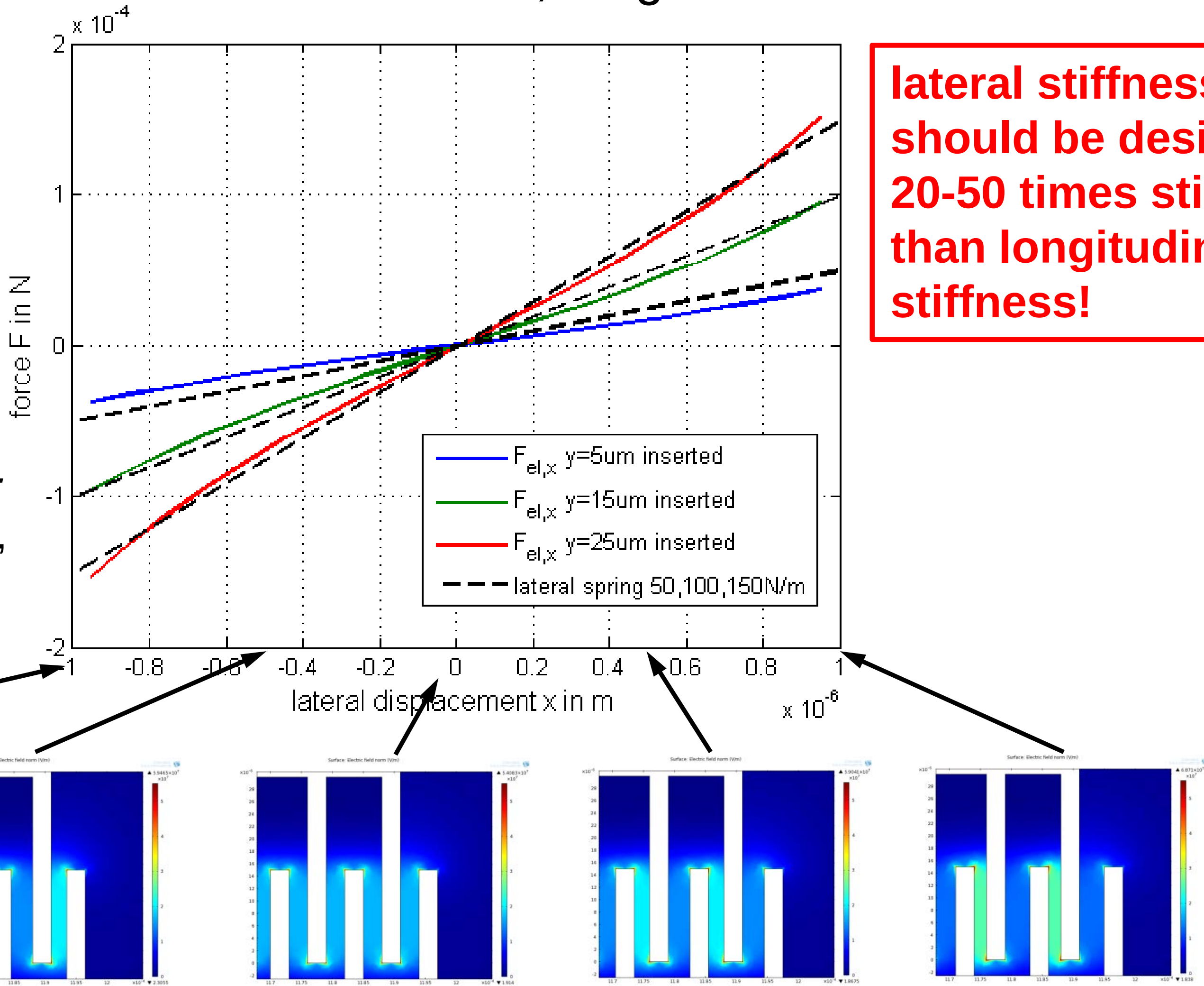
Lateral (in-)stability

- ”wanted” comb movement in longitudinal (*y*) direction
- combs=massive parallel, differential parallel-plate actuators in *x* direction => if unbalanced, large lateral force

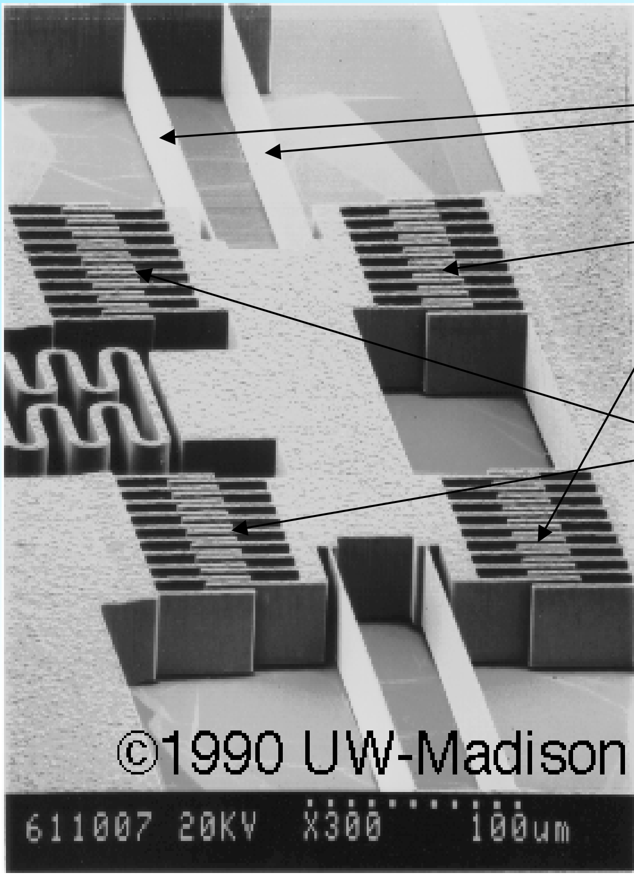




lateral stiffness should be designed 20-50 times stiffer than longitudinal stiffness!

Parameters (2.5D sim):
N=100, V=50V, g=3µm,
h=30µm, w=3µm,
L=30µm, k_y=1N/m

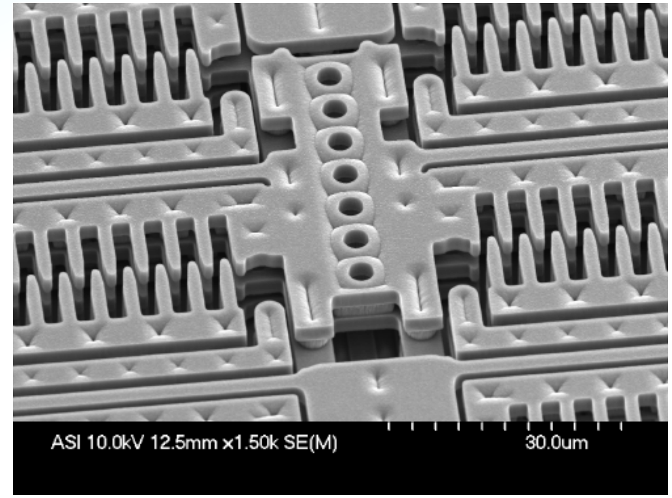
Examples

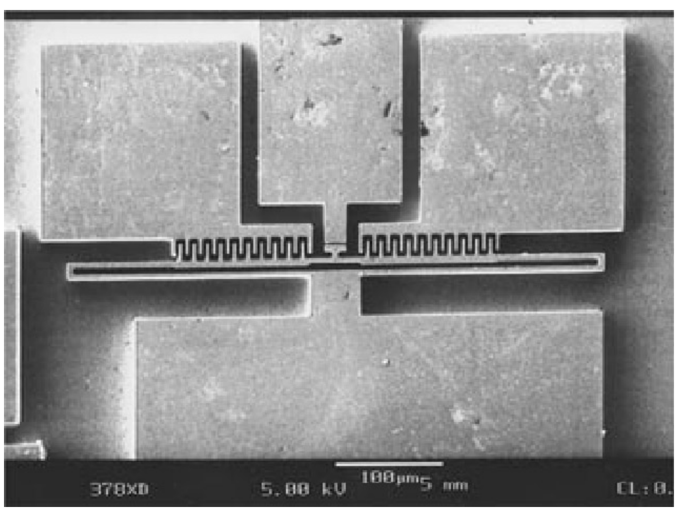


Suspension (springs)

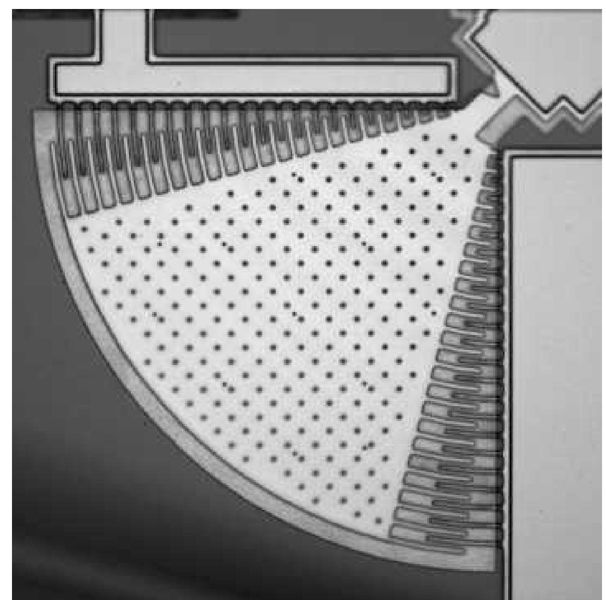
comb drive (pull)

comb drive (push)

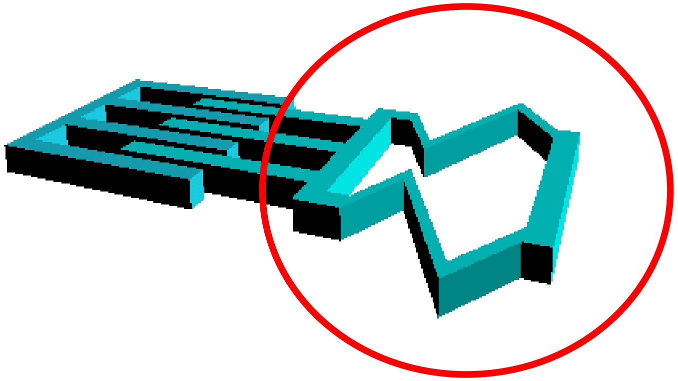




comb drive for angular movement



4. Mechanical-spring restoring mechanisms



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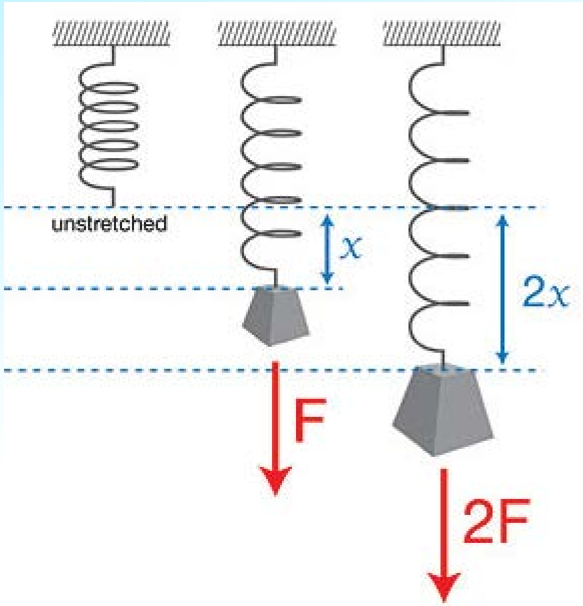
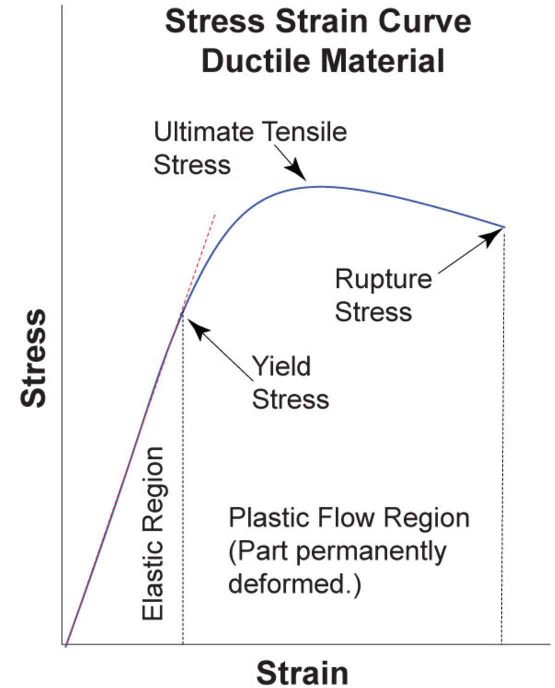
Mechanical Springs: Hook’s law



$$F_s(x) = -kx$$

F .. spring force
x .. displacement
k .. spring constant



- Hook’s law applies only to elastic region of stress/strain
- in MEMS, silicon has near-perfectly lineaer elasticity for stress <1 GPa
- Rule-of-thumb: keep cantilever deflection to a few % of its length => elastic region => linear, long life-time
- FEM software can simulate peak stress in geometry to check whether actuator operation still in linear range

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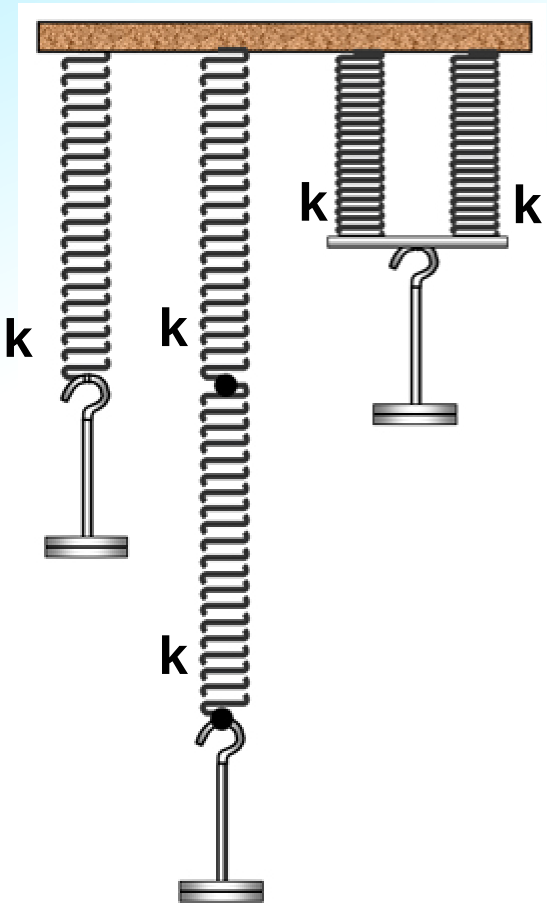
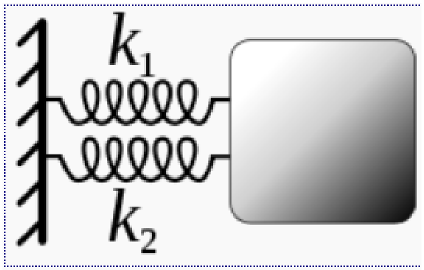
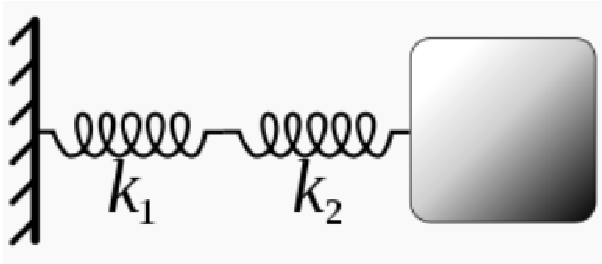
Multiple-spring systems



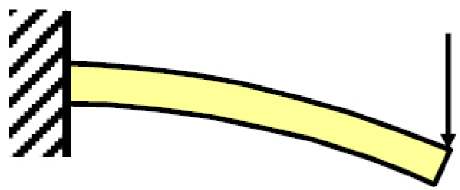
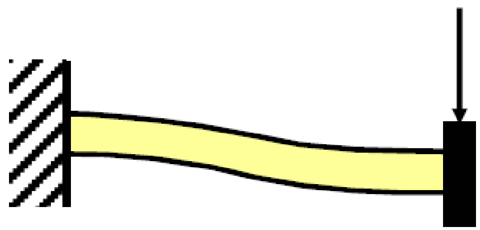
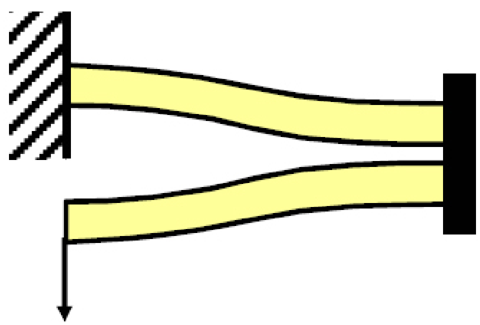


$$k_{eq} = k_1 + k_2$$



$$\frac{1}{k_{eq}} = \frac{1}{k_1} + \frac{1}{k_2}$$

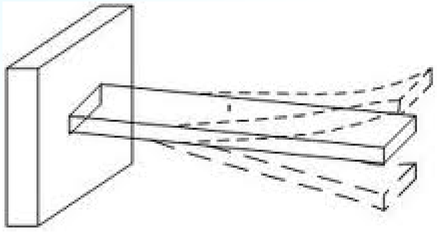
Text-book spring calculations

Type of Beam	Schematic	Spring Constant
Free Cantilever Beam		$k = \dfrac{3EI}{L^3} = \dfrac{EWT^3}{4L^3}$
Guided Cantilever Beam		$k = \dfrac{12EI}{L^3} = \dfrac{EWT^3}{L^3}$
Folded Cantilever Beams for Comb Drives		$k = \dfrac{6EI}{L^3} = \dfrac{EWT^3}{2L^3}$

E .. Young's modulus of elasticity
T .. thickness of the beam
W.. width of beam (out of plane-of-movement)

I .. area moment of inertia (=2nd moment of inertia)
L .. length of beam

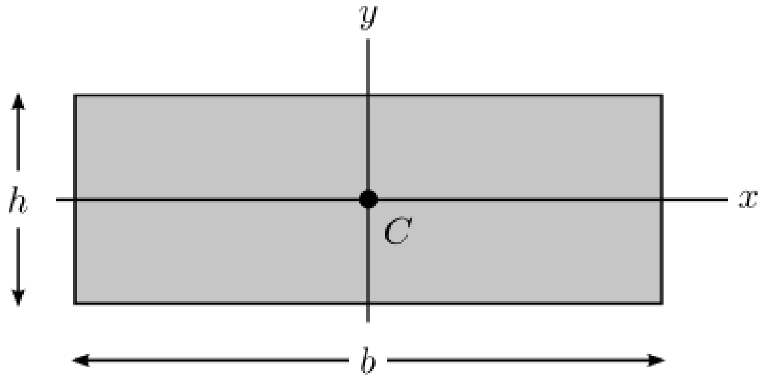
Area moment of inertia of bent cantilevers



- stiffness of a cross-sectional area against bending of an extended structure of that cross-section

$$I_x = \int \int_A y^2 dx dy$$

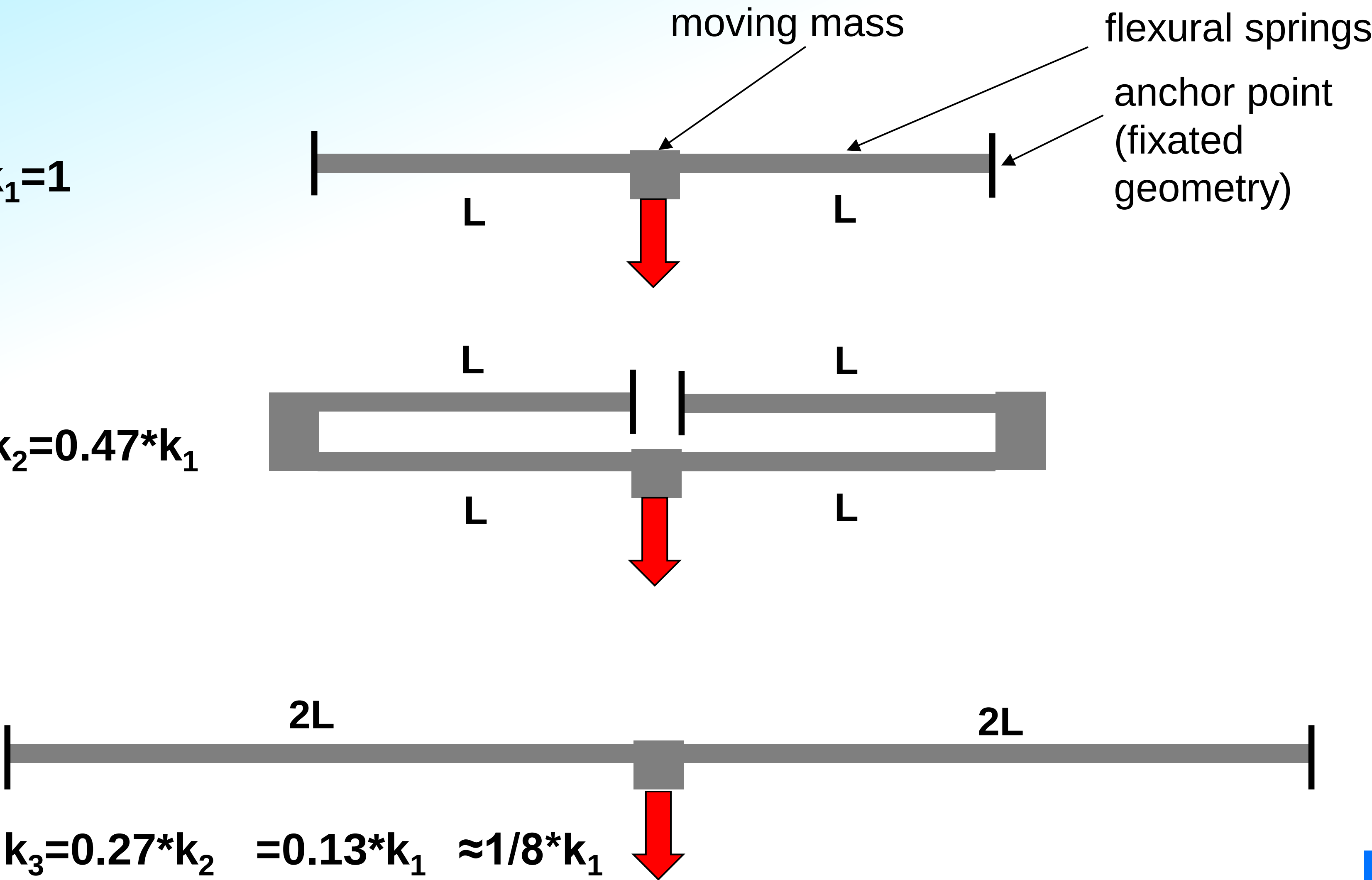
- bending of a rectangular cross-sectional cantilever along *x* or *y* axis:



$$I_x = \frac{bh^3}{12}$$

$$I_y = \frac{hb^3}{12}$$

Folded springs for area efficiency and reducing stiffness



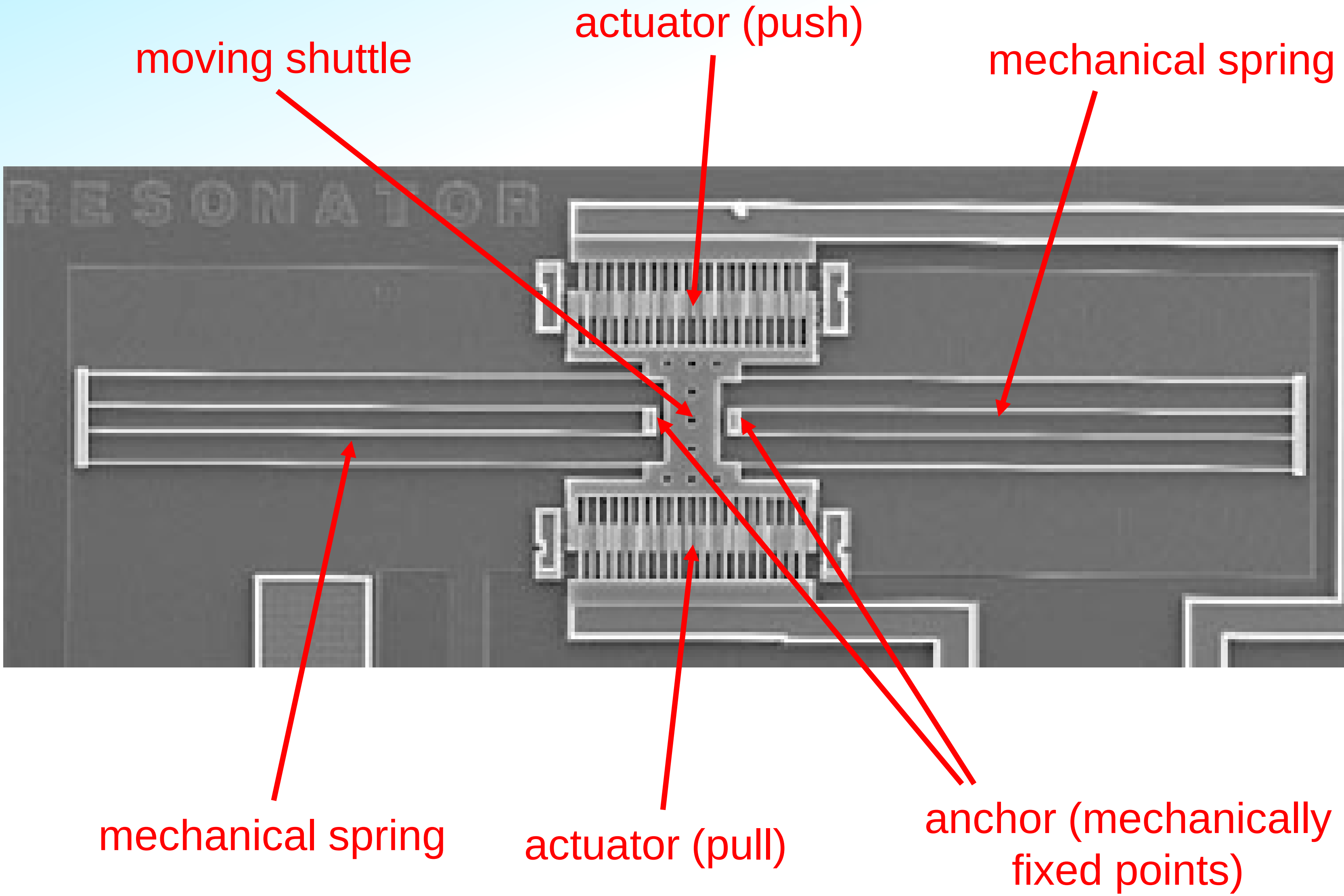
$k_1=1$

$k_2=0.47*k_1$

$k_3=0.27*k_2 \quad =0.13*k_1 \quad \approx 1/8*k_1$

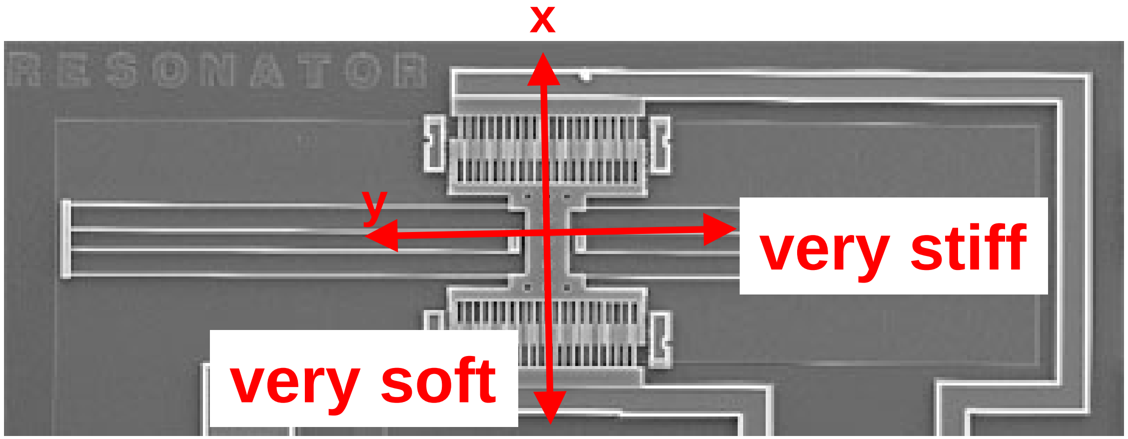
$(k \sim L^3)$

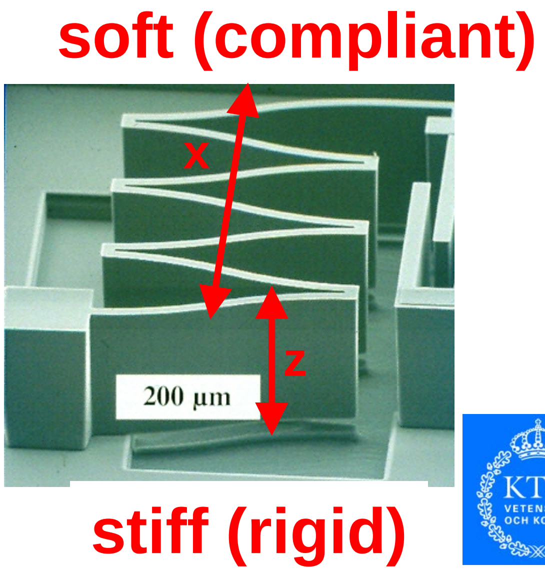
Springs and MEMS actuators



Springs and MEMS actuators

- certain directions of movement are preferred, other directions of movement must be blocked
- mechanical suspension geometry designed for having different spring constants in different directions
- example: comb-drive
  - soft in direction of fingers => favored movement
  - stiff to lateral direction => suppressed movement





- SOI MEMS process (used in this course):
  - spring in z=very very stiff
  - spring in x,y=designed by geometry

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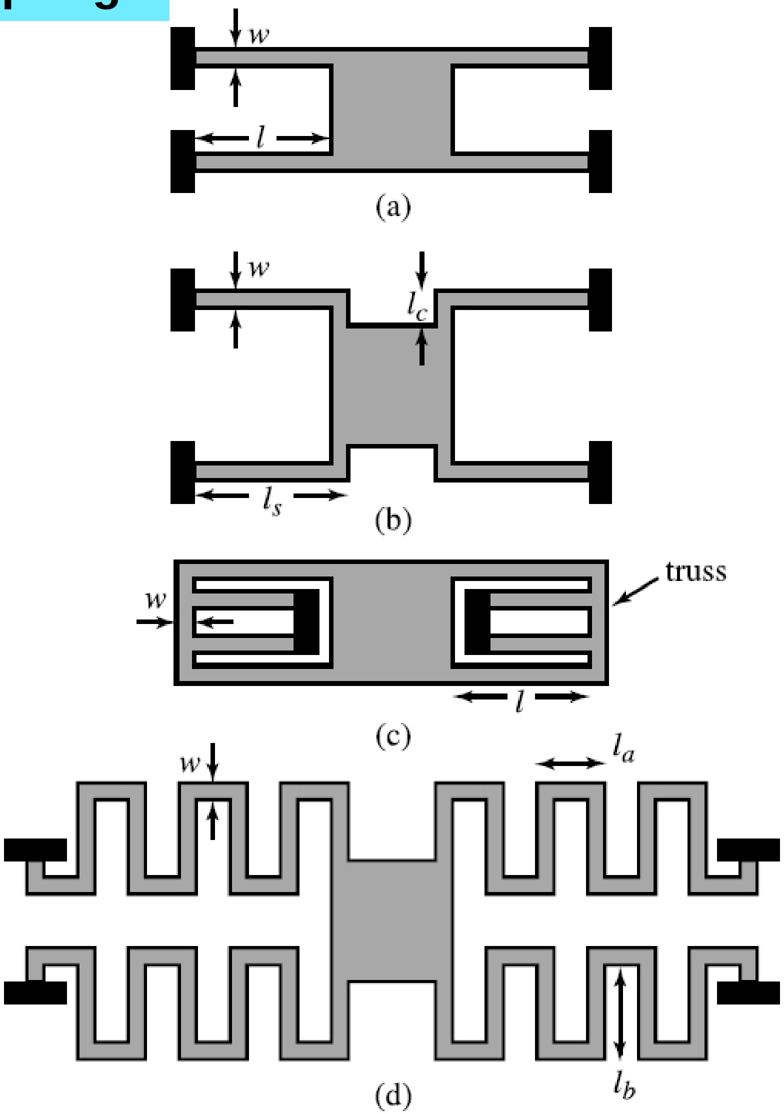
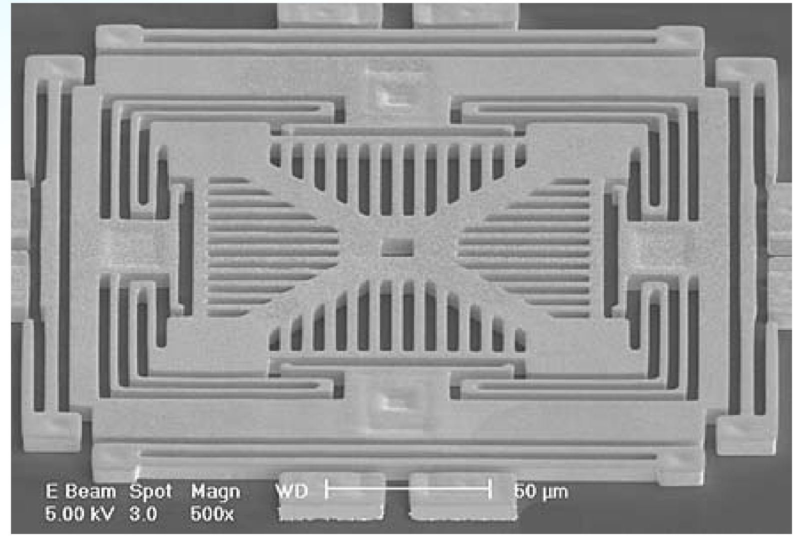
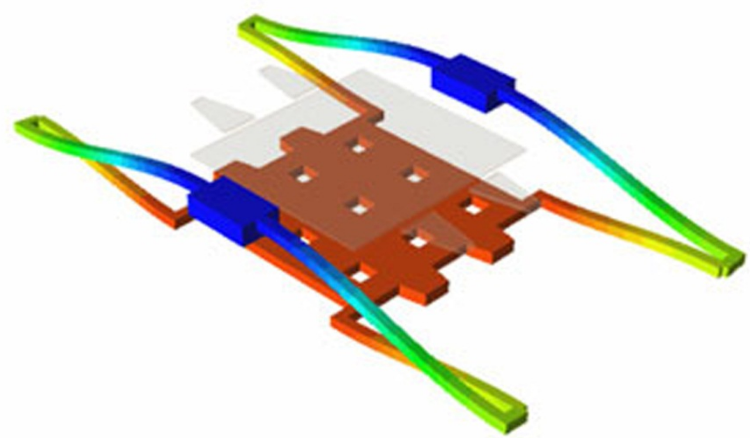
More Examples



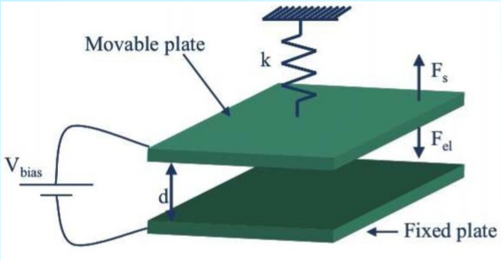


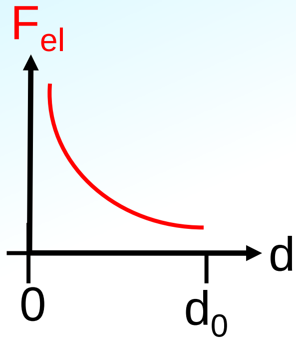


- try to figure out how stiff the different examples are for different directions *x*, *y*, *z*

5. Actuators and restoring mechanisms working together: stable and unstable operation points

Example 1: Parallel-plate actuator



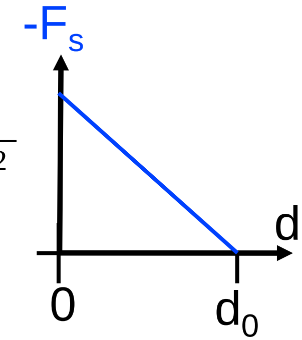


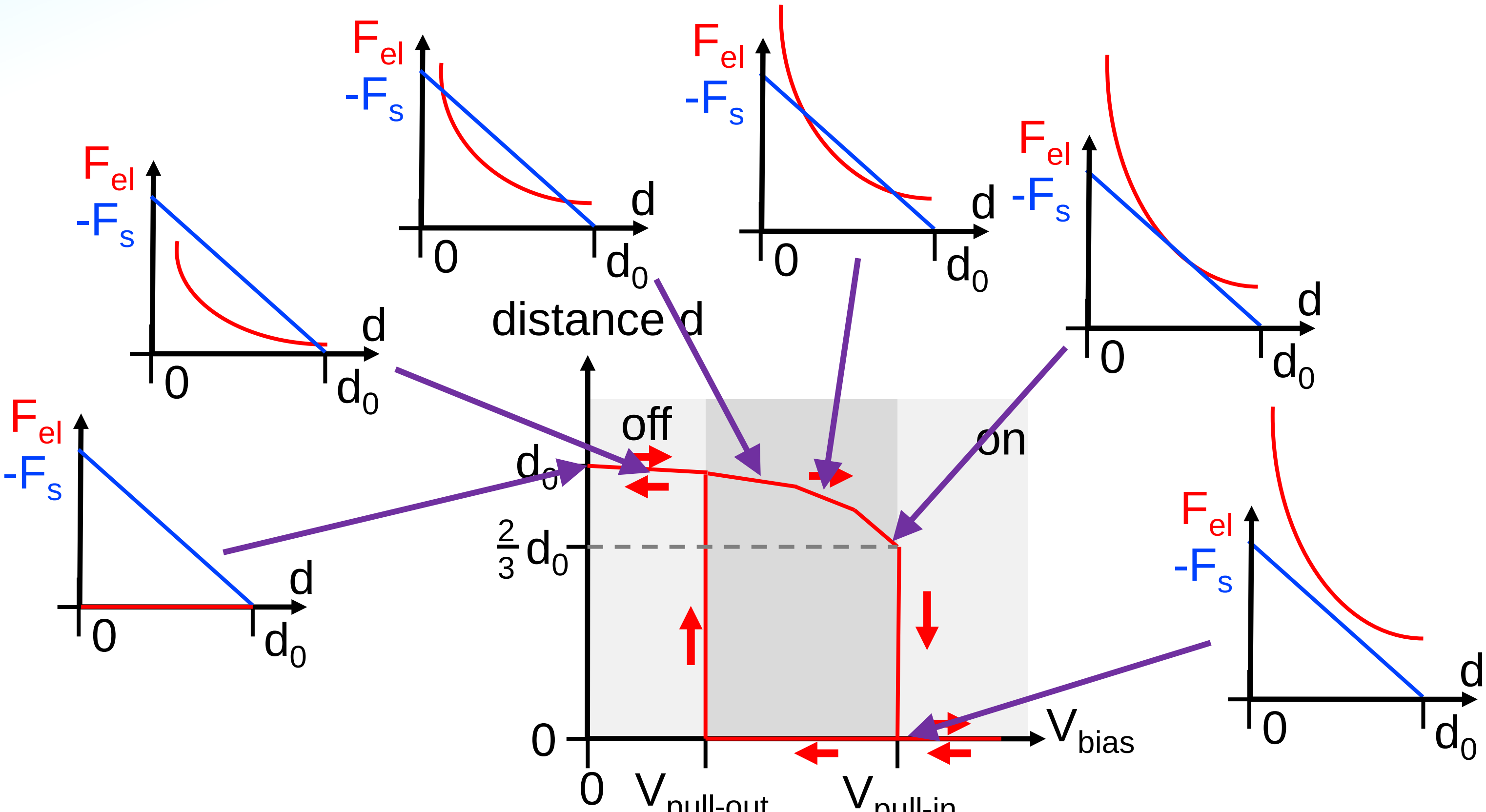
Actuation force:

$$\vec{F}_{el} = \frac{1}{2}\varepsilon_0\varepsilon_r A\frac{V^2}{(s_0 - s)^2}$$

Restoring force:

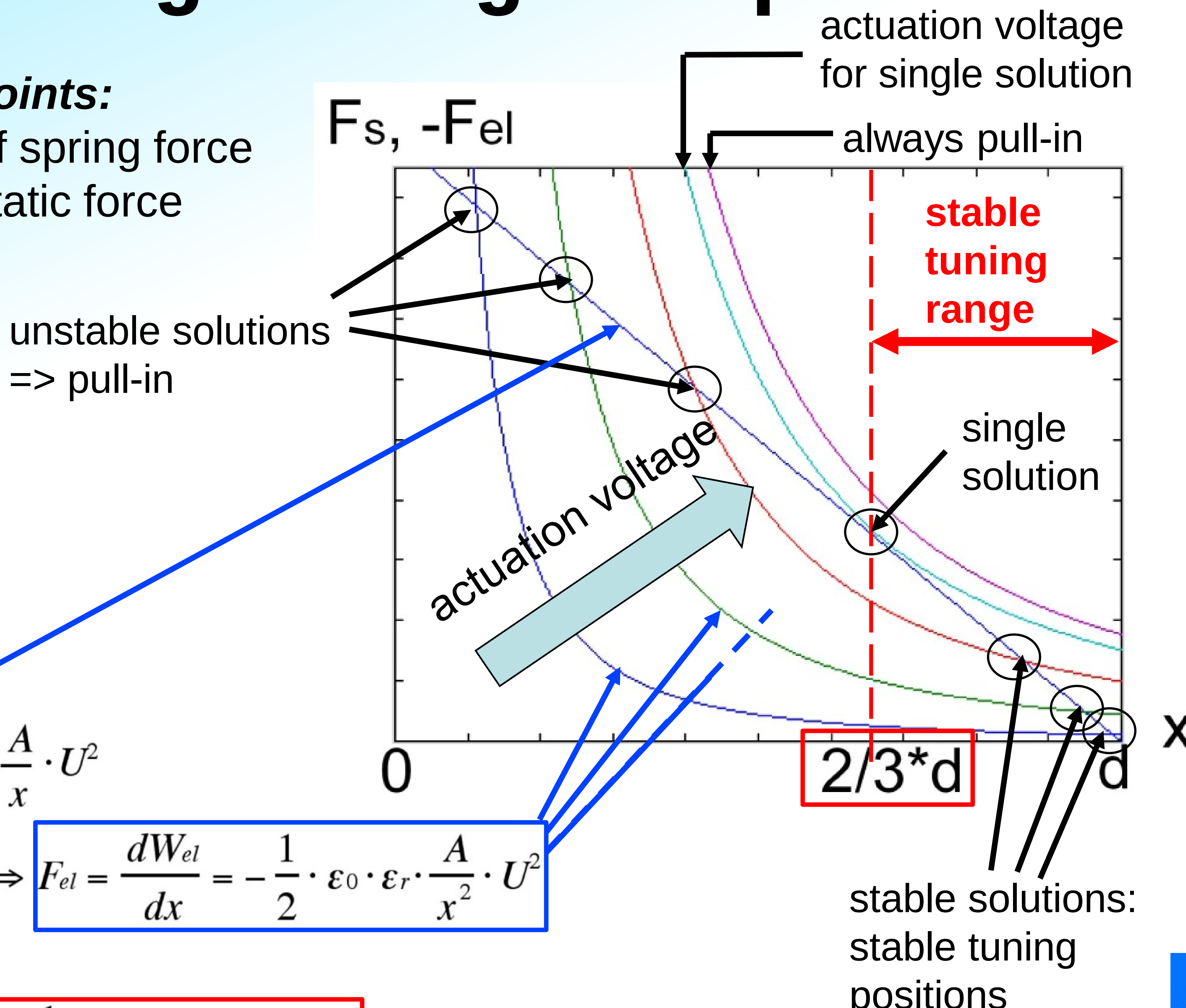
$$\vec{F}_s = -ks$$





Analog tuning and pull-in

Operation points:
equilibrium of spring force with electrostatic force



$$\boxed{F_s = k \cdot (d - x)}$$

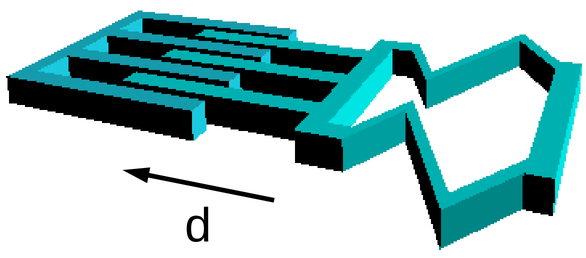
$$W_{el} = \frac{1}{2} \cdot \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{x} \cdot U^2$$

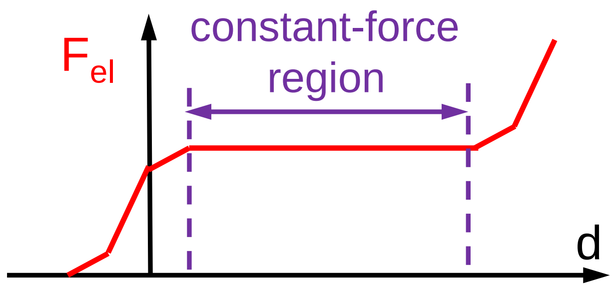
$$dW_{el} = F_{el} \cdot dx \Rightarrow \boxed{F_{el} = \frac{dW_{el}}{dx} = -\frac{1}{2} \cdot \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{x^2} \cdot U^2}$$

$$\boxed{Fs + Fel = 0}$$

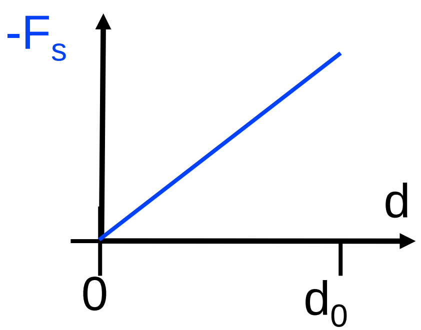
$$\boxed{k \cdot x^3 - k \cdot d \cdot x^2 + \frac{1}{2} \varepsilon_0 \cdot \varepsilon_r \cdot A \cdot U^2 = 0}$$

Example 2: Comb-drive actuator working against mechanical spring





Actuation force



Restoring force

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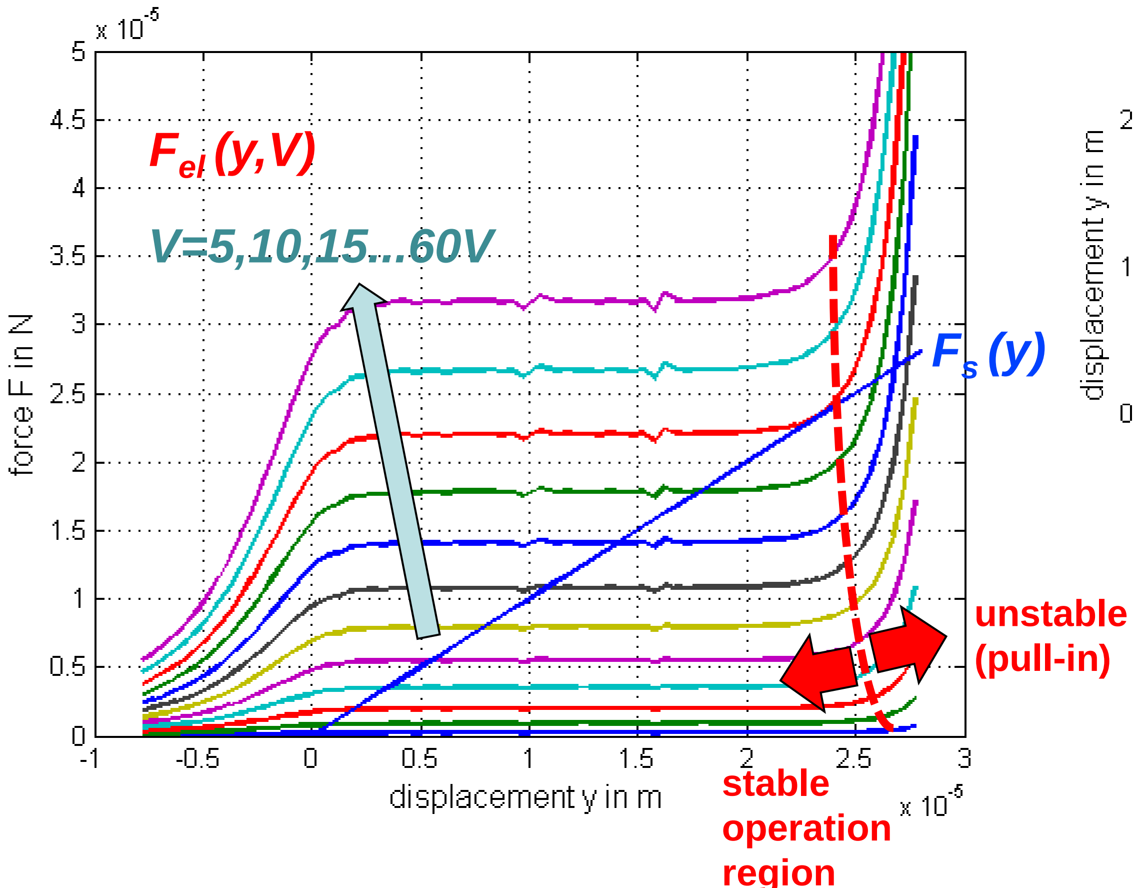
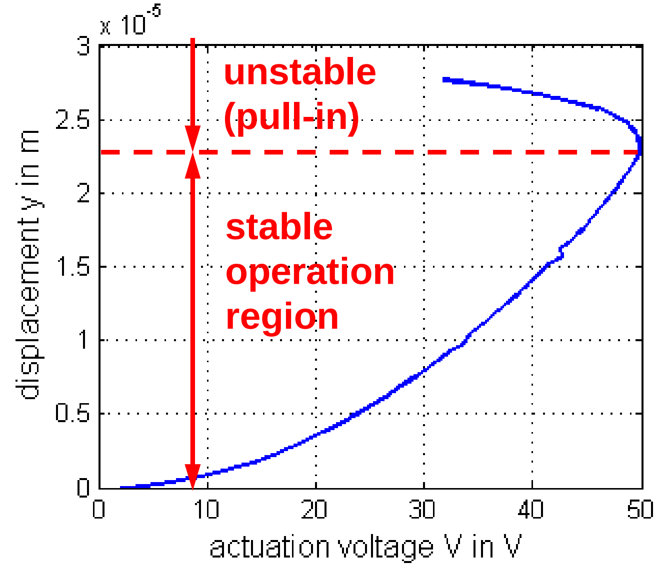
Comb-drive actuator operation points

Force plot:



Displacement vs. voltage:



Parameters (2.5D simulation):

N=100 g=3µm h=30µm w=3µm L=30µm k_y=1N/m

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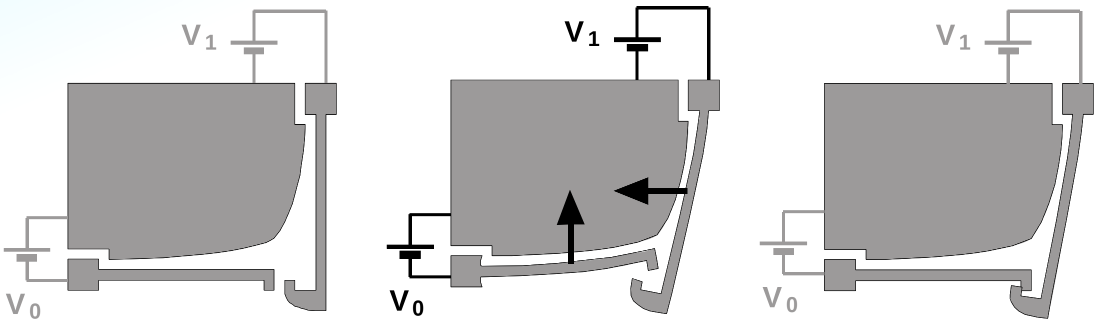
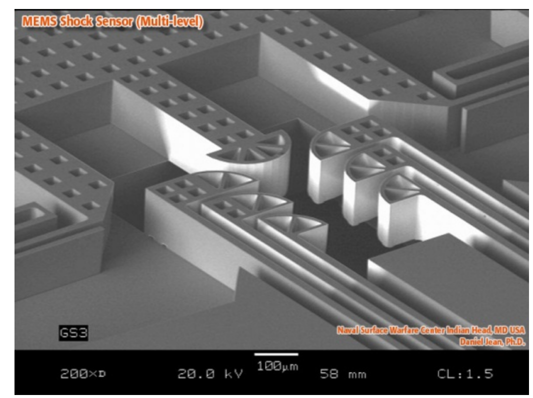
6. Some hints for your project...

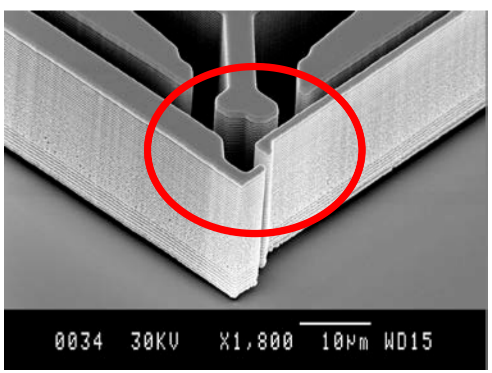
Interlocking Mechanisms

- *mechanically multi-stability:*
  actuator stays in deflected position without applying external energy

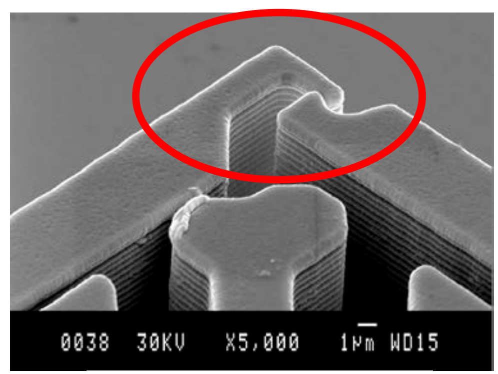


V_0=OFF V_1=OFF V_0=ON V_1=ON V_0=OFF V_1=OFF



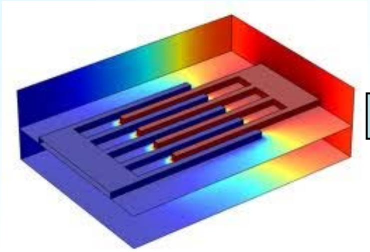


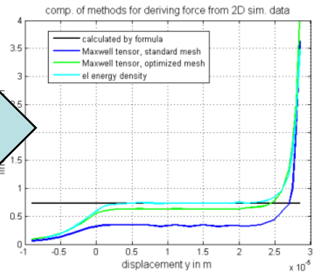
unlocked



interlocked

Deriving electro-static forces in FEM





1. *Solving electrostatic model in FEM software*

Results: - E-potential distribution in the domains (volumes)
- charge distributions on boundaries (surfaces)

2. *Deriving electrostatic forces, 2 methods:*

1. *E-field forces on surface charges (Maxwell tensor):* line integration of (charges*E_n) over boundaries of moving electrode

$$F_{el} = \oint QE_n$$

   Comment*:* less accurate, very sensitive to mesh choice and field singularities

2. *Differential total capacitive energy:* integration of electric energy density over all dielectric domains

$$W_{el} = \iiint_V \epsilon |E|^2$$

$$F_{el} = \frac{dW_{el}}{ds} \approx \frac{\Delta W_{el}}{\Delta s}$$

   Comment: more accurate, less sensitive to mesh settings and field singularities

Mechanical spring design with FEM

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1. choose proper spring geometry according to desired stiffness in different directions, preferred direction of movements, unpreferred directions of movement
2. roughly estimate the stiffness of the chosen geometry with analytical formulas
3. make an FEM model
4. sequentially apply a test force in various axes
5. measure the deflection in the various axes
6. calculate the stiffness in the various axes, by:

$$k_i = \frac{F_i}{x_i}$$

k_i .. spring constant in axis direction $i=\{x, y, z\}$
F_i .. applied test force in direction i
x_i .. simulated result for movement in direction i

7. check the plausibility of the results

(if using point forces be careful that the 2.5D thickness of the mechanical model is properly set in a 2D simulation)

Efficient Actuator Design

- efficiency=optimum usage of time and ressources for fulfilling the design goals
- read, understand specifications; find suitable concepts
- determine basic constellation of actuators/springs
- FEM simulation strategies:
  1. simulate sub-components independently => much more time efficient
     - simulate actuator in different positions, simulate force without deflection
     - simulate parts of actuators (fraction of a comb-drive)
     - simulate restoring mechanism without actuators, apply virtual forces in different directions
     - choose 2D (fast) over 3D (time-consuming)
     - simulate small parts in 3D to get an error estimation of 2D simulations
  2. simulate whole system together
     - very time and ressources intensive
     - gives you final picture of the whole behaviour
- **NEVER TRUST FEM RESULTS! Check plausibility of simplified structures with formulas!**

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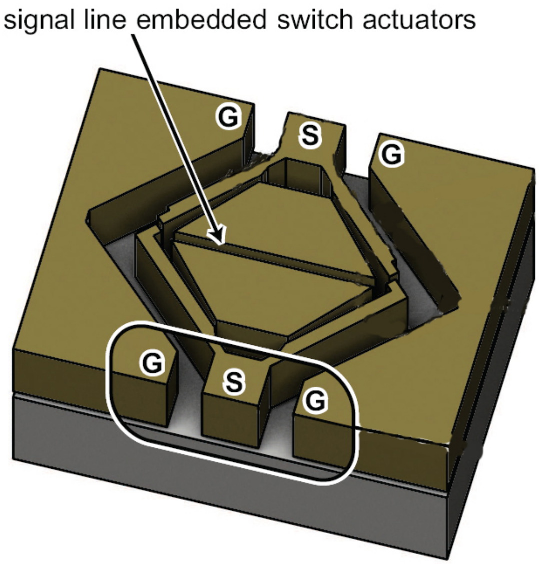
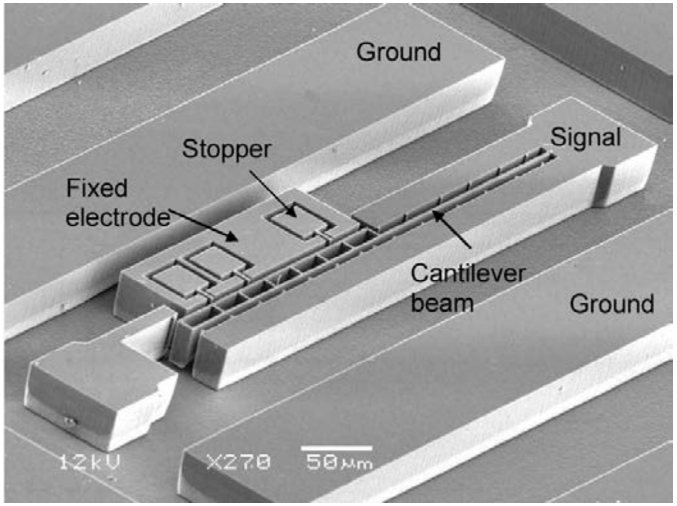
Possible Actuators in EK2360

- technology: SOI MEMS process
  - bulk micromachined structures (etched SOI device layer)
  - metal coated (thin-film technology)

- degree of freedom for moving elements
  - *laterally* moving elements in SOI device layer (lateral stiffness to be designed by lateral device features)
  - vertical movements very very restricted (vertical stiffness given by SOI device layer thickness)

- possible electrostatic actuators:
  - parallel-plate (A1)
  - curved-electrode (A2)
  - comb-drive (A3)
  - reluctance linear (A4)





Questions?