Electrostatic Sensors and Actuators

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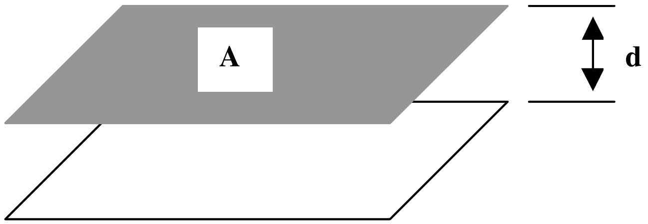
Outline

- Basic Principles
  - capacitance formula
  - capacitance configuration
- Applications examples
  - sensors
  - actuators
- Analysis of electrostatic actuator
  - second order effect - “pull in” effect
- Application examples and detailed analysis

Basic Principles

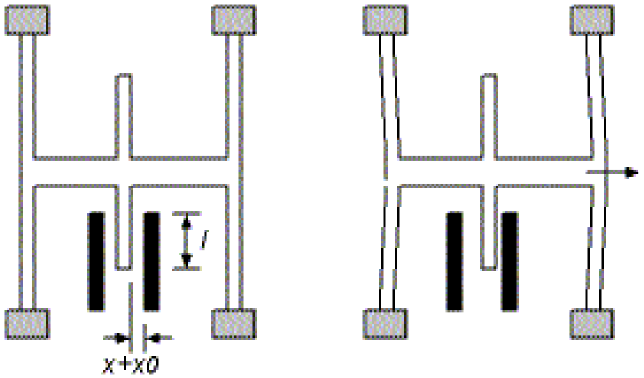
- Sensing
  - capacitance between moving and fixed plates change as
    - distance and position is changed
    - media is replaced
- Actuation
  - electrostatic force (attraction) between moving and fixed plates as
    - a voltage is applied between them.

- Two major configurations
  - parallel plate capacitor (out of plane)
  - interdigitated fingers - IDT (in plane)



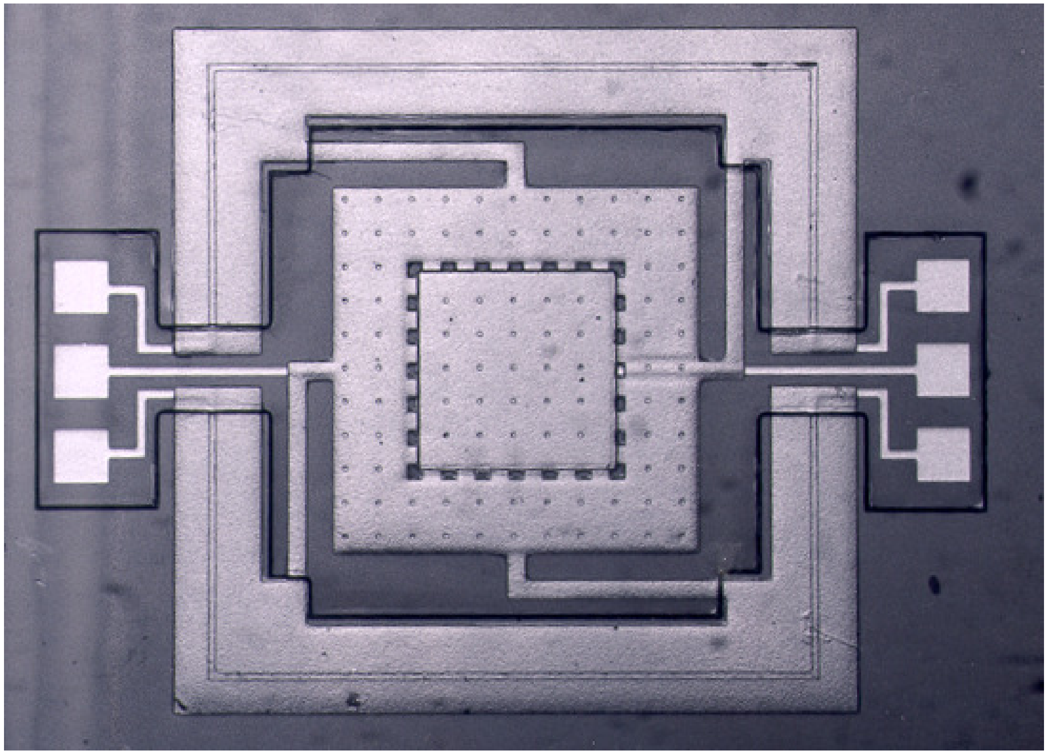
Parallel plate configuration

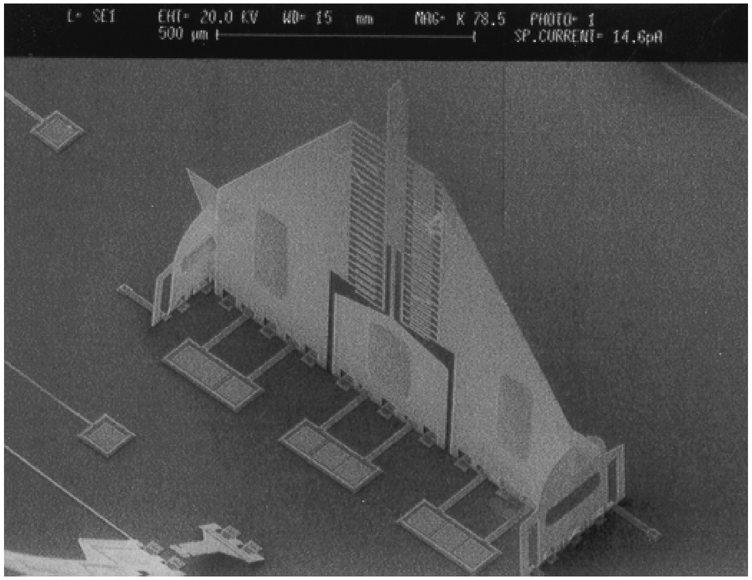
Interdigitated finger configuration

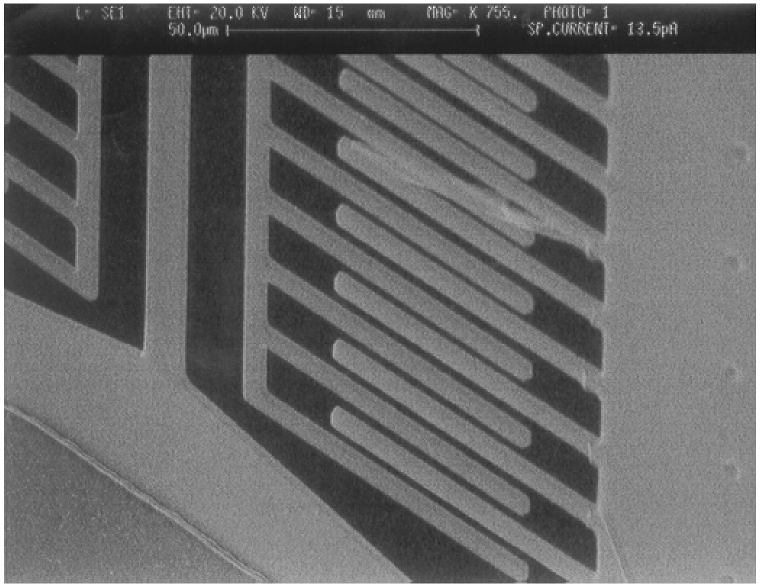


Examples

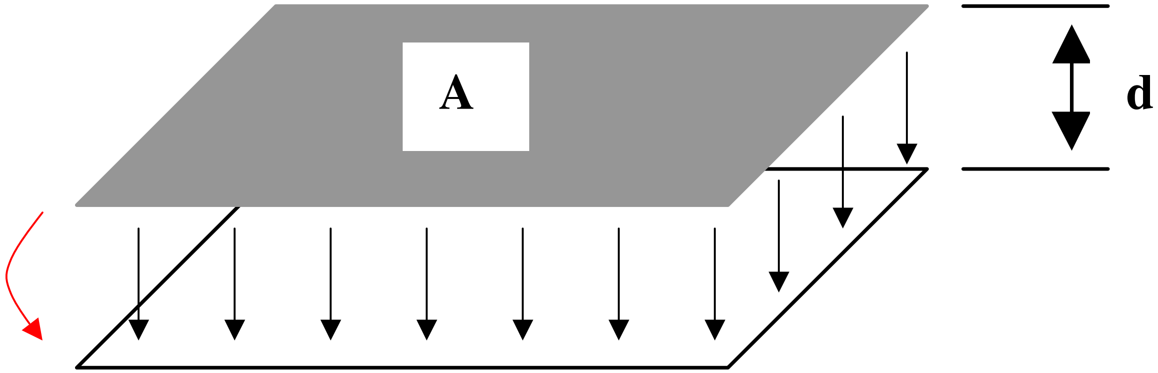
- Parallel Plate Capacitor
- Comb Drive Capacitor







Parallel Plate Capacitor



Fringe electric field
(ignored in first order
analysis)

$$C = \frac{Q}{V}$$

$$E = Q / \varepsilon A$$

$$C = \frac{Q}{\frac{Q}{\varepsilon A} d} = \frac{\varepsilon A}{d}$$

- Equations without considering fringe electric field.
- A note on fringe electric field: The fringe field is frequently ignored in first-order analysis. It is nonetheless important. Its effect can be captured accurately in finite element simulation tools.

Forces of Capacitor Actuators

- Stored energy $E = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$
- Force is derivative of energy with respect to pertinent dimensional variable $F = \frac{\partial E}{\partial d} = \frac{1}{2}\frac{\partial C}{\partial d}V^2$
- Plug in the expression for capacitor $C = \frac{Q}{\frac{Q}{\varepsilon A}d} = \frac{\varepsilon A}{d}$
- We arrive at the expression for force $F = \frac{\partial E}{\partial d} = -\frac{1}{2}\frac{\varepsilon A}{d^2}V^2 = -\frac{1}{2}\frac{CV^2}{d}$

Relative Merits of Capacitor Actuators

Pros

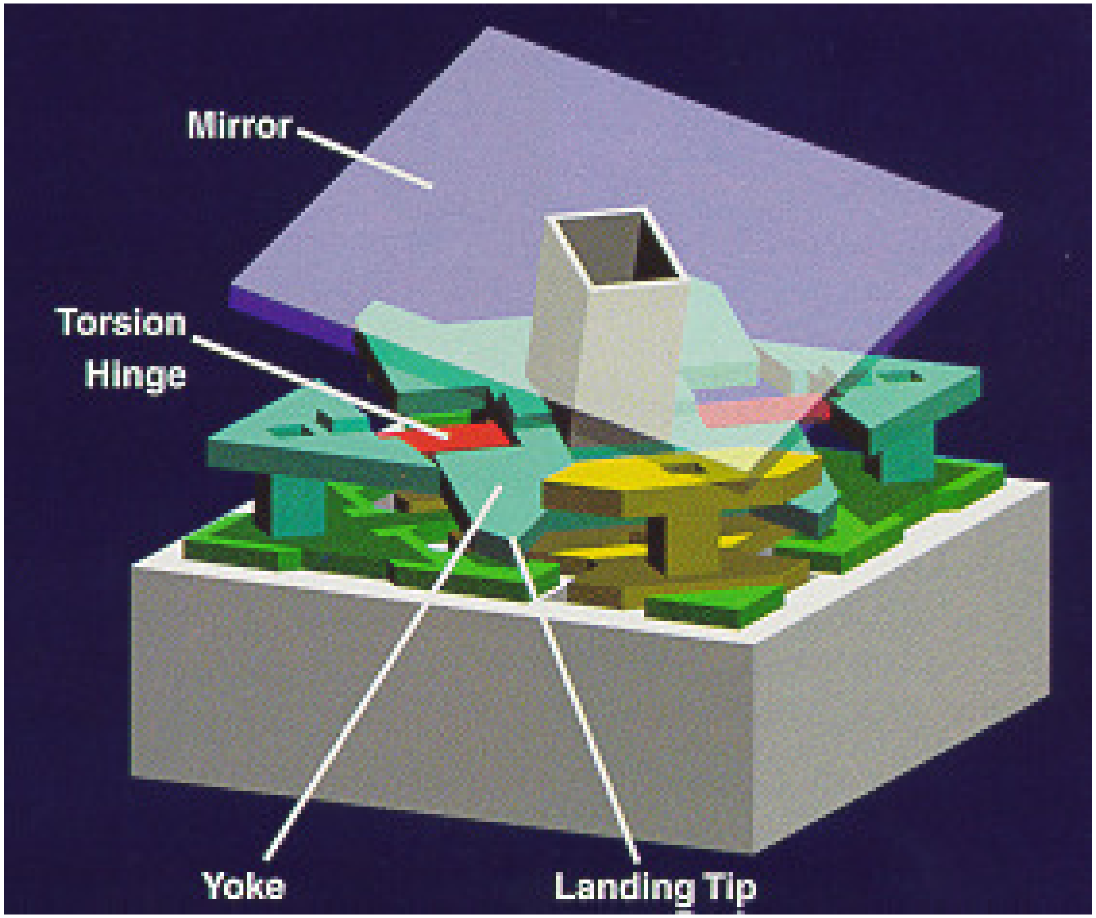
- Nearly universal sensing and actuation; no need for special materials.
- Low power. Actuation driven by voltage, not current.
- High speed. Use charging and discharging, therefore realizing full mechanical response speed.

Cons

- Force and distance inversely scaled - to obtain larger force, the distance must be small.
- In some applications, vulnerable to particles as the spacing is small - needs packaging.
- Vulnerable to sticking phenomenon due to molecular forces.
- Occasionally, sacrificial release. Efficient and clean removal of sacrificial materials.

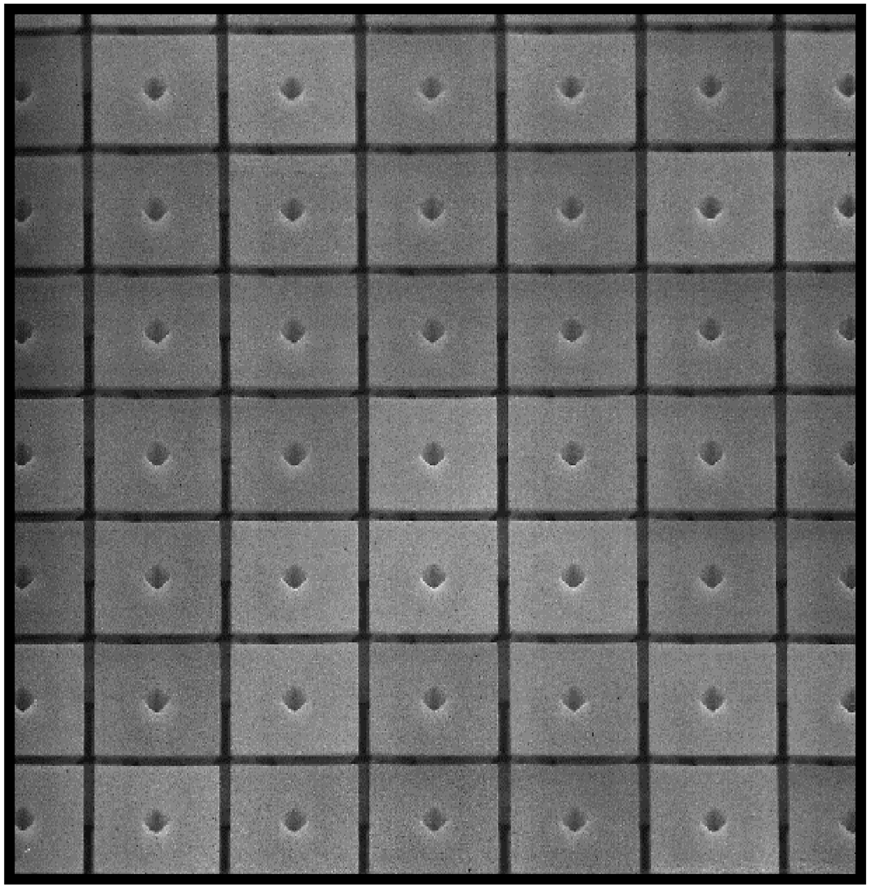
Optical Micro Switches

- Texas Instrument DLP



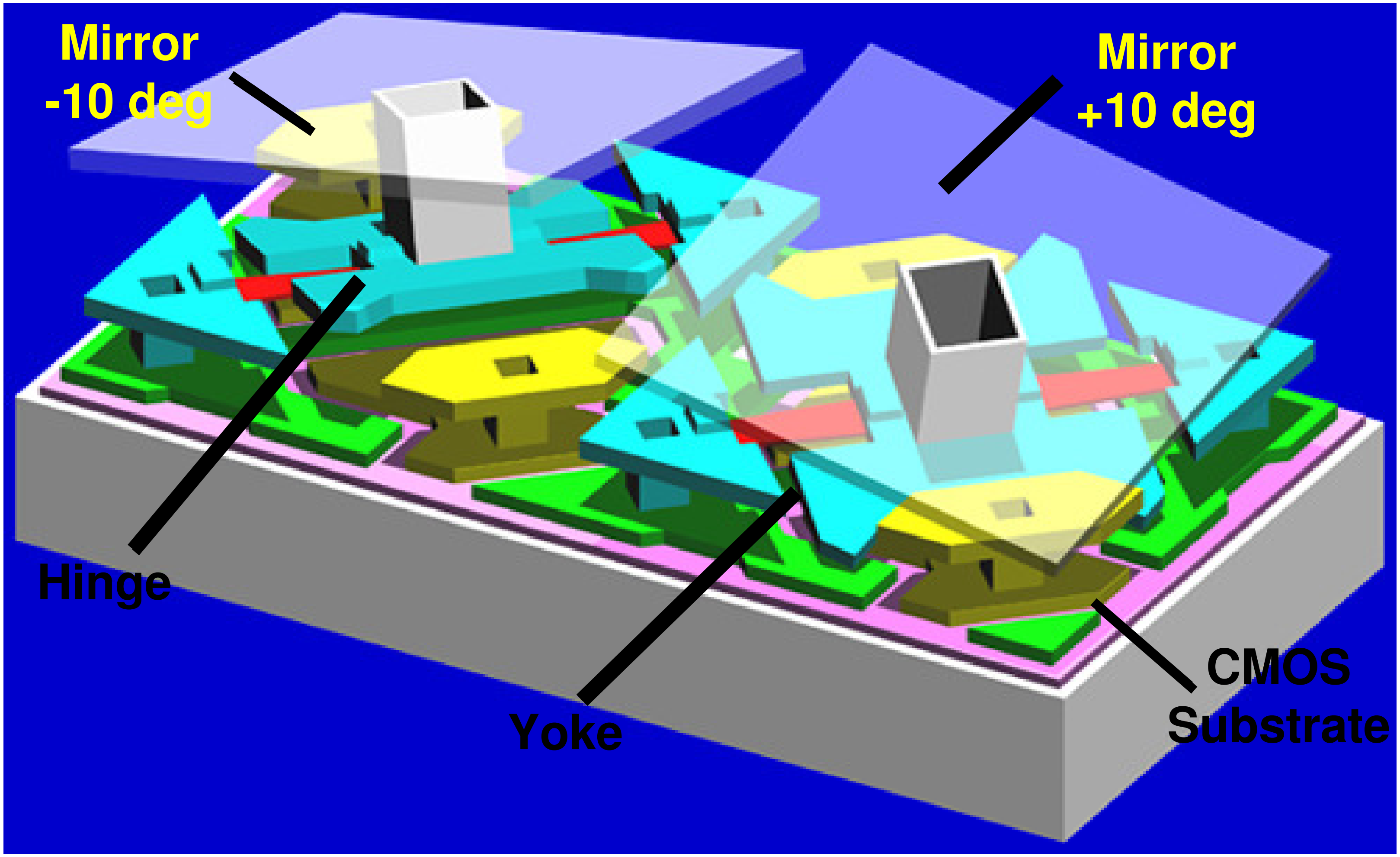
- Torsional parallel plate capacitor support
- Two stable positions (+/- 10 degrees with respect to rest)
- All aluminum structure
- No process steps entails temperature above 300-350 ^{o}C.

“Digital Light” Mirror Pixels

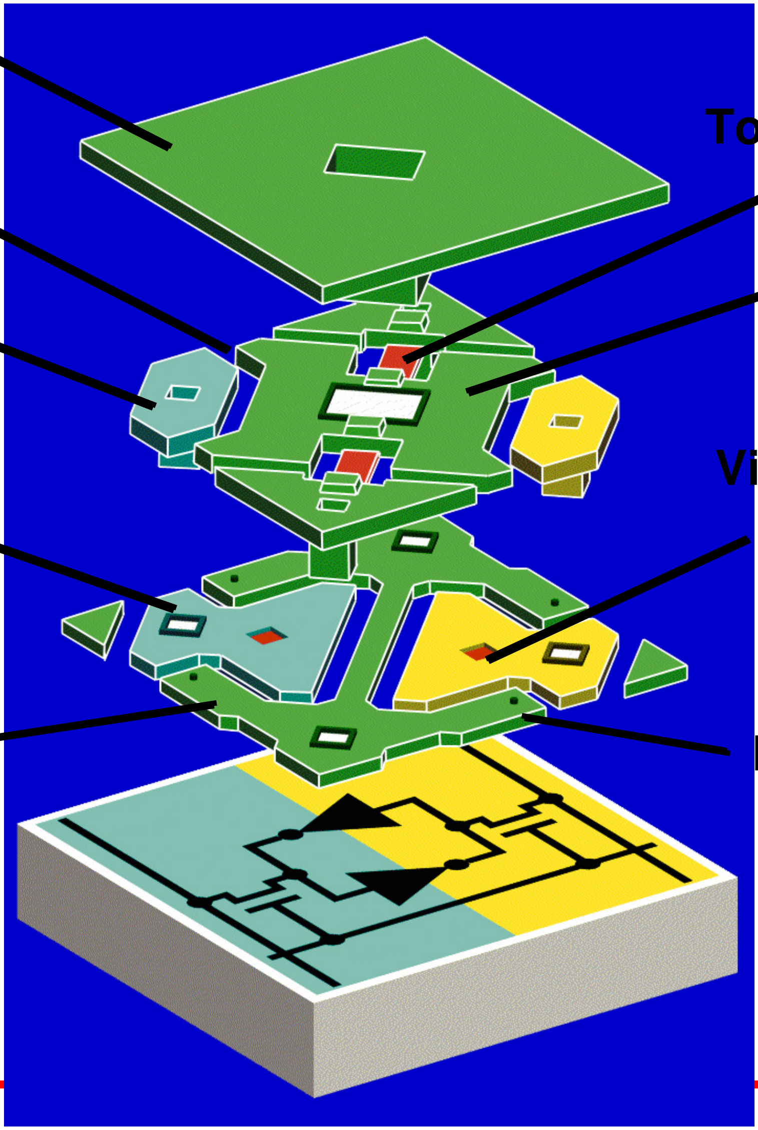


- **Mirrors are on 17 μm center-to-center spacing**
- **Gaps are 1.0 μm nominal**
- **Mirror transit time is <20 μs from state to state**
- **Tilt Angles are minute at ±10 degrees**
- **Four mirrors equal the width of a human hair**

Digital Micromirror Device (DMD)



DMD™ Pixel Exploded View



Mirror

Landing Tip

Mirror Address Electrode

Yoke Address Electrode

Bias/Reset Bus

Torsion Hinge

Yoke

Via 2 Contact to CMOS

Landing Site

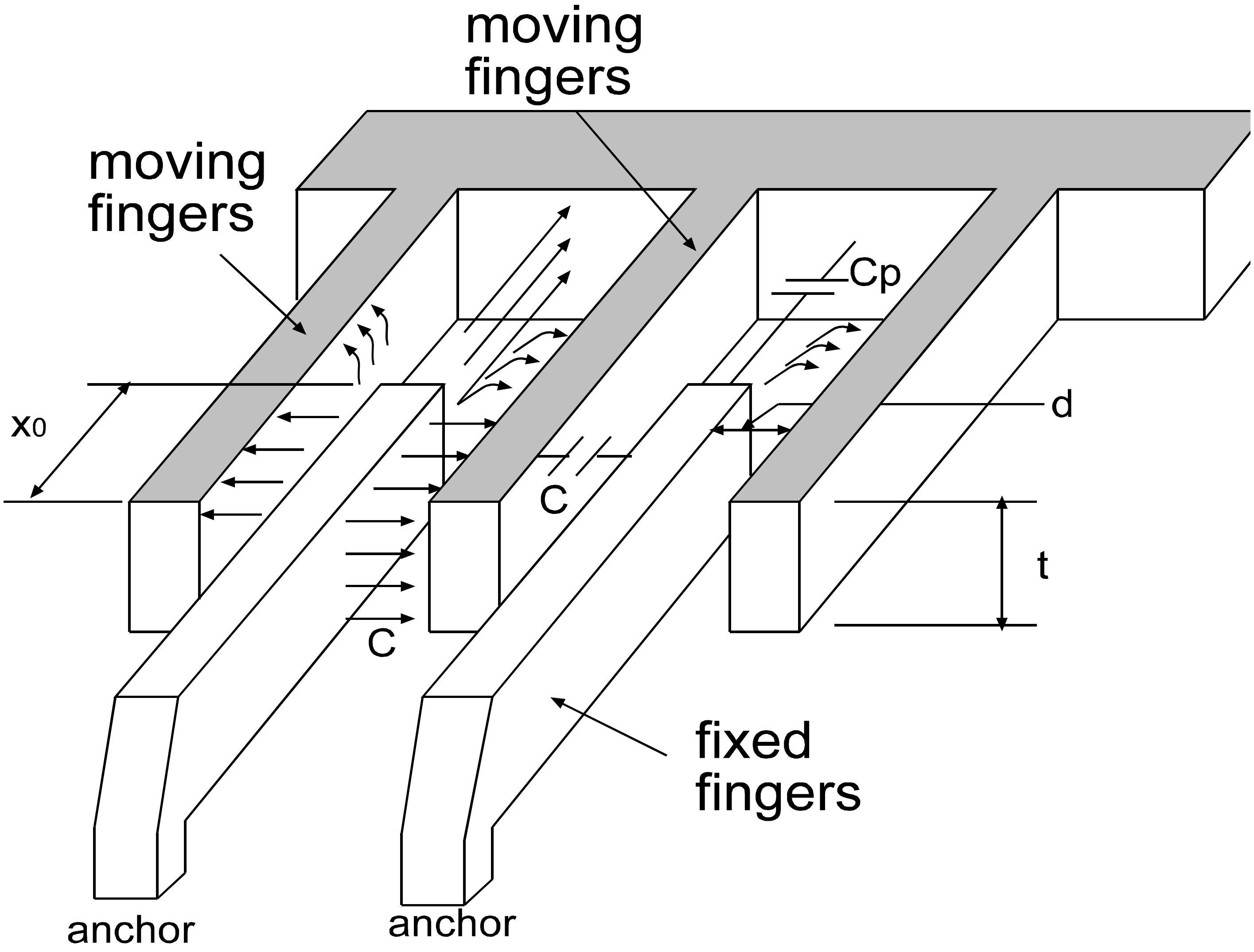
Mirror Layer

Yoke and Hinge Layer

Metal-3 Layer

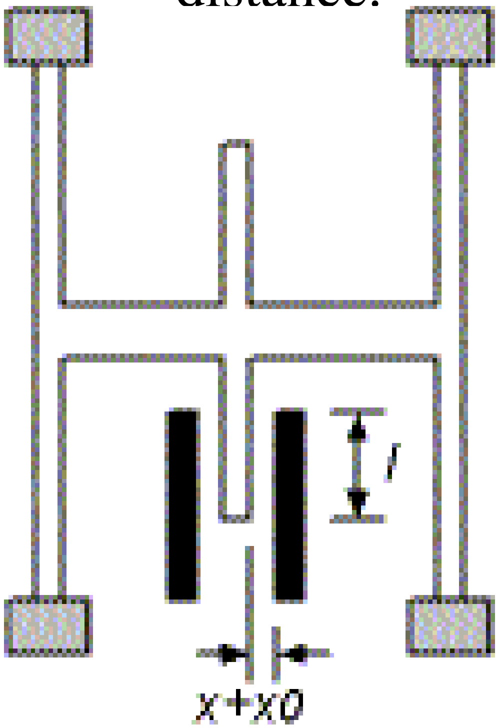
Memory Cell (CMOS SRAM)

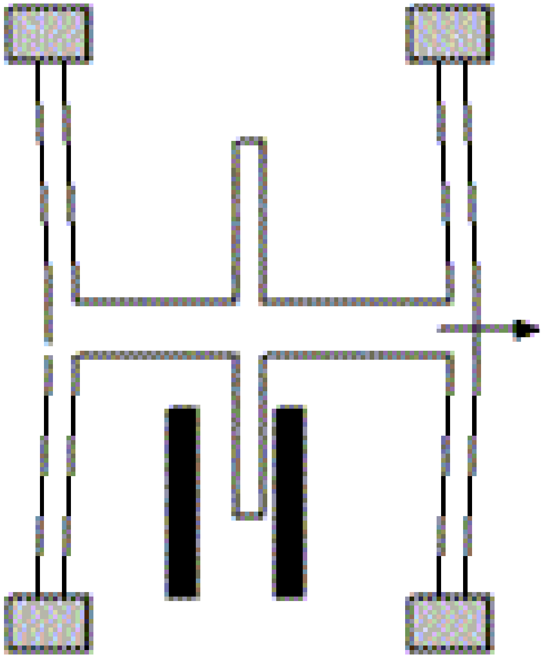
Perspective View of Lateral Comb Drive



Transverse Comb Drive Devices

- Direction of finger movement is orthogonal to the direction of fingers.
- Pros: Frequently used for sensing for the sensitivity and ease of fabrication
- Cons: not used as actuator because of the physical limit of distance.

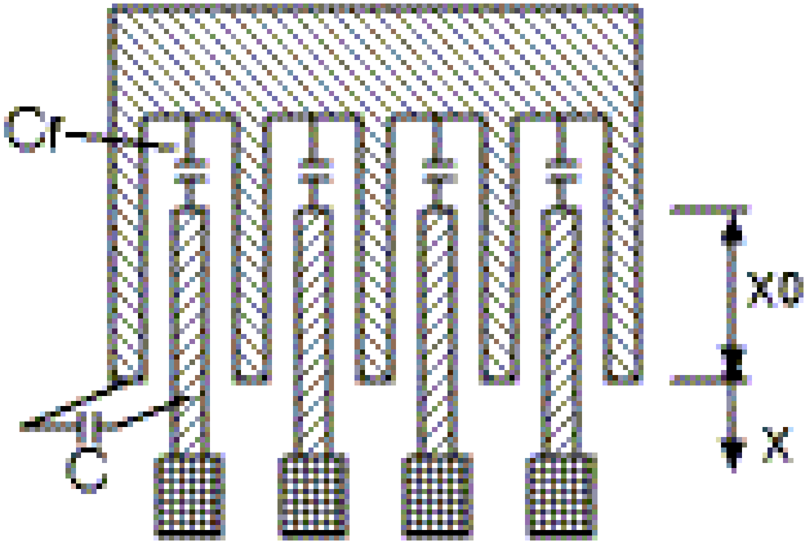




$$C_{sl} = N\left(\frac{\varepsilon_0 lt}{x_0 + x} + C_f\right)$$

$$C_{sr} = N\left(\frac{\varepsilon_0 lt}{x_0 - x} + C_f\right)$$

Lateral Comb Drive Actuators



$$C_{tot} = N[\frac{2\varepsilon_0 t(x+x_0)}{d} + c_p]$$

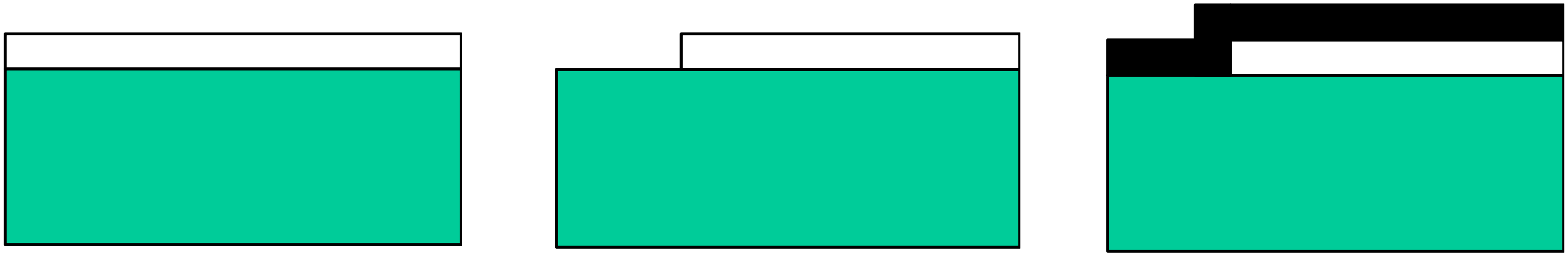
$$F\big|_{x=0} = \frac{N\varepsilon_0 t}{d} V^2$$

N=4 in above diagram.

- Total capacitance is proportional to the overlap length and depth of the fingers, and inversely proportional to the distance.
- Pros:
  - Frequently used in actuators for its relatively long achievable driving distance.
- Cons
  - force output is a function of finger thickness. The thicker the fingers, the large force it will be.
  - Relatively large footprint.

Basic Sacrificial Layer Processing

- Step 1: Deposition of sacrificial layer
- Step 2: patterning of the sacrificial layer
- Step 3: deposit structural layer (conformal deposition)
- Step 4: liquid phase removal of sacrificial layer
- Step 5: removal of liquid - drying.



Process and Chemical Compatibility

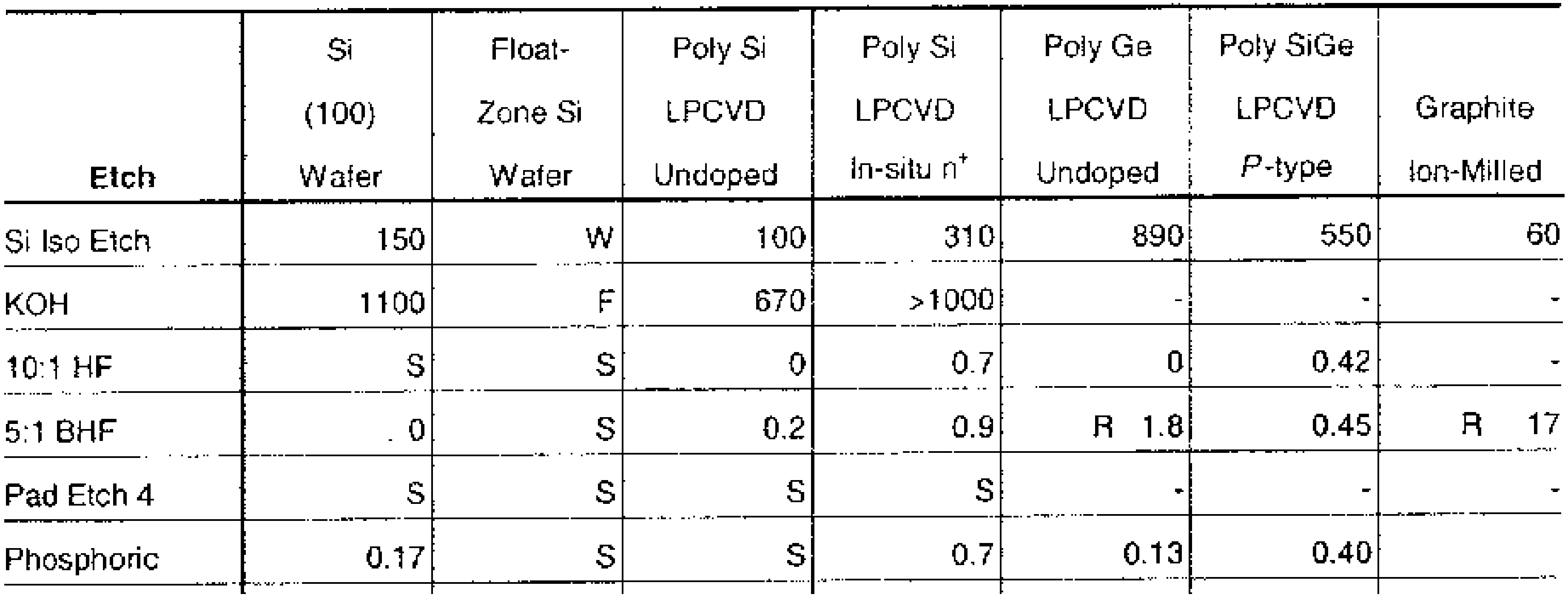
- For a two layer process
- The deposition of the structural layer must not damage the sacrificial layer
  - Thermal stability
- The pattering of the structural layer must not damage the sacrificial layer
  - Chemical and thermal stability
- The removal of the sacrificial layer must not damage the structural layer
  - Chemical and thermal stability

Let’s Analyze

- Structural layer: polycrystal silicon
- Sacrificial layer: LPCVD oxide

TABLE II

ETCH RATES OF Si, Ge, SiGe, AND C (nm/min)



Etch	Si (100) Wafer	Float-Zone Si Wafer	Poly Si LPCVD Undoped	Poly Si LPCVD In-situ n^+	Poly Ge LPCVD Undoped	Poly SiGe LPCVD *P*-type	Graphite Ion-Milled
Si Iso Etch	150	W	100	310	890	550	60
KOH	1100	F	670	>1000	-	-	-
10:1 HF	S	S	0	0.7	0	0.42	-
5:1 BHF	0	S	0.2	0.9	R 1.8	0.45	R 17
Pad Etch 4	S	S	S	S	-	-	-
Phosphoric	0.17	S	S	0.7	0.13	0.40	

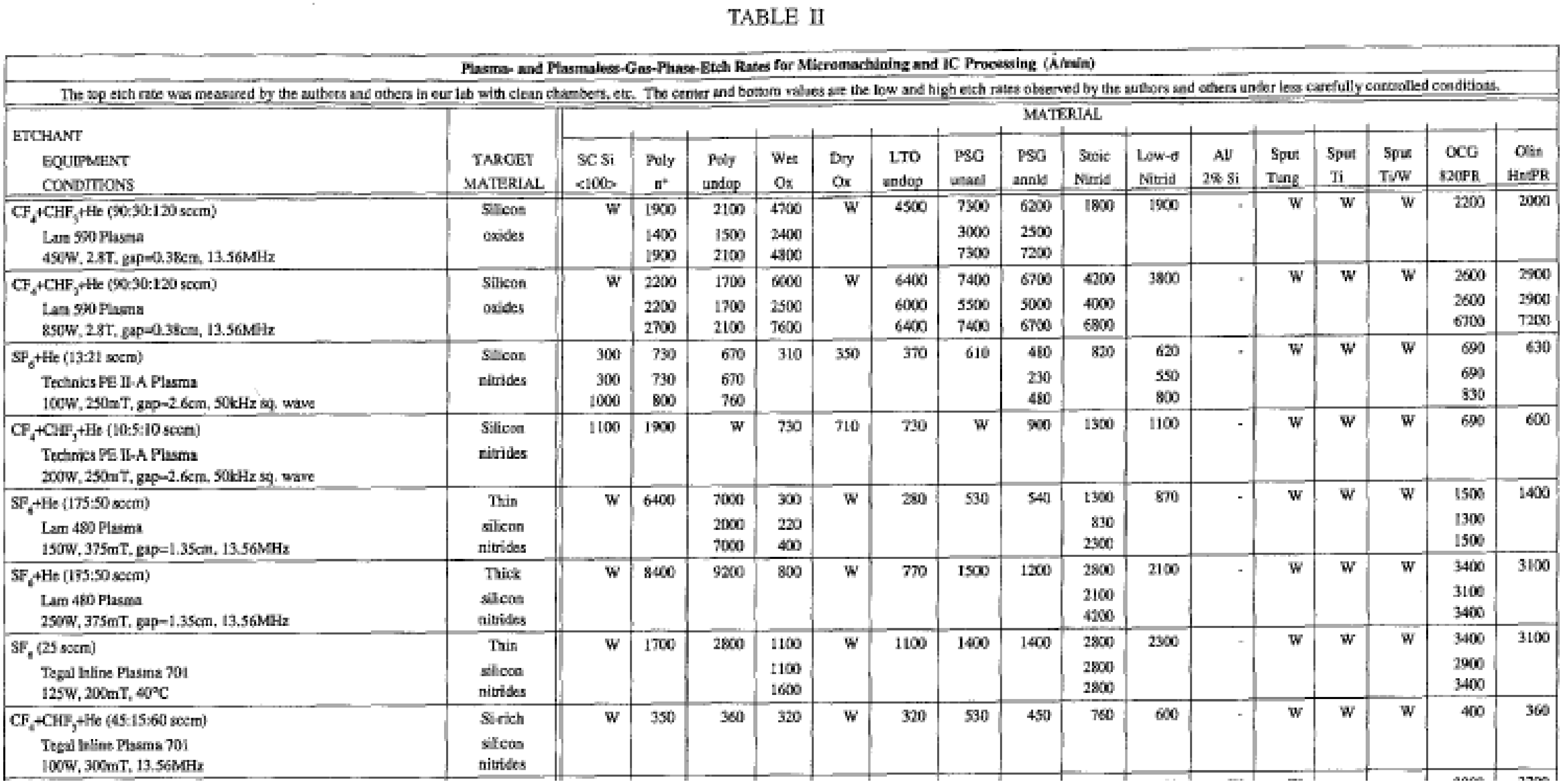


TABLE II

ETCHANT EQUIPMENT CONDITIONS	TARGET MATERIAL	MATERIAL															
Plasma- and Plasmaless-Gas-Phase-Etch Rates for Micromachining and IC Processing (Å/min)																	
The top etch rate was measured by the authors and others in our lab with clean chambers, etc. The center and bottom values are the low and high etch rates observed by the authors and others under less carefully controlled conditions.																	
		SC Si <100>	Poly n^+	Poly undop	Wet Ox	Dry Ox	LTO undop	PSG unanl	PSG annld	Stoic Nitrid	Low-σ Nitrid	Al/ 2% Si	Sput Tung	Sput Ti	Sput Ti/W	OCG 820PR	Olin HntPR
CF_4+CHF_3+He (90:30:120 sccm) Lam 590 Plasma 450W, 2.8T, gap=0.38cm, 13.56MHz	Silicon oxides	W	1900 1400 1900	2100 1500 2100	4700 2400 4800	W	4500	7300 3000 7300	6200 2500 7200	1800	1900	-	W	W	W	2200	2000
CF_4+CHF_3+He (90:30:120 sccm) Lam 590 Plasma 850W, 2.8T, gap=0.38cm, 13.56MHz	Silicon oxides	W	2200 2200 2700	1700 1700 2100	6000 2500 7600	W	6400 6000 6400	7400 5500 7400	6700 5000 6700	4200 4000 6800	3800	-	W	W	W	2600 2600 6700	2900 2900 7200
SF_6+He (13:21 sccm) Technics PE II-A Plasma 100W, 250mT, gap=2.6cm, 50kHz sq. wave	Silicon nitrides	300 300 1000	730 730 800	670 670 760	310	350	370	610	480 230 480	820	620 550 800	-	W	W	W	690 690 830	630
CF_4+CHF_3+He (10:5:10 sccm) Technics PE II-A Plasma 200W, 250mT, gap=2.6cm, 50kHz sq. wave	Silicon nitrides	1100	1900	W	730	710	730	W	900	1300	1100	-	W	W	W	690	600
SF_6+He (175:50 sccm) Lam 480 Plasma 150W, 375mT, gap=1.35cm, 13.56MHz	Thin silicon nitrides	W	6400	7000 2000 7000	300 220 400	W	280	530	540	1300 830 2300	870	-	W	W	W	1500 1300 1500	1400
SF_6+He (175:50 sccm) Lam 480 Plasma 250W, 375mT, gap=1.35cm, 13.56MHz	Thick silicon nitrides	W	8400	9200	800	W	770	1500	1200	2800 2100 4200	2100	-	W	W	W	3400 3100 3400	3100
SF_6 (25 sccm) Tegal Inline Plasma 701 125W, 200mT, 40°C	Thin silicon nitrides	W	1700	2800	1100 1100 1600	W	1100	1400	1400	2800 2800 2800	2300	-	W	W	W	3400 2900 3400	3100
CF_4+CHF_3+He (45:15:60 sccm) Tegal Inline Plasma 701 100W, 300mT, 13.56MHz	Si-rich silicon nitrides	W	350	360	320	W	320	530	450	760	600	-	W	W	W	400	360

More Involved Criteria

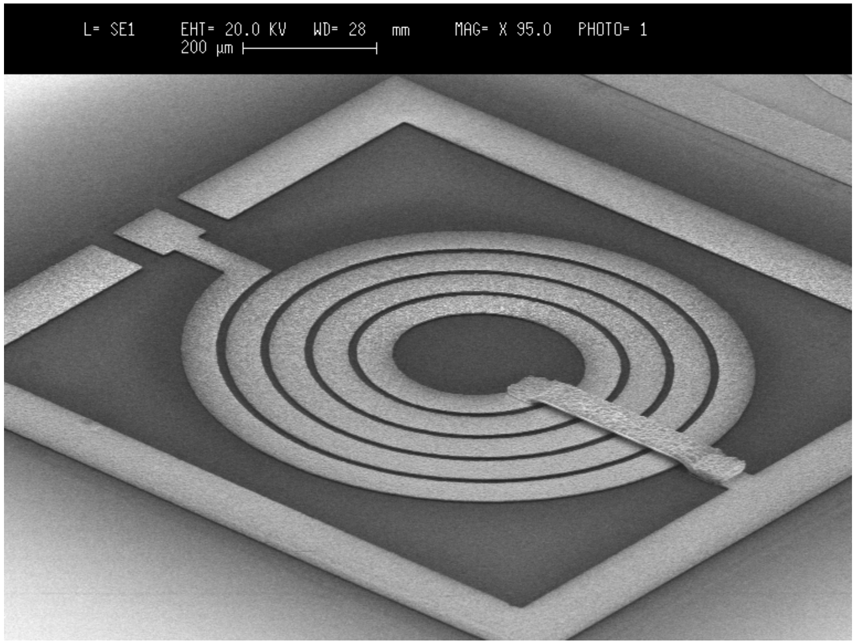
- For a two layer process

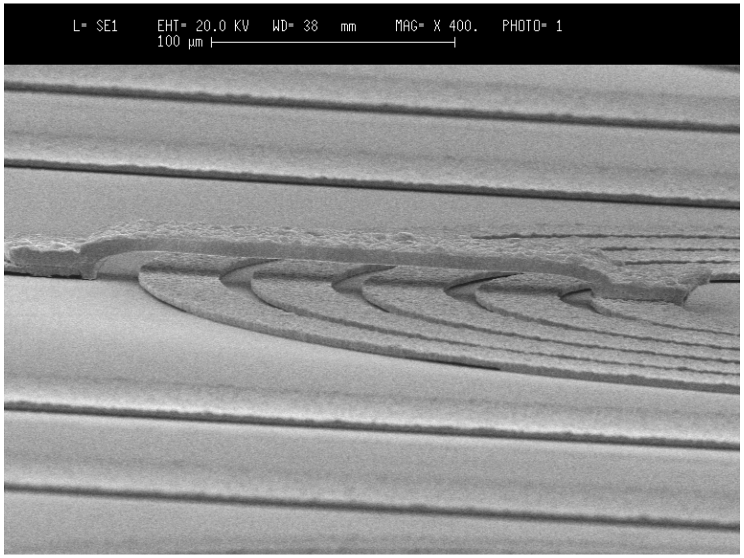
- The deposition of the structural layer must not damage the sacrificial layer
  - Thermal stability
- The pattering of the structural layer must not damage the sacrificial layer
  - Chemical and thermal stability
- The removal of the sacrificial layer must not damage the structural layer
  - Chemical and thermal stability

- The structural layer should not bend uncontrollably
- The structural layer should not be stuck to the bottom

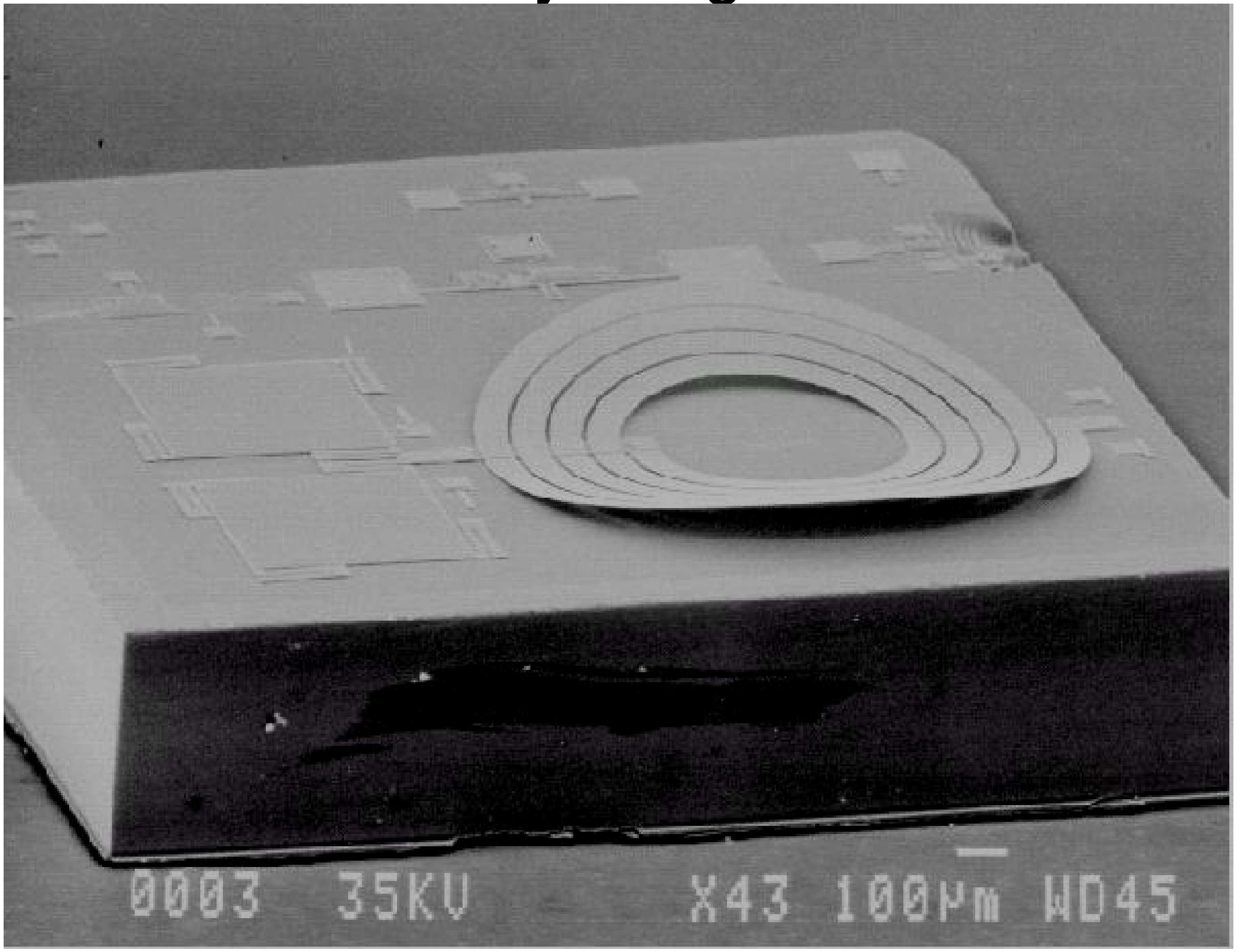
Surface Micromachined Inductor

- Air bridge can be formed using sacrificial etching.

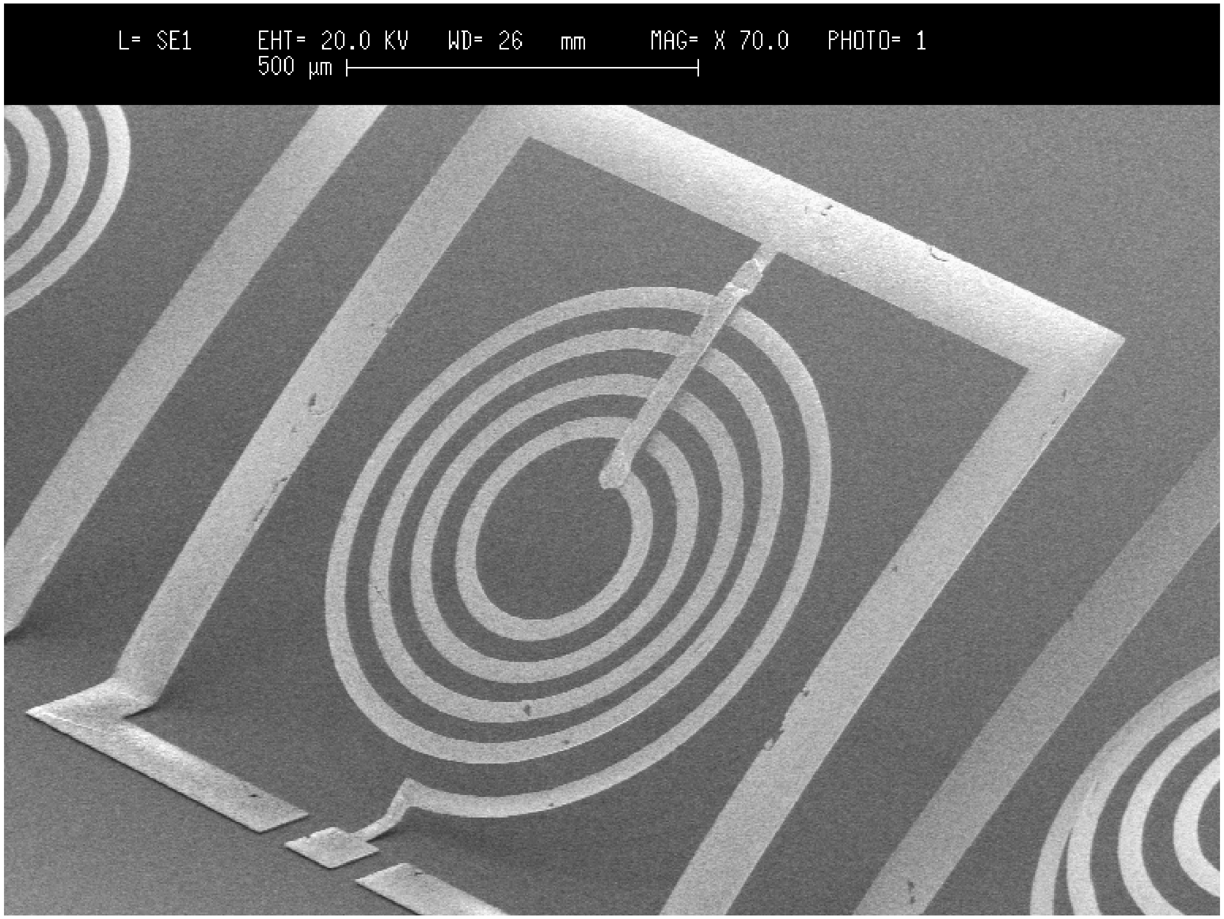




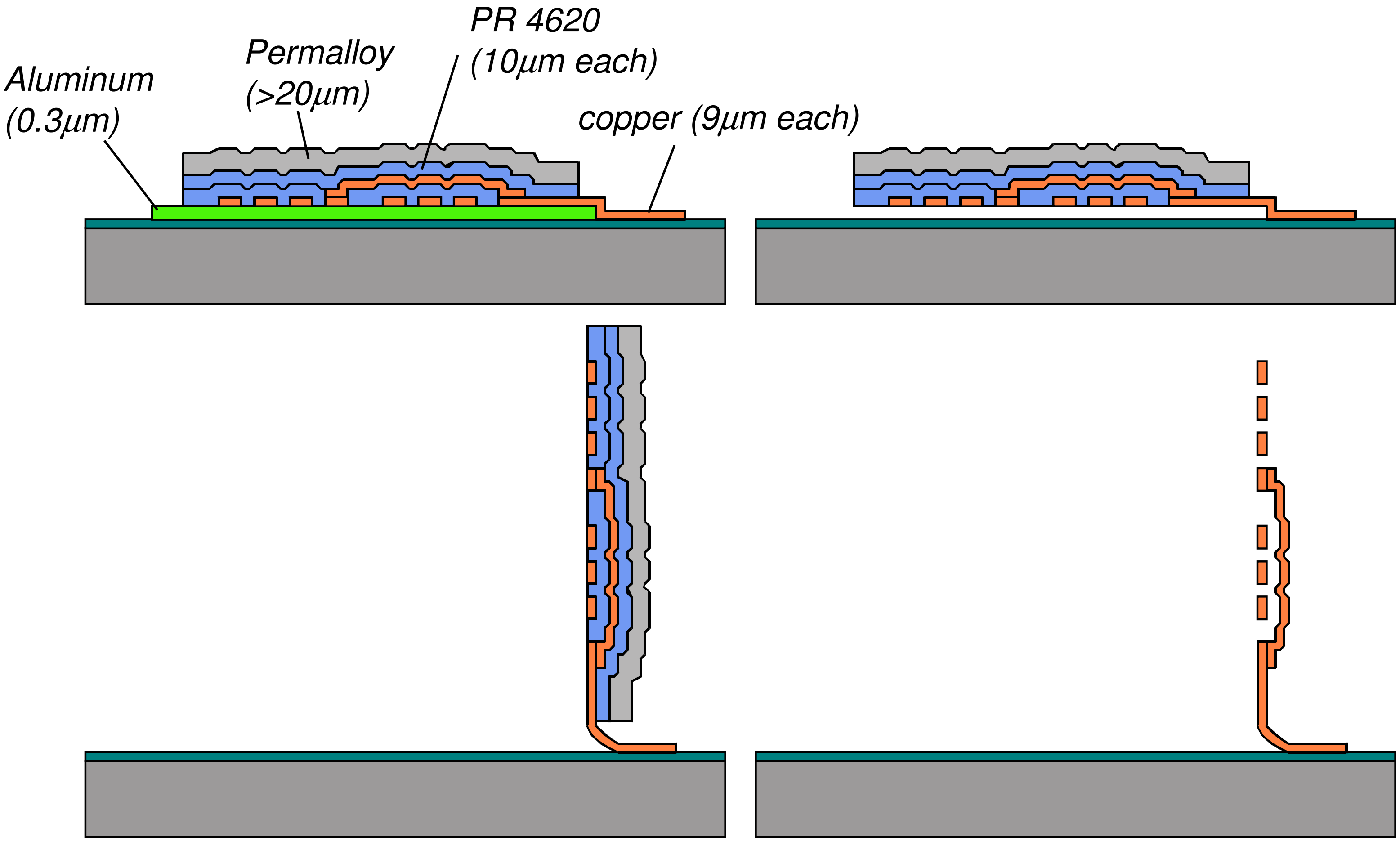
Inductor - By Lucent Technologies
Stress can be an enemy, or a friend. Most likely an enemy though ☺



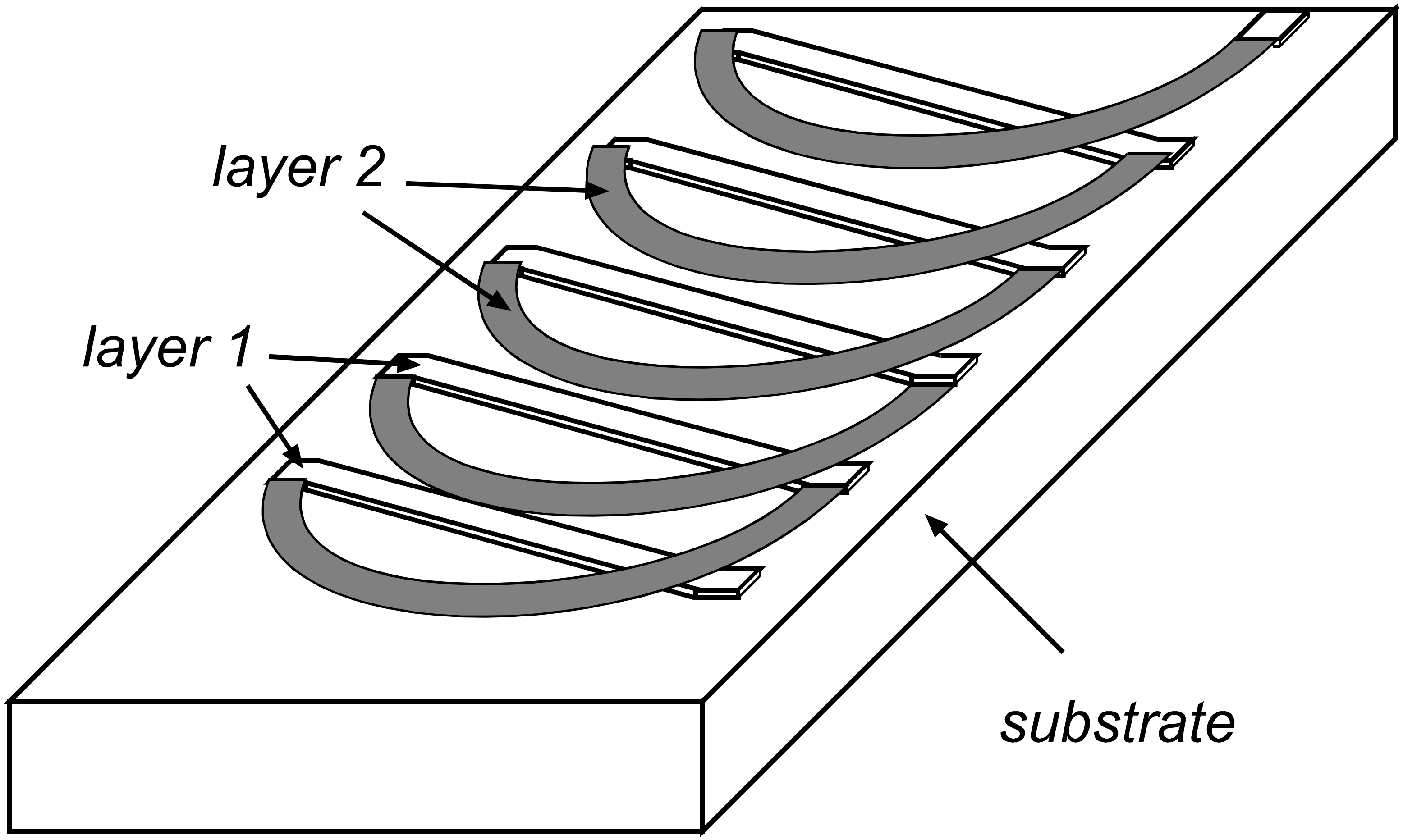
Surface Micromachined, Out of Plane Structures

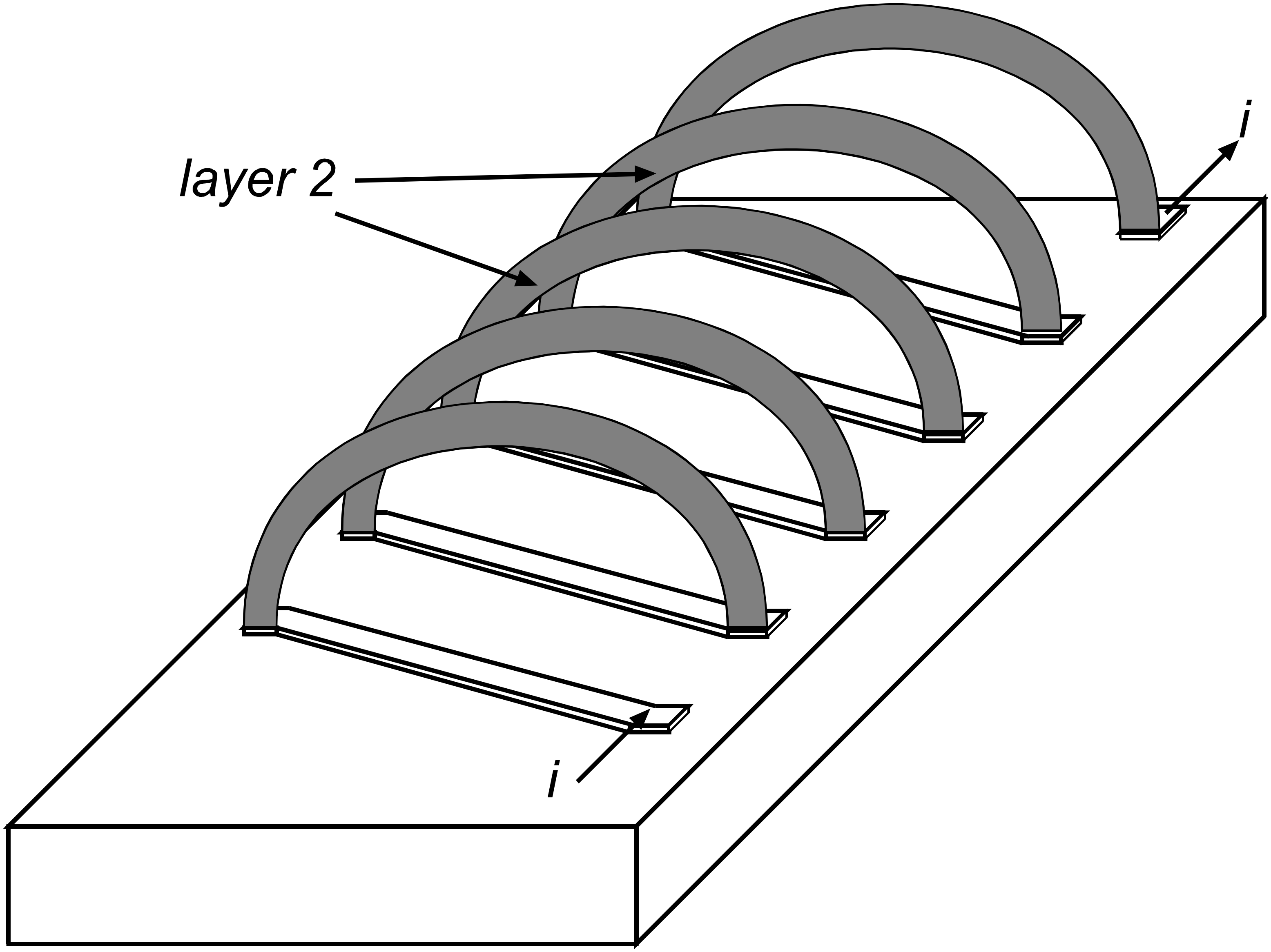


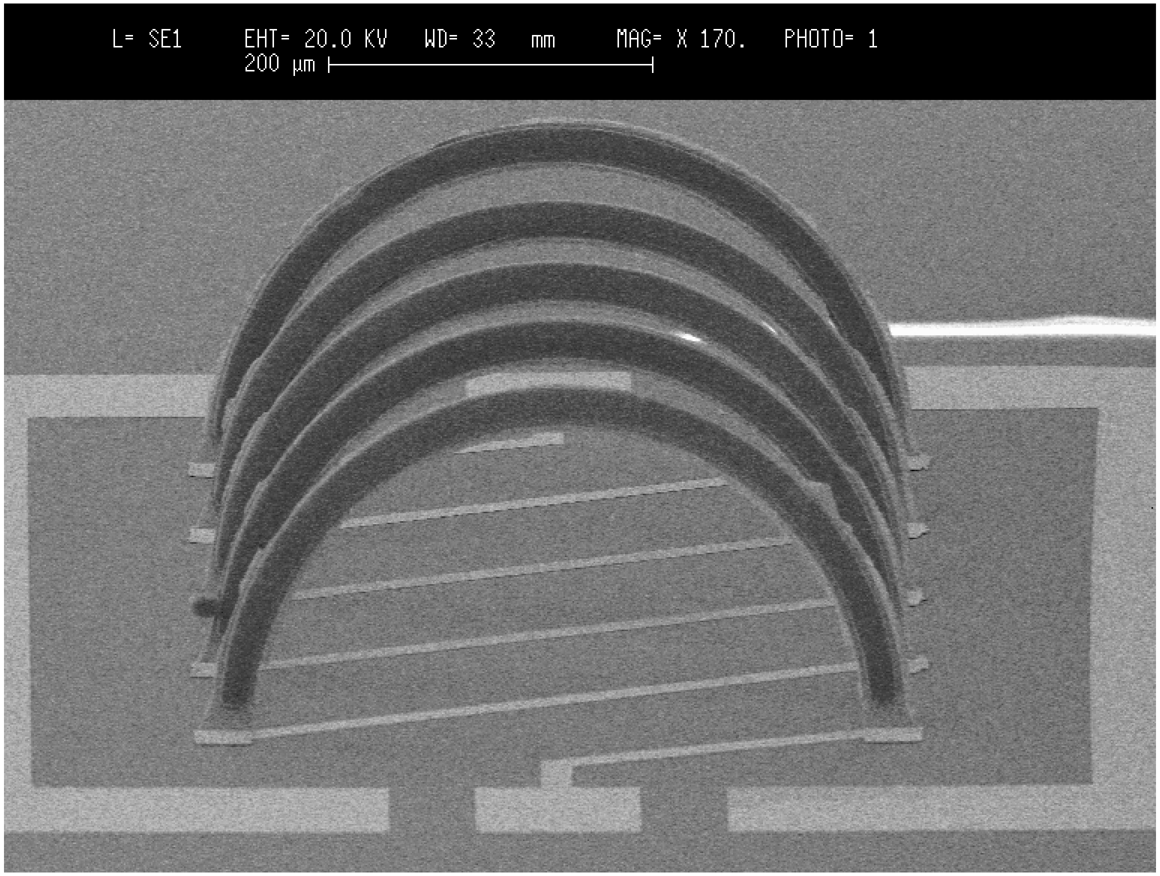
Metal Sacrificial Layers



A New Method

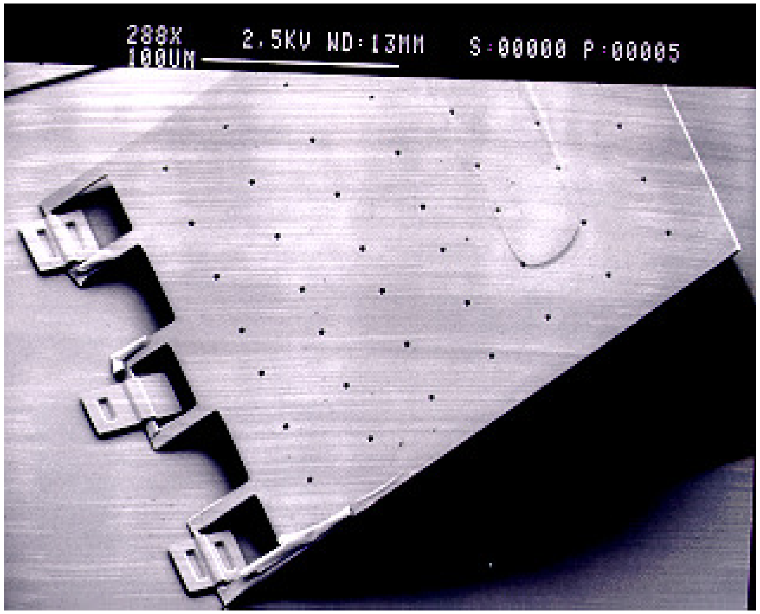


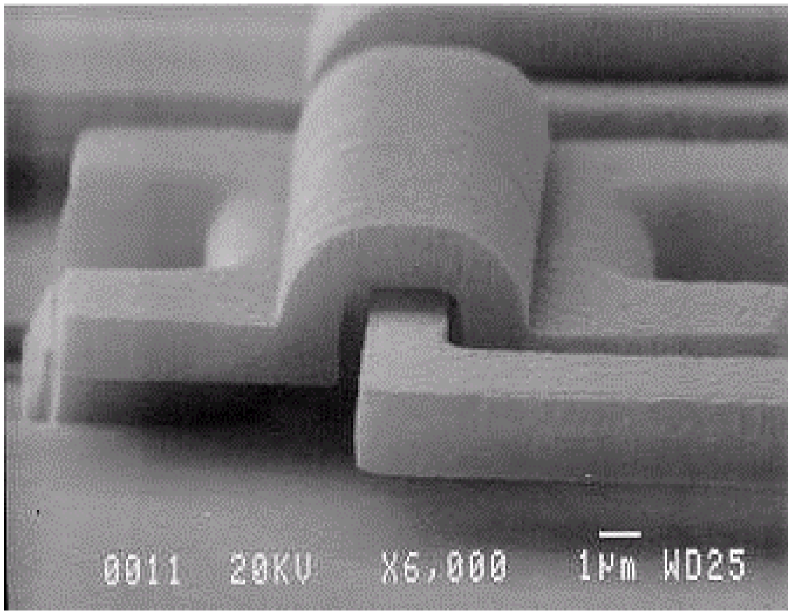

layer 2
i
i


L= SE1 EHT= 20.0 KV WD= 33 mm MAG= X 170. PHOTO= 1
200 µm

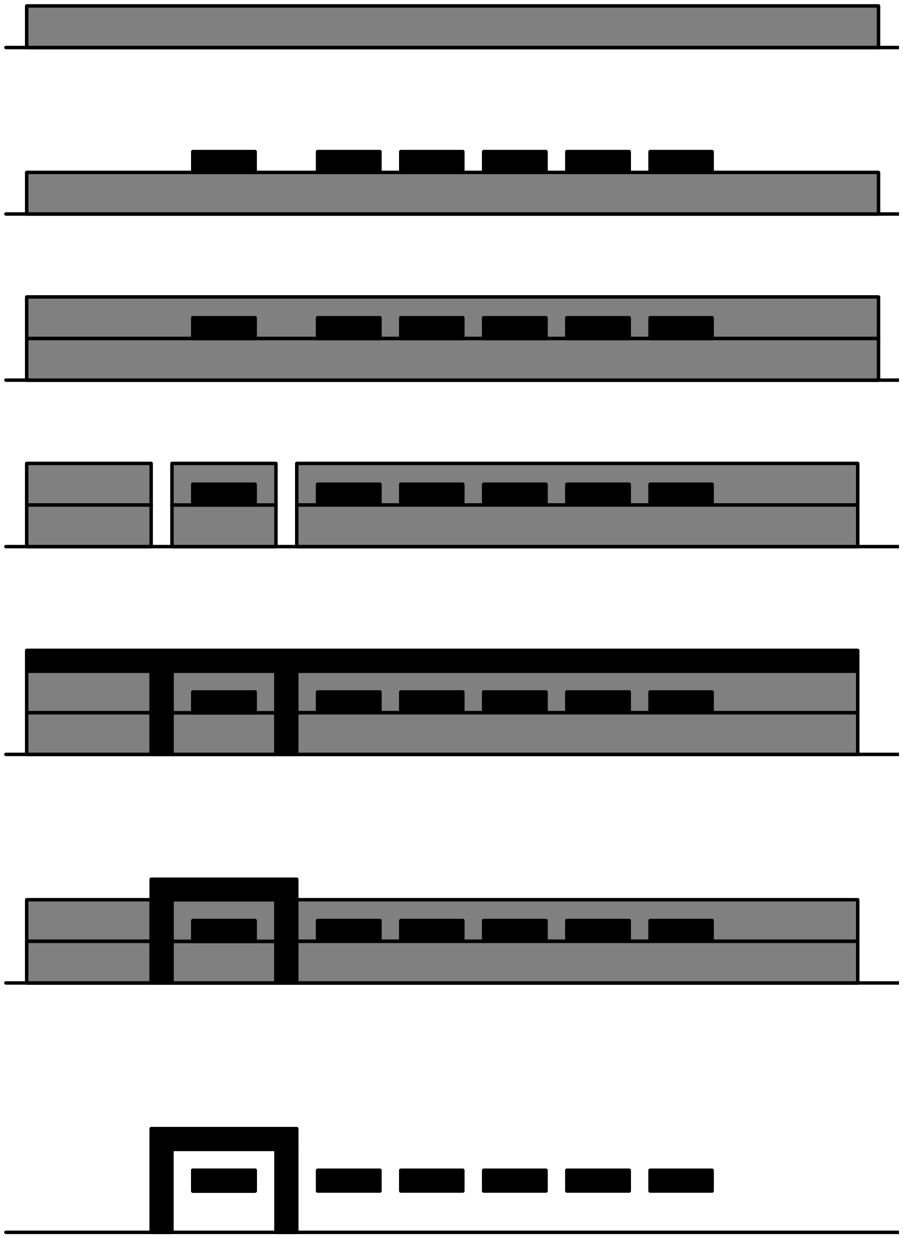
Hinges

- Used in micro optics component assembly.





Hinge Fabrication



- Step 1: deposition of sacrificial layer.
- Step 2: deposition of structural layer.
- Step 3: deposition of second sacrificial layer.
- Step 4: etching anchor to the substrate.
- Step 5: deposition of second structural layer.
- Step 6: patterning of second structural layer
- Step 7: Etch away all sacrificial layer to release the first structural layer.

For a four layer process …

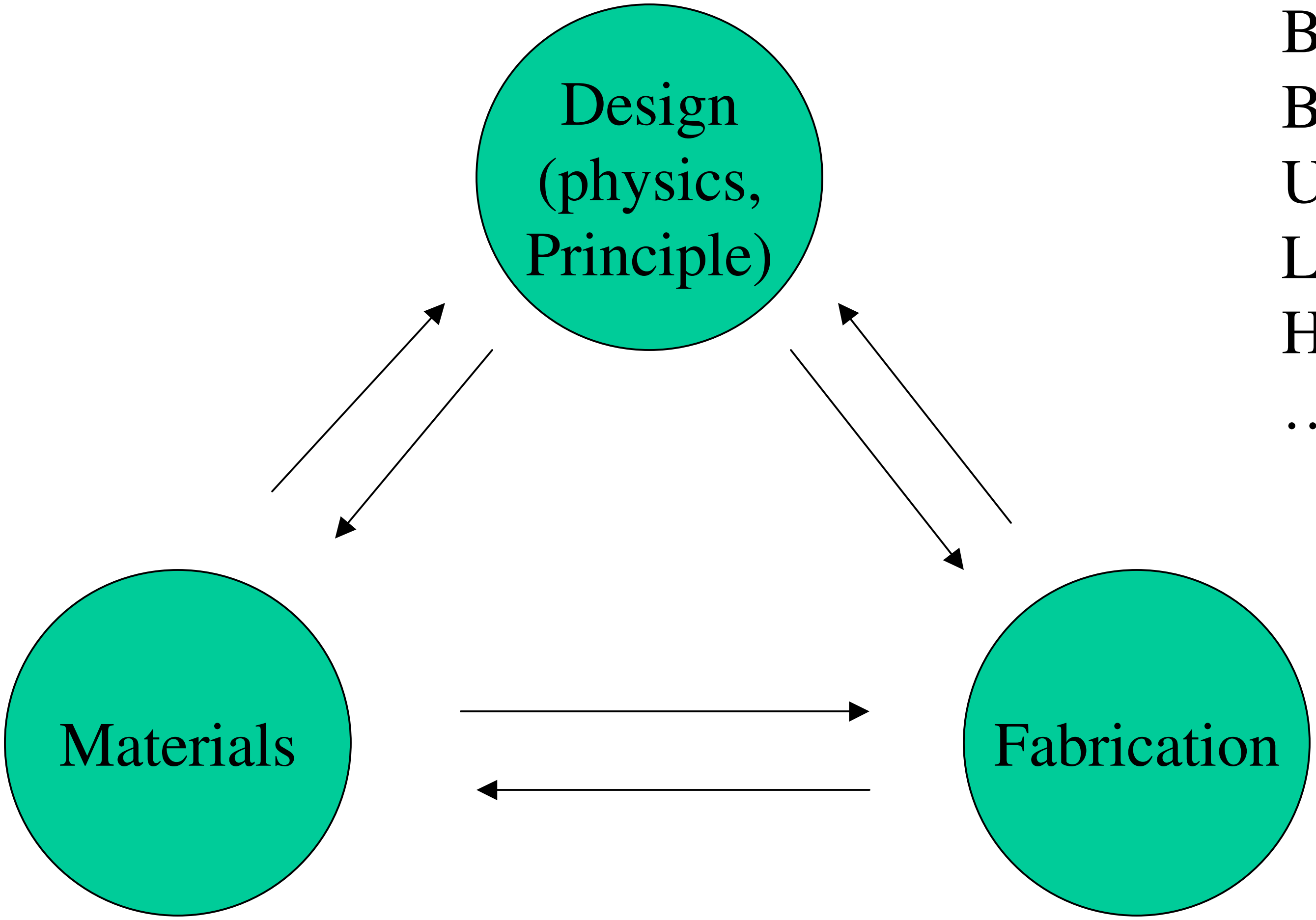
- Sacrificial layers (Sac1, sac2)
- Structural layers (str 1, str 2)

- Str1 deposition must not affect sac1
- Str1 patterning must not affect sac1
- Sac2 deposition must not affect sac1
- Sac2 deposition must not affect str1
- Sac2 patterning must not affect str1
- Sac2 patterning must not affect sac1 (if sac 1 is exposed)
- Str 2 deposition must not affect sac2
- Str 2 deposition must no affect str1
- Str 2 deposition must not affect sac1
- Str 2 patterning must not affect sac2, str1, sac1
- Sac 1 removal must not affect str 2, str1
- Sac 2 removal must not affect str 2, str1

To make things more complex and challenging

- Certain layers need to be made of a certain material;
- Stress control issues may dictate certain layer materials;
- Electrical performances may dictate certain layer materials;
- Economic issues may dictate certain layer materials;

Three Pillars of MEMS



Design (physics, Principle)

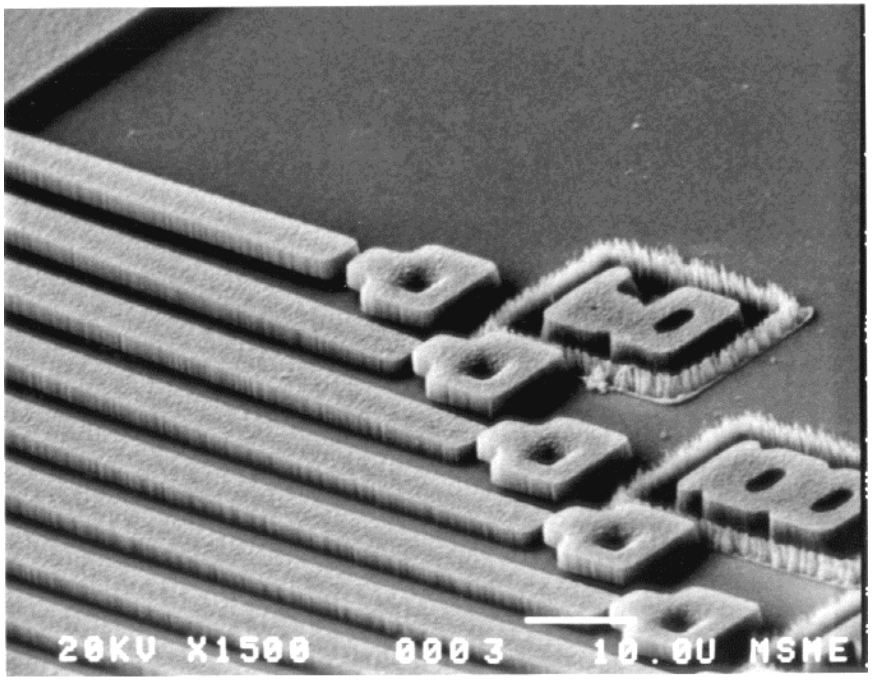
Materials

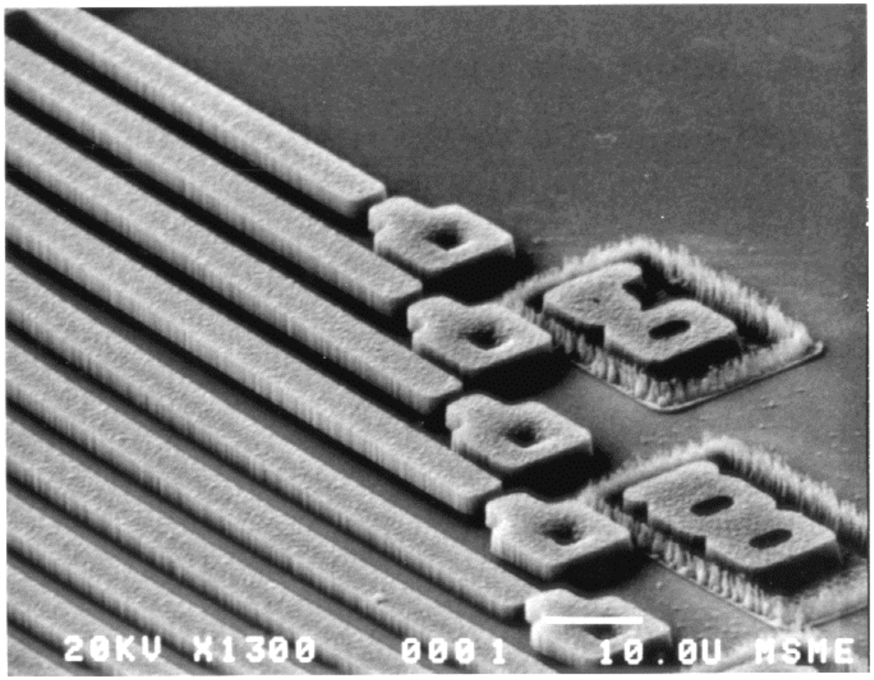
Fabrication

Goals:

Better performance
Better yield
Unique advantages
Lower cost
Higher yield
…

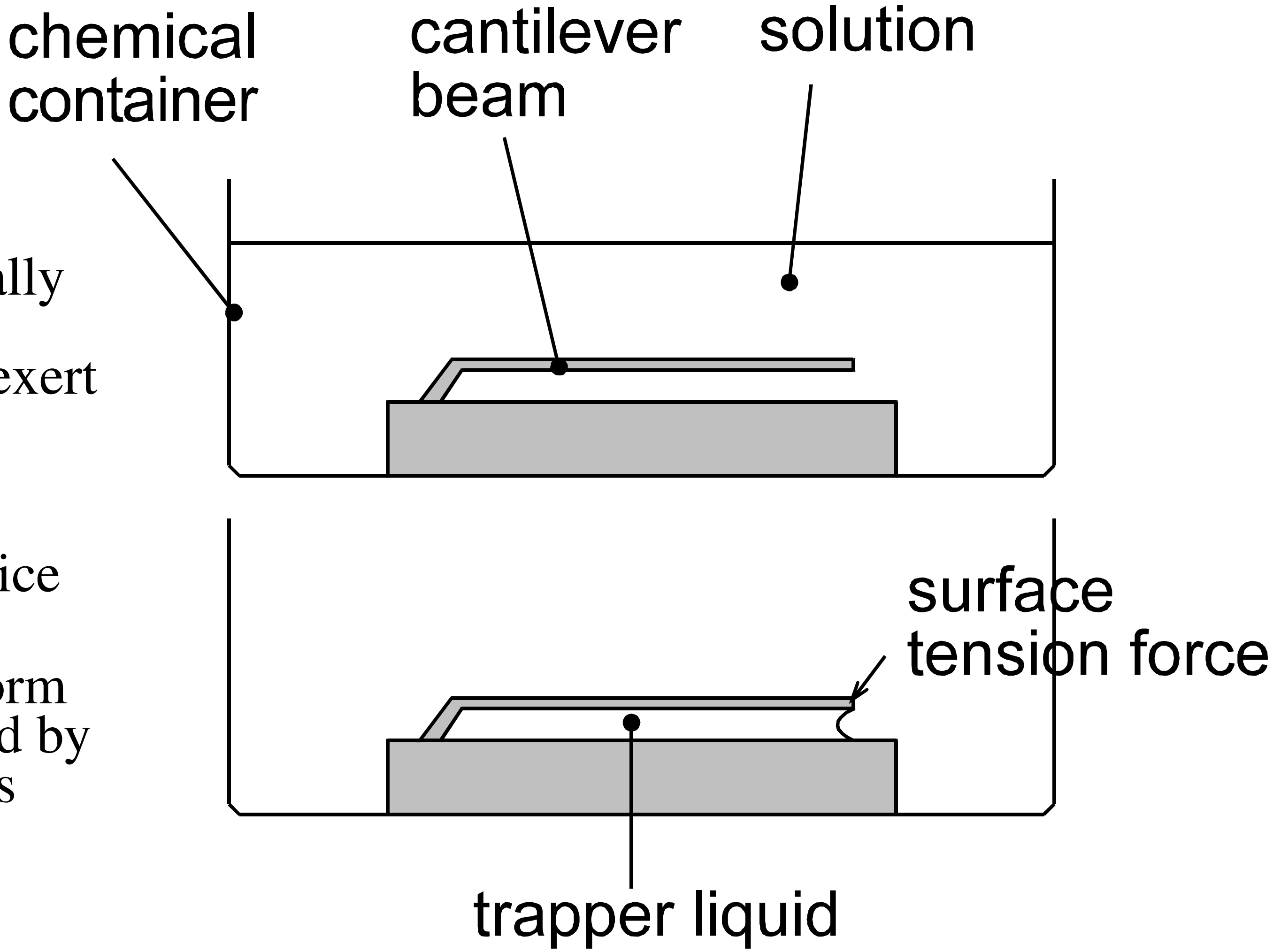
Stiction = Sticking and Friction





Origin of Stiction

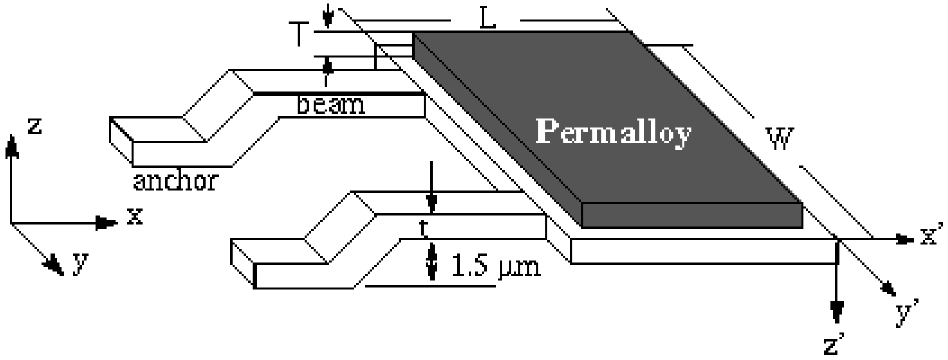
- As the liquid solution gradually vaporizes, the trapped liquid exert surface tension force on the microstructure, pulling the device down.
- Surfaces can form permanent bond by molecule forces when they are close.

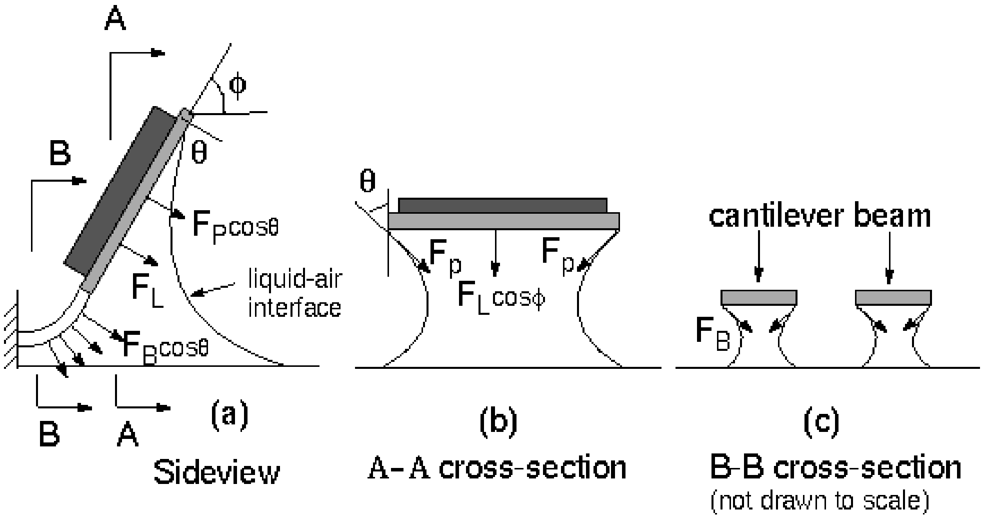


Antistiction Method I - Active Actuation Method

- Use magnetic actuation to pull structures away form the surface
  - reduced surface tension length of arm

- Limitations
  - only works for structures with magnetic material.





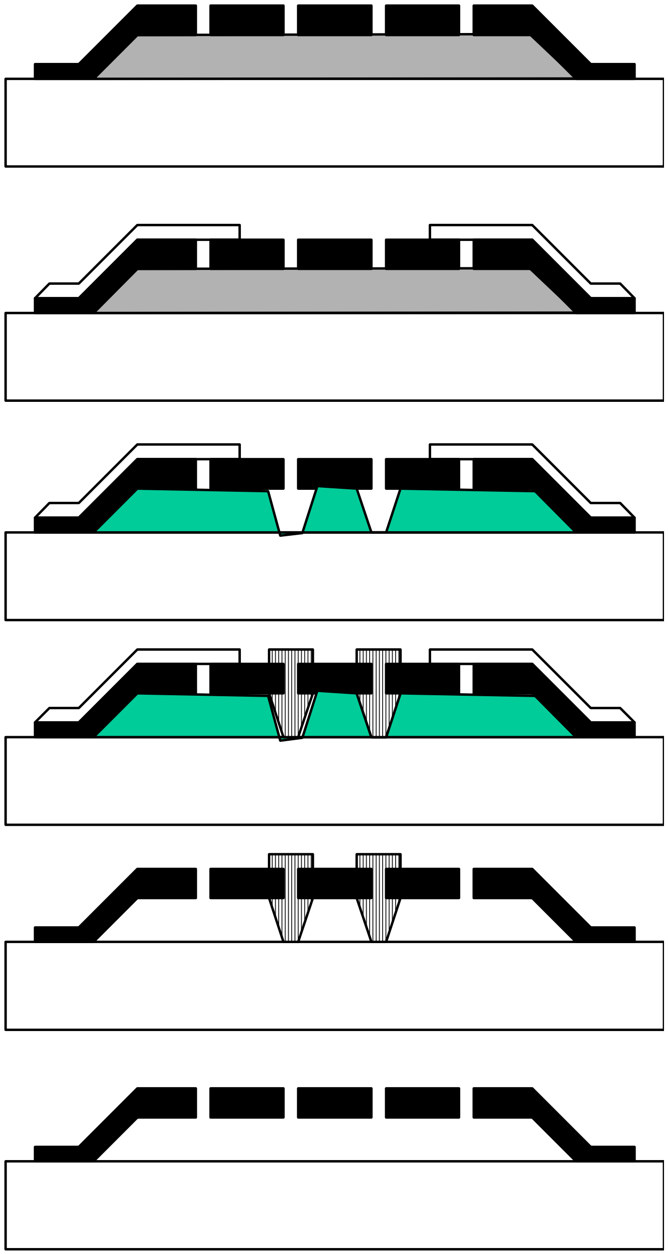
(a) Sideview

(b) A-A cross-section

(c) B-B cross-section (not drawn to scale)

Antistiction Method II - Organic Pillar

- Use organic pillar to support the structure during the liquid removal.
- The organic pillar is removed by oxygen plasma etching.



Analyze selectivity and choose etchants

Antistiction Drying Method III - Phase Change Release Method

Supercritical CO_2 Drying

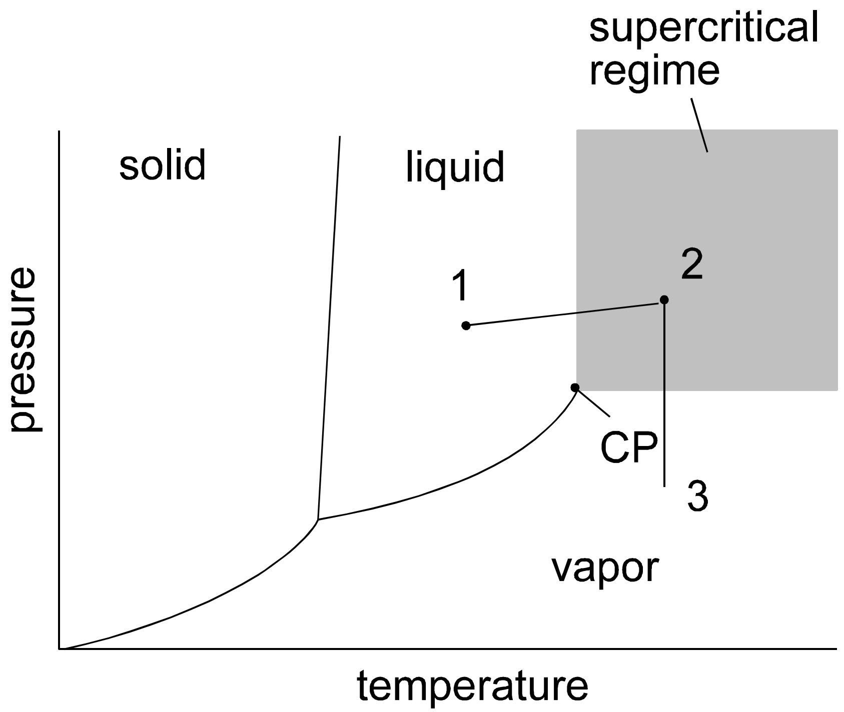
- Avoid surface tension by relaying on phase change with less surface tension than water-vapor.
- * p. 128-129
- Supercritical state: temp > 31.1 ^{o}C and pressure > 72.8 atm.
- Step 1: change water with methanol
- Step 2: change methanol with liquid carbon dioxide (room temperature and 1200 psi)
- Step 3: content heated to 35 ^{o}C and the carbon dioxide is vented.

- Free-standing cantilever beams upto 850 µm can stay released.

Super Critical Drying

- When a substance in the liquid phase at a pressure greater than the critical pressure is heated, it undergoes a transition from a liquid to a supercritical fluid at the critical temperature.
- This transition does not involve interfaces.

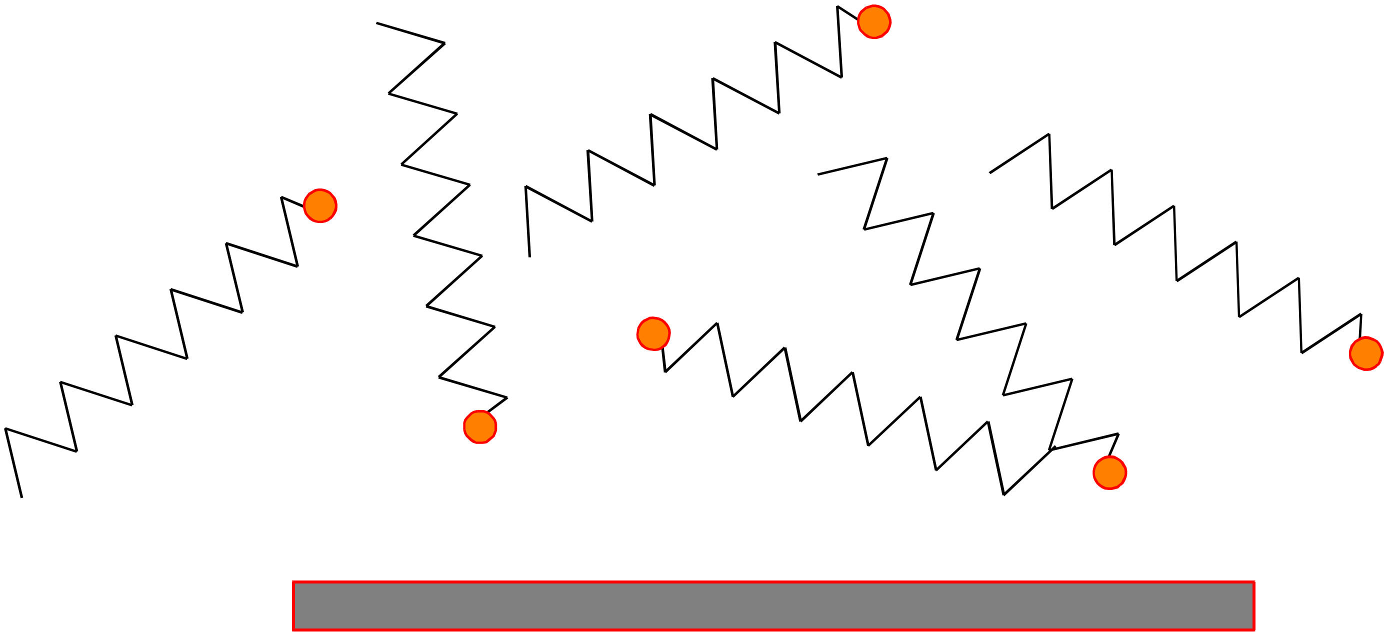
- Criteria
  - chemically inert, non-toxic
  - low critical temperature
- CO_2
  - critical temperature 31.1 ^oC
  - critical pressure 72.8 atm.(or 1073 psi)



- Exchange methanol with liquid CO2 at 25^{o}C and 1200 psi
- closeoff vessel and heated to 35 ^{o}C, no interface is formed.
- Vent vessel at a constant temperature above critical temperature.

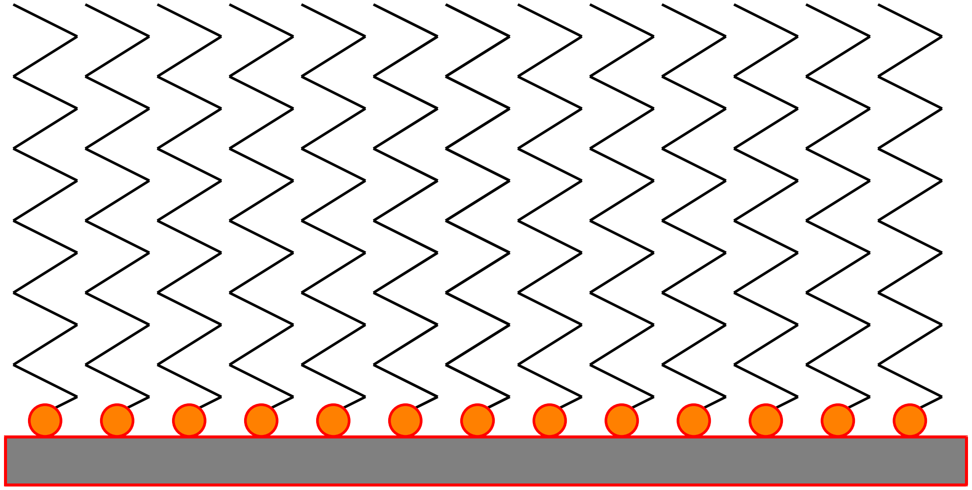
Antistiction Method III - Self-assembled Monolayer

- Forming low stiction, chemically stable surface coating using self-assembly monolayer (SAM)
- SAM file is comprised of close packed array of alkyl chains which spontaneously form on oxidized silicon surface, and can remain stable after 18 months in air.
- OTS: octadecyltrichlorosilane (forming $C_{18}H_{37}SiCl_3$)



Result of SAM Assembly

- Surface oxidation: H_2O_2 soak
- SAM formation
  - isopropanol alcohol rinse
  - CCl_4 rinse
  - OTS solution
  - CCl_4 rinse



Structural-Sacrificial Compatibility

TABLE 11.1 Possible Combination of Sacrificial Layer (Columns) and Structural Layer (Rows). "No" Indicates Generally Impossible Combinations.

	Sacrificial layer			
Structural layer	CVD PSG or thermal oxide	Photoresist	Parylene	Metal
LPCVD polysilicon	OK	No, deposition temperature too high for resist	No, deposition temperature too high for Parylene	No, many metals cannot sustain the high temperature of LPCVD polysilicon
LPCVD silicon nitride	OK	No, deposition temperature too high for resist	No, deposition temperature too high for resist	No, deposition temperature too high for resist
Metal	OK[1]	OK[2]	OK[3]	OK (if different metals)
Photoresist	No, HF etching solution may attack resist	No, structural layer and sacrificial layer are etched simultaneously	No, all methods for etching Parylene (including dry etching) attack the resist structural layer	OK
Parylene	OK	OK, organic solvents may attack resist but not Parylene	N/A	OK

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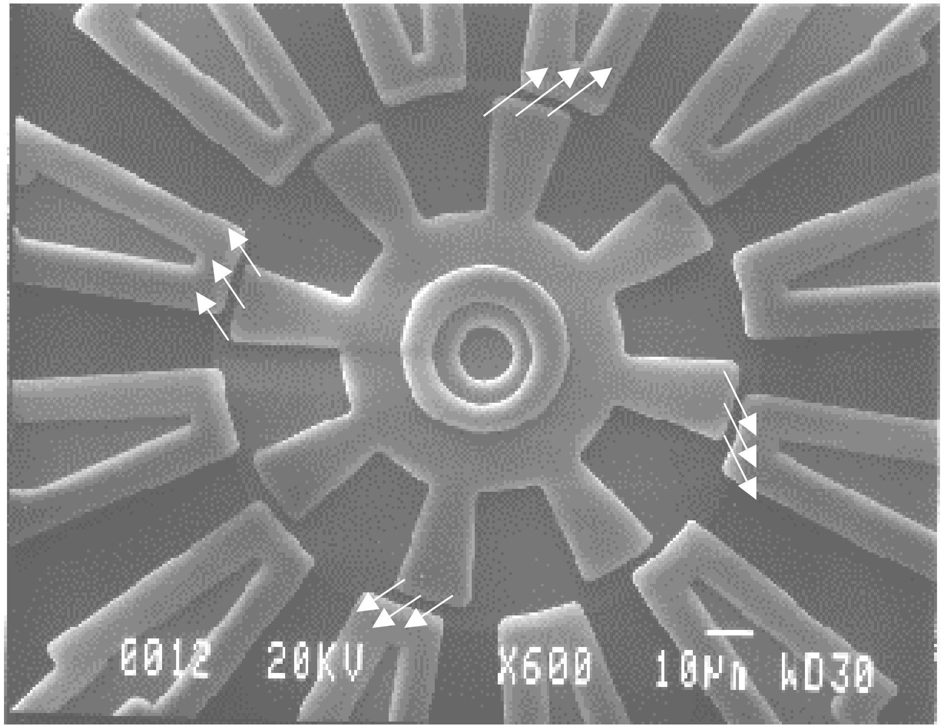
[1] Certain oxide etchants (such as concentrated HF) may attack certain metal.

[2] Evaporated metal may increase the temperature of wafer and cause polymer to locally melt. Carefully processing control is required.

[3] The Parylene (as sacrificial layer) must be removed using oxygen plasma, which may oxidize certain metals.

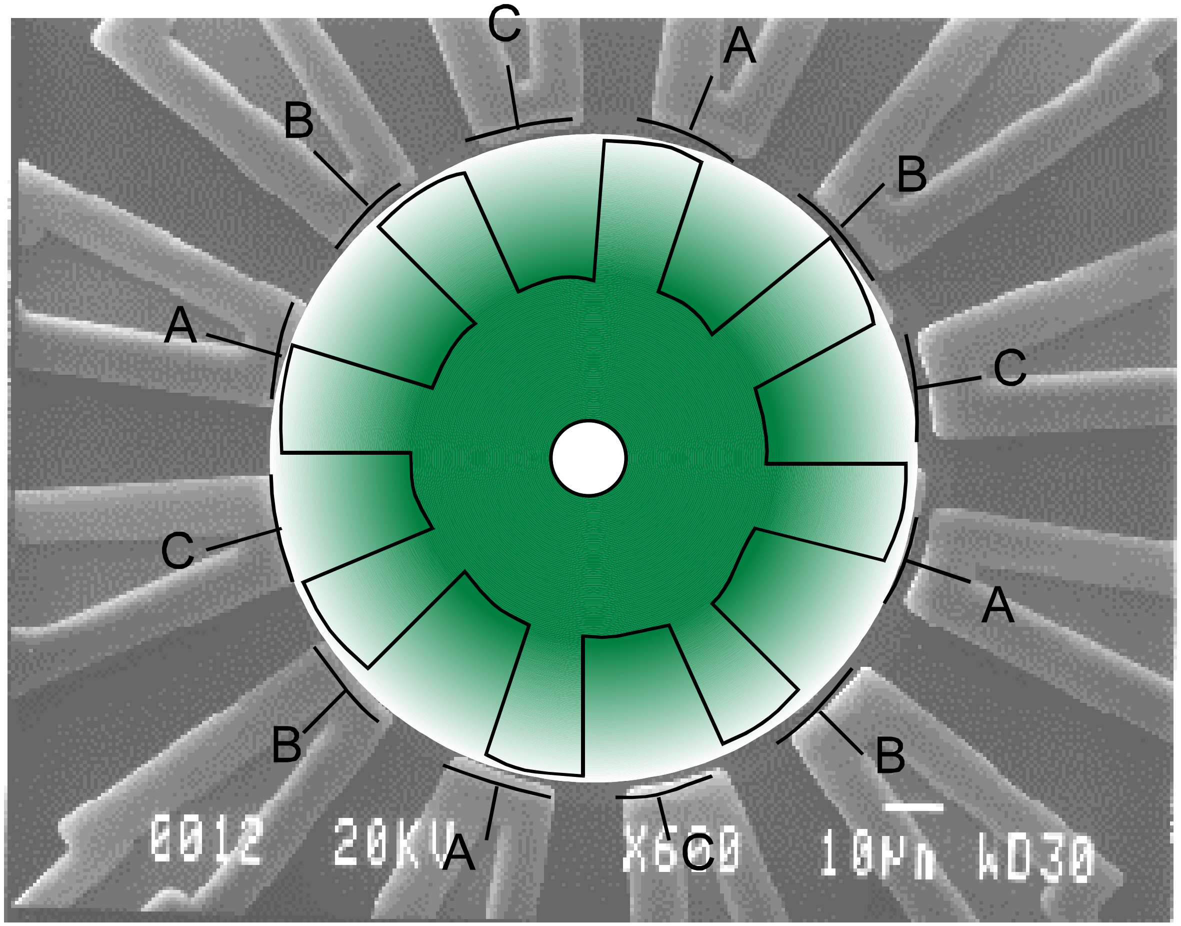
Why?

Actuators that Use Fringe Electric Field - Rotary Motor

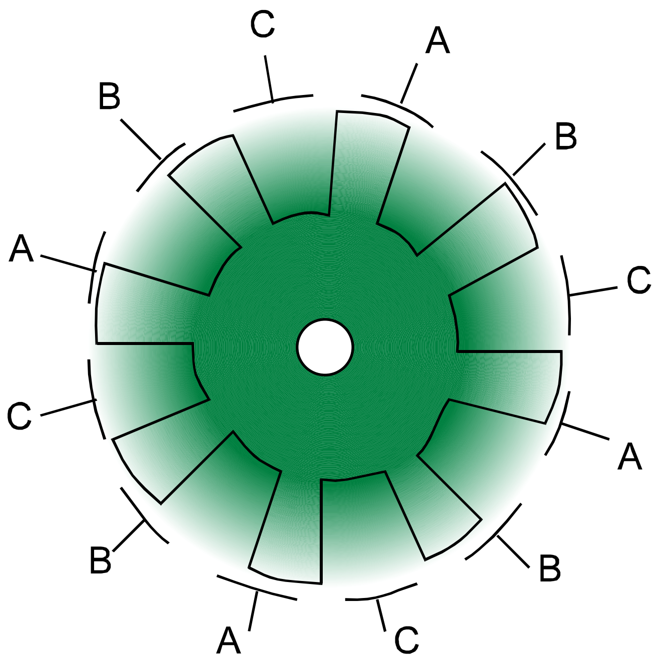


- Three phase electrostatic actuator.
- Arrows indicate electric field and electrostatic force. The tangential components cause the motor to rotate.

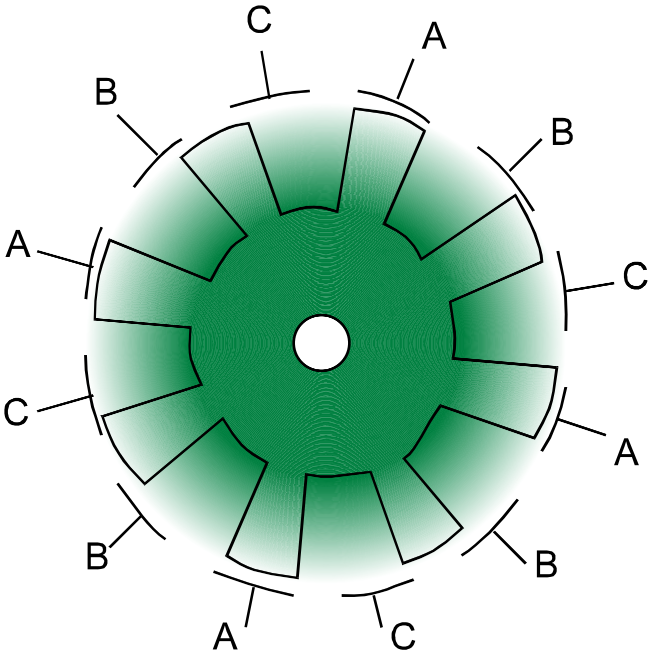
Three Phase Motor Operation Principle



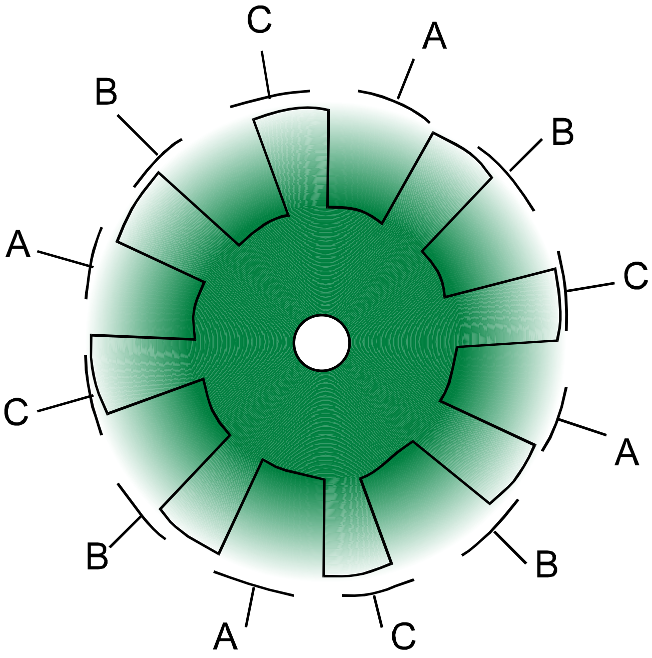
Starting Position -> Apply voltage to group A electrodes



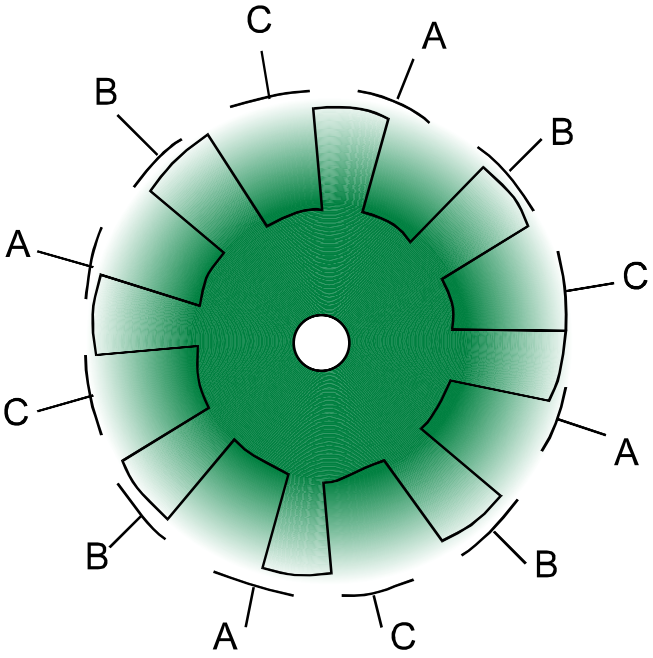
Motor tooth aligned to A -> Apply voltage to Group C electrodes



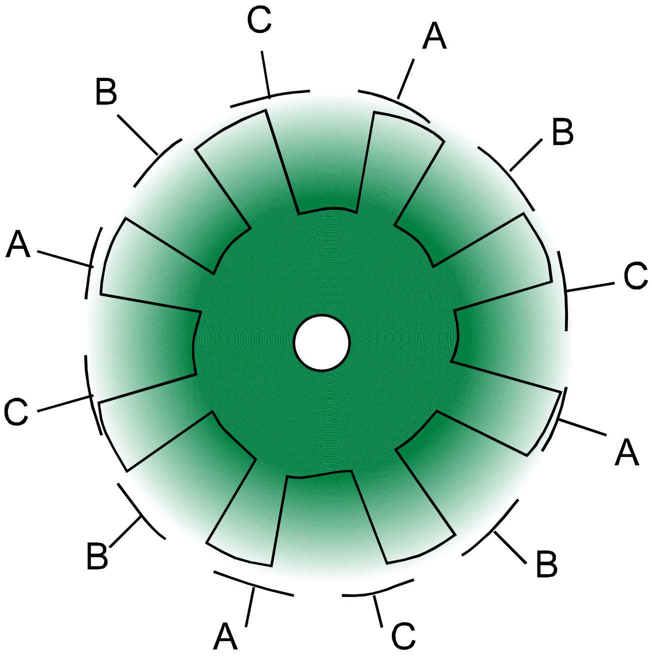
Motor tooth aligned to C -> Apply voltage to Group B electrodes

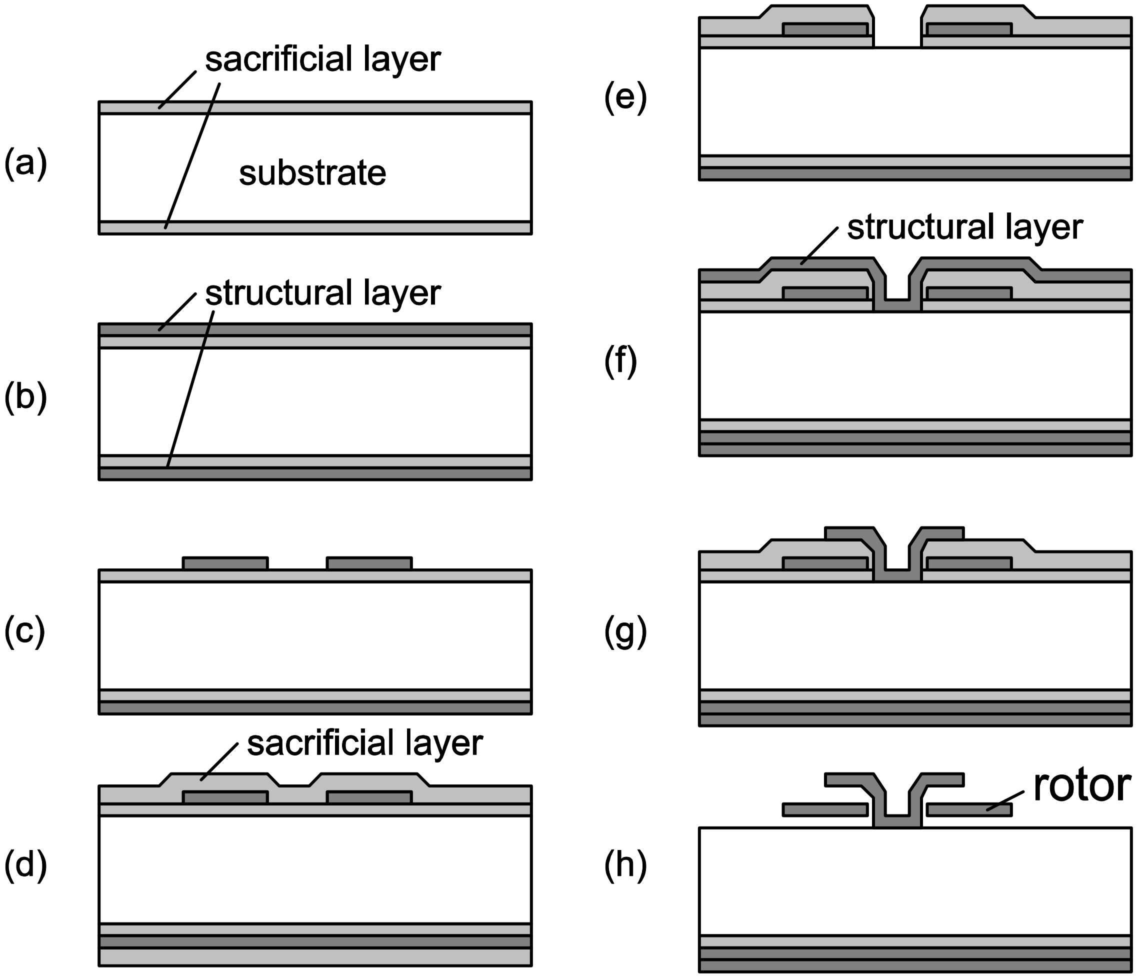


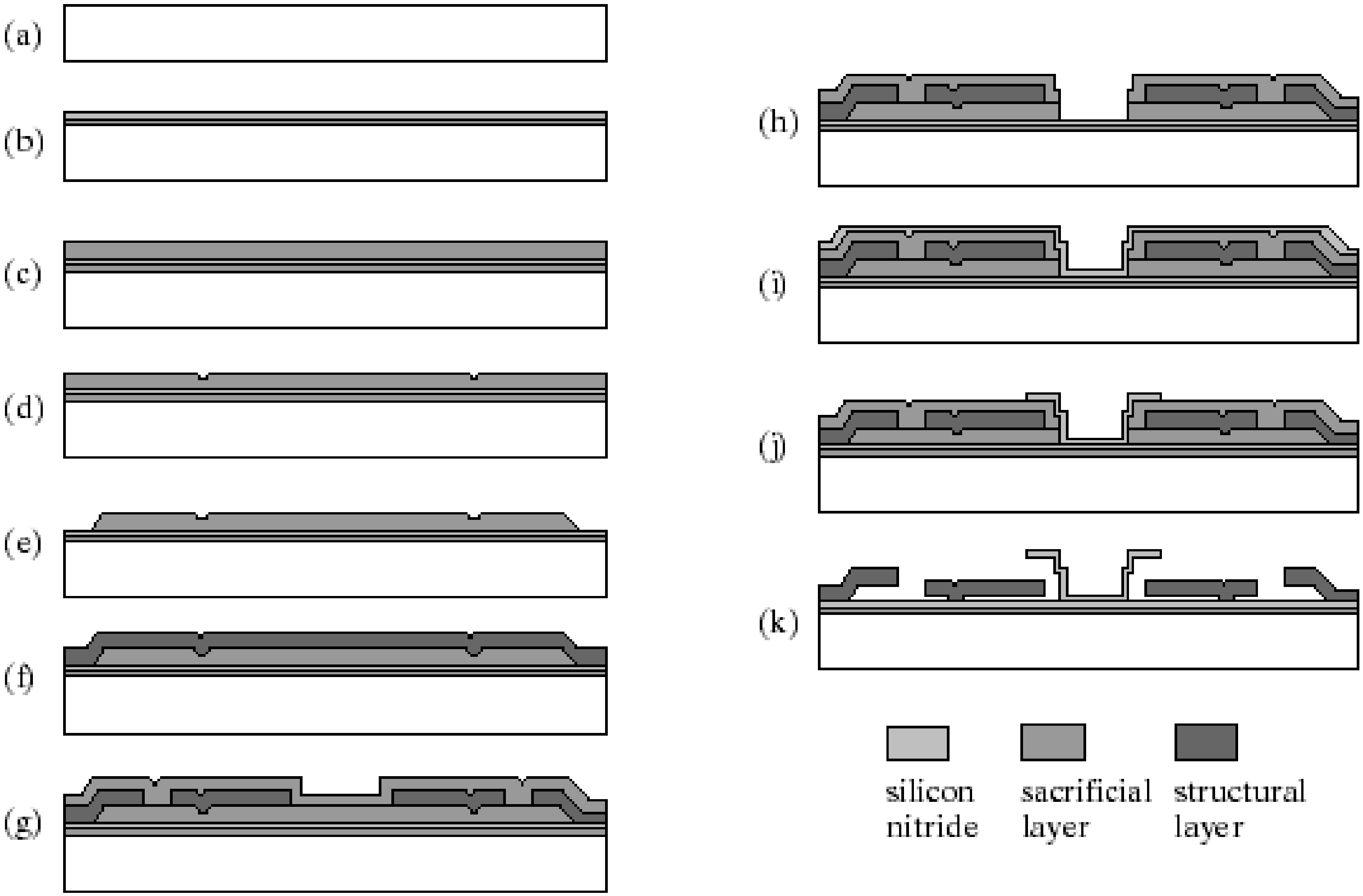
Motor tooth aligned to B -> Apply voltage to Group A electrodes

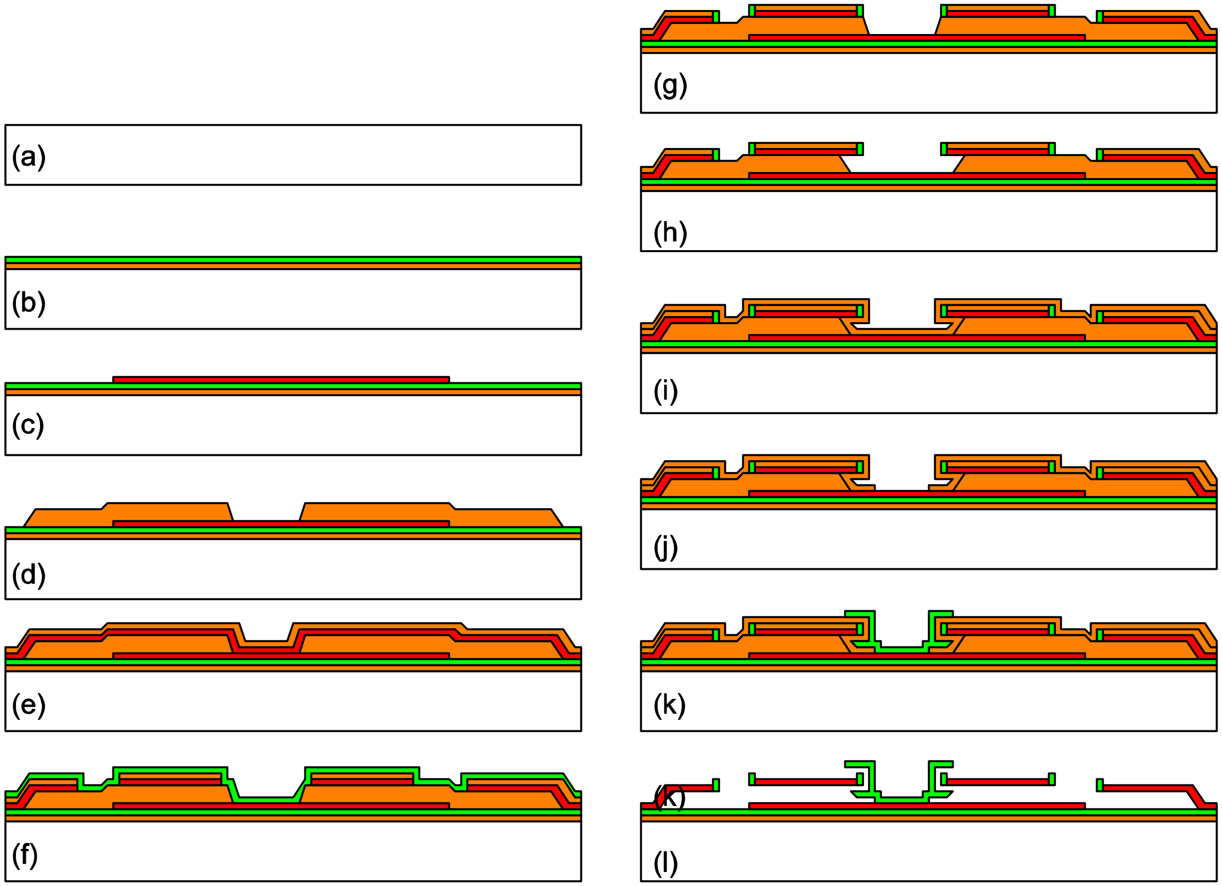


Motor tooth aligned to A -> Apply voltage to Group C electrodes




sacrificial layer
(a)
substrate
structural layer
(b)
(c)
sacrificial layer
(d)
(e)
structural layer
(f)
(g)
rotor
(h)

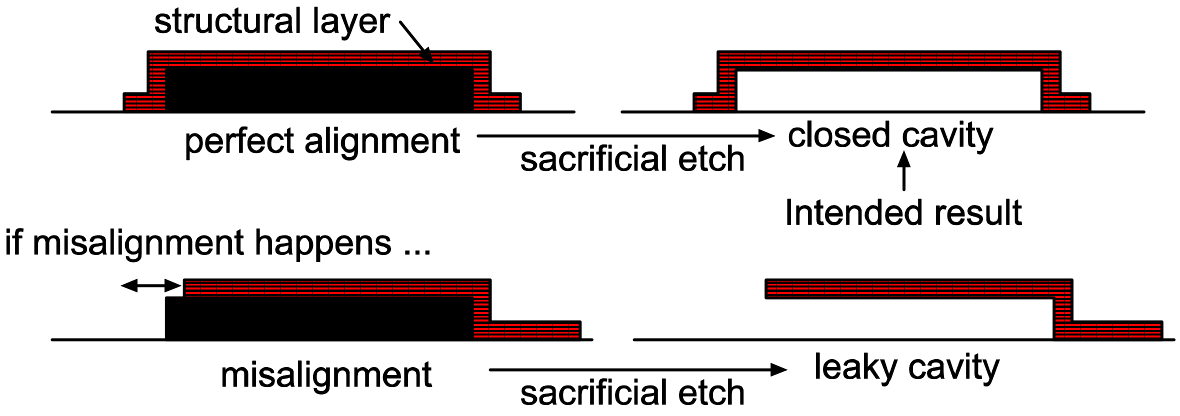

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
silicon nitride
sacrificial layer
structural layer


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(k)
(l)

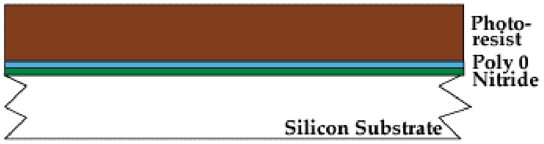
Foundry Process

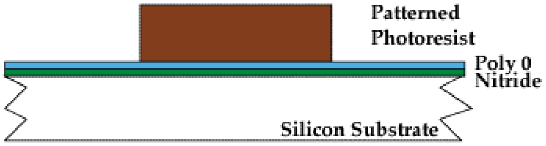
- Why:
  - Reduce the cost of development by providing standard and unusual processes at reasonable cost.
- How:
  - Wafer sharing: many processes are performed on one wafer with many users sharing the mask.
    - Drawback: limited process materials and steps
  - Machine sharing: a user's wafer is dedicated and ships back-and-forth among several vendors.
    - Drawback: long development and transport time
  - Dedicated foundry: a user's wafer is handled at one site by dedicated personnel.
    - Drawback: highest cost among all forms of foundry process.

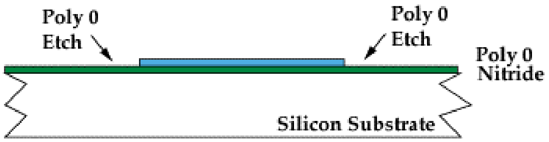
The Importance of Design Rules

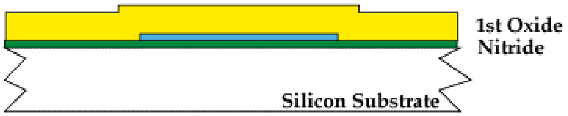


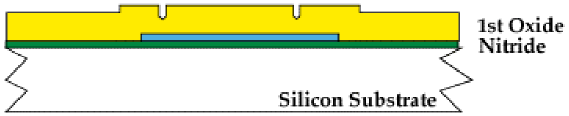
Example: MUMPS Process
Multi User MEMS Process

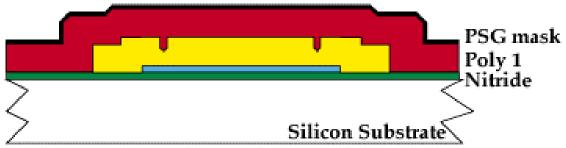


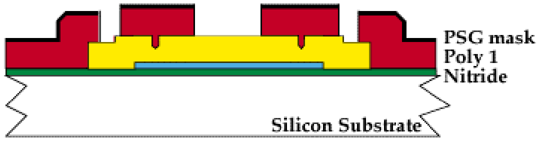


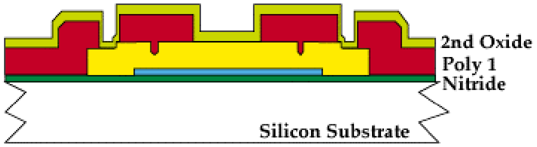


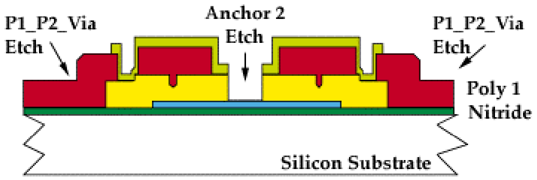


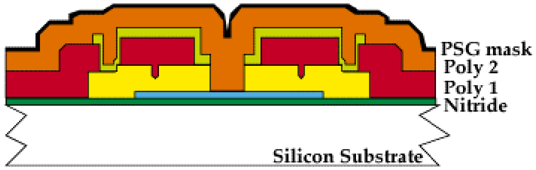


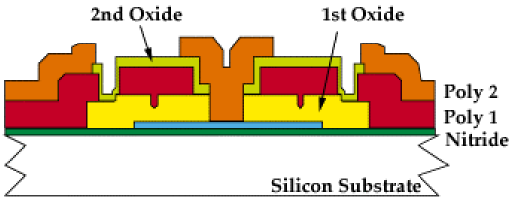


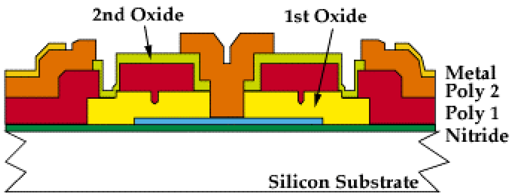


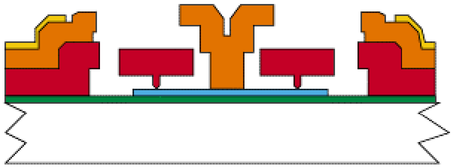




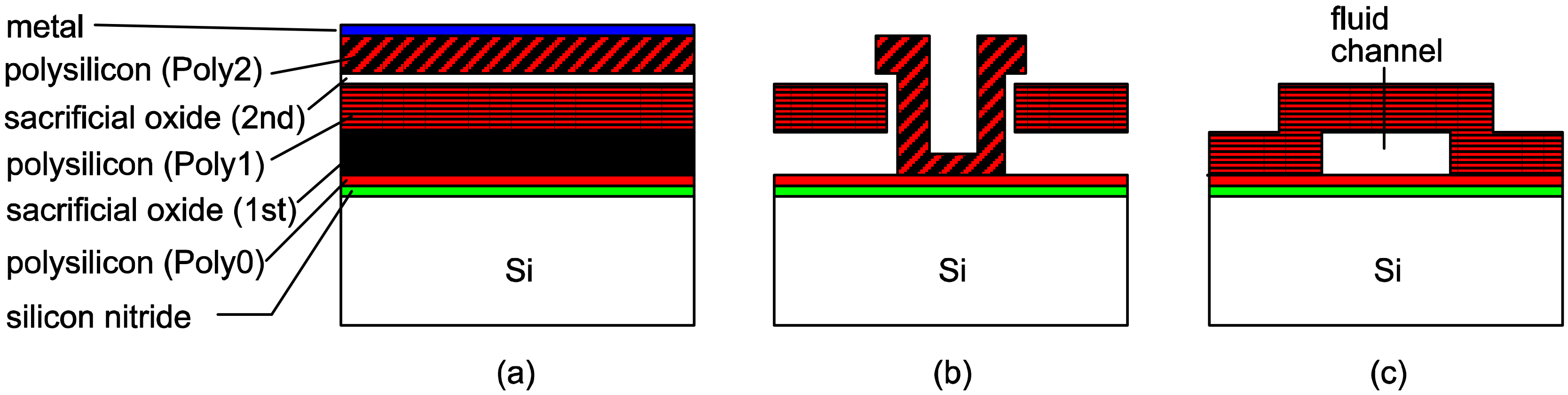


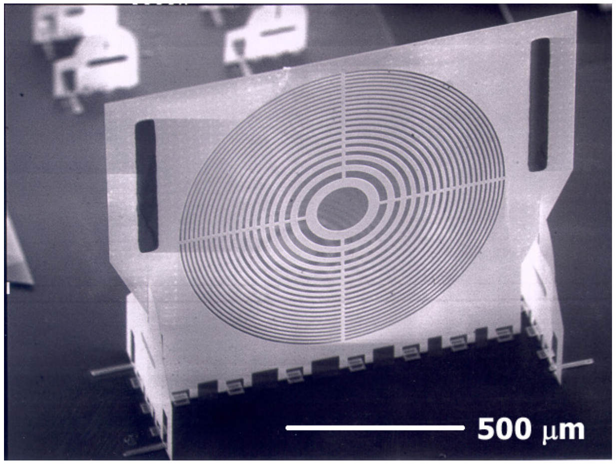


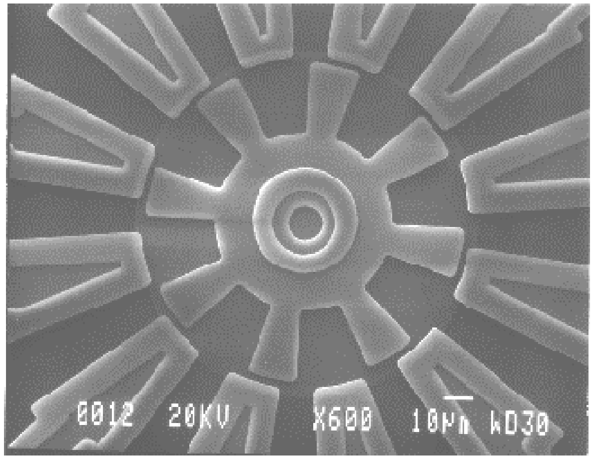


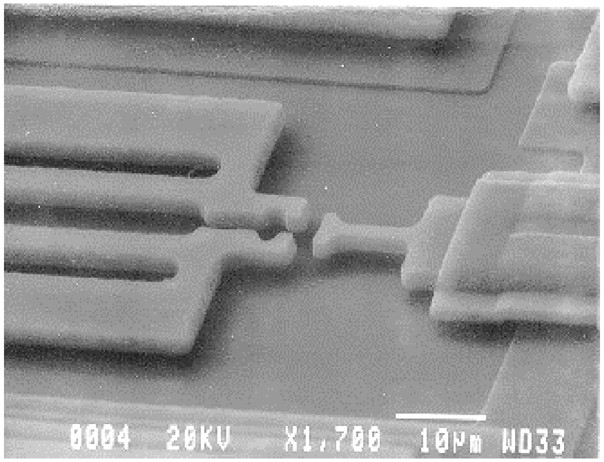


The Versatility of MUMPS





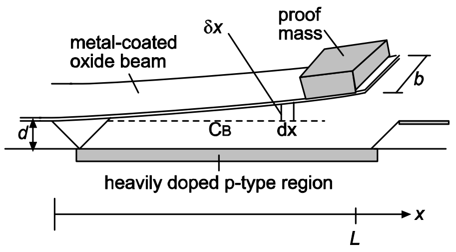


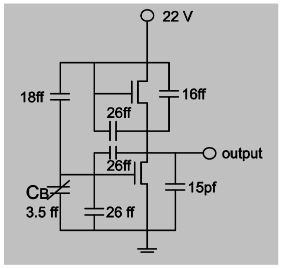


Compatibility Table

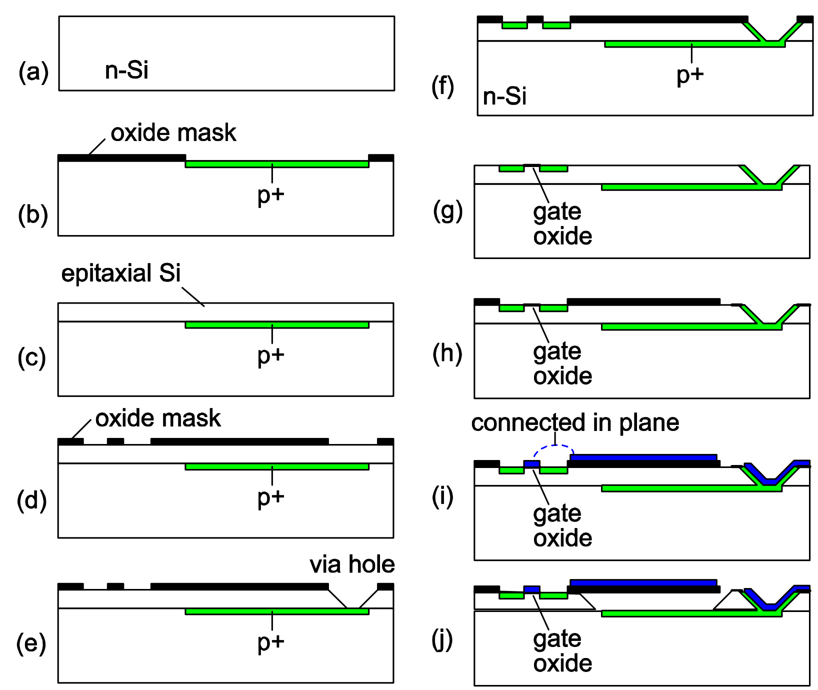
	Polysilicon	Silicon oxide	Photoresist (cured)	Metal
Dry plasma etching	Yes	Yes, slower speed	Yes, slow	No. Sputtering is possible
HF wet etching	No	Yes	No, avoid long soak	No, avoid long contact
Uncured photoresist	No	No	Yes	No
Photoresist developer	No	No	Yes	No
Organic rinse	No	No	Yes	No
Baking	No	No	No	No
Metal etchant	No	No	No	Yes

Case 4.1, Electrostatic Actuators





read-out circuit

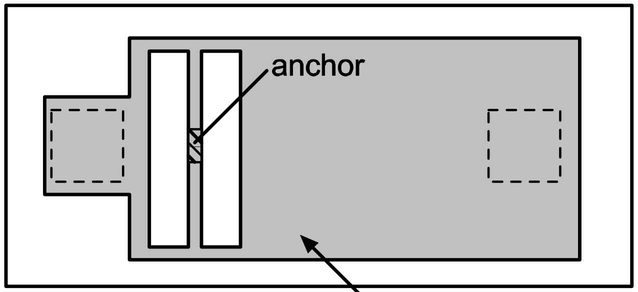


- Curved beam due to intrinsic stress in the cantilever.
- Helps:
  - Release
- Hinders:
  - Capacitance calculation

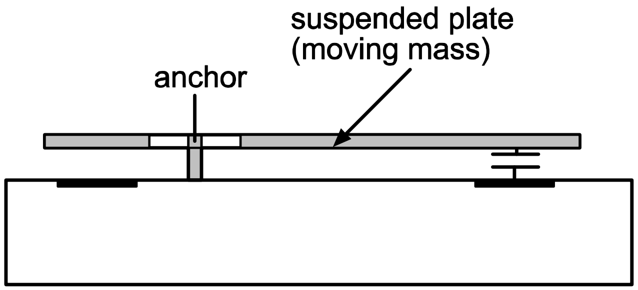
How good is the design and process?

- Design:
  - Advantage:
    - Direct integration of mechanical cantilever with FET transistors
  - Low noise sensor
- Materials
  - Relatively difficult material
  - Exotic wafer
- Processes
  - Difficulties:
    - Cantilever release using web silicon etchant may be a problem
  - Requires foundry process and new process development if industrialized

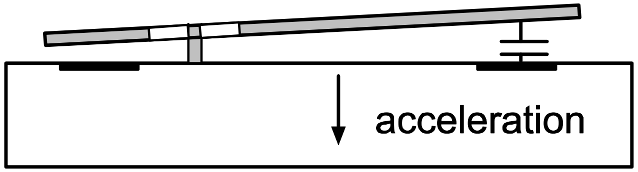
Case 4.2: Torsional Capacitive Accelerometer



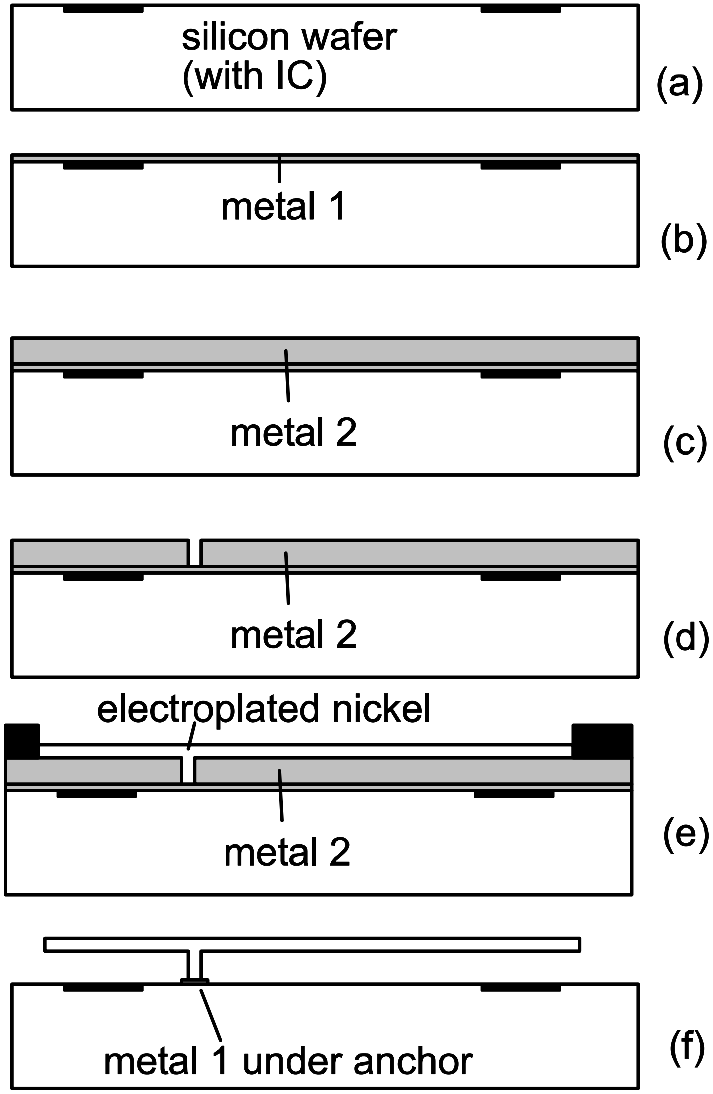
Top view



Side view (a=0)



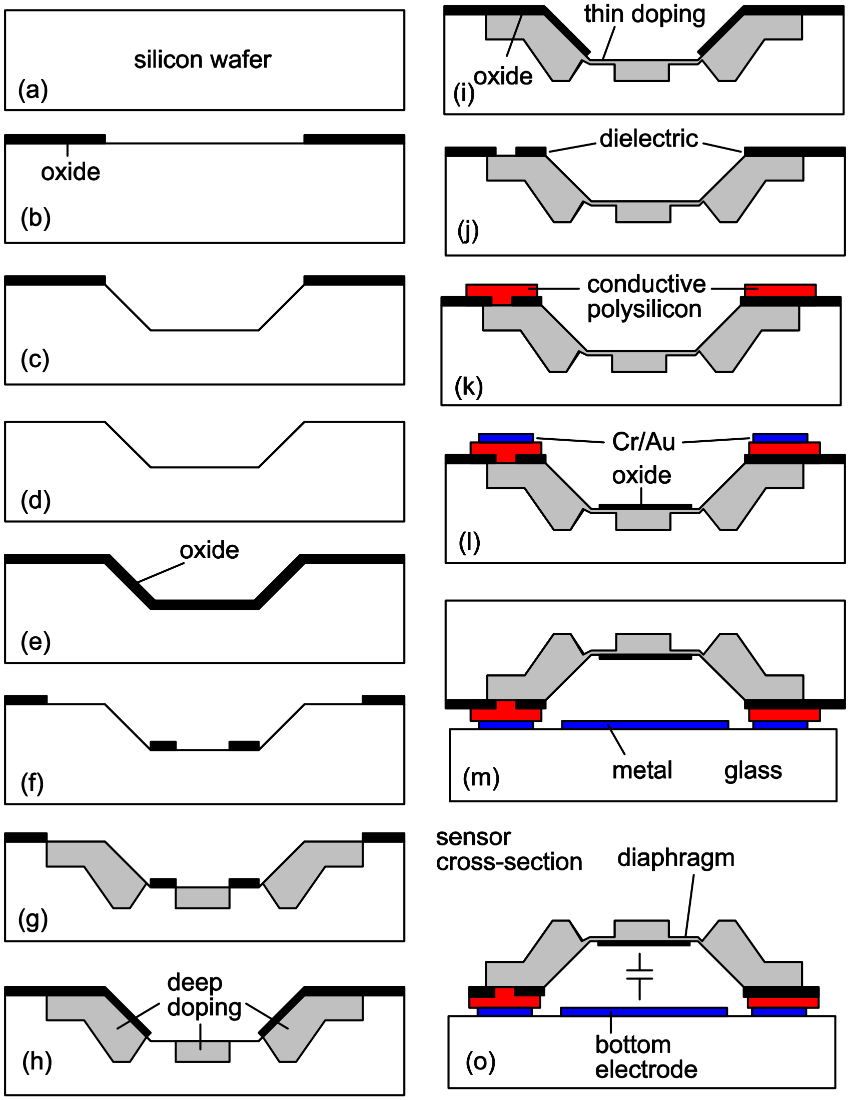
Side view (under acceleration)



How good is this design?

- Design:
  - Simple
  - No electronics integration
    - Greater noise
- Material:
  - Simple
  - Readily available
- Fabrication process
  - Does not require exotic materials or processes
  - Sacrificial release may be a problem, like the previous case

Case 4.3: Membrane Parallel Plate Pressure Sensor



Evaluation

- Design:
  - Results in hermetically sealed structures
  - Result in large gap distance to reduce damping
- Materials:
  - Silicon materials
  - Doped silicon
- Fabrication:
  - Length steps
  - Delicate bonding and handling
  - Process development is lengthy

Conclusions

- Electrostatic sensing and actuation
  - Types of electrode configurations
  - Advantages and weaknesses
- Surface micromachining
  - Criteria for designing a successful process
  - Basic knowledge of materials, etchants, and their interactions
  - Analyze the quality of a process