Nanolectronics

Information Processing with Micro-Electro-Mechanical-Systems (MEMS)

Lecture #7

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Outline

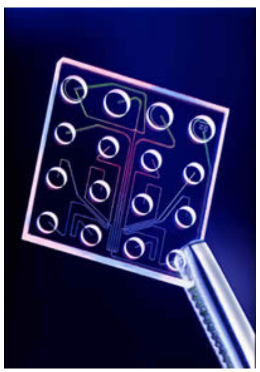
- **Introduction: Micro/Nano-Electro-Mechanical Systems**
- **M/NEM switches/relays for logic**
- **M/NEM resonators:**
  - Passive resonators, filters and mixers
  - Resonant gate or body transistors to amplify small signals **M/NEM inertial sensors:**
  - Accelerometers

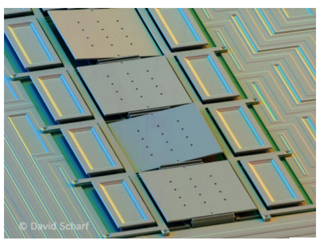
Introduction

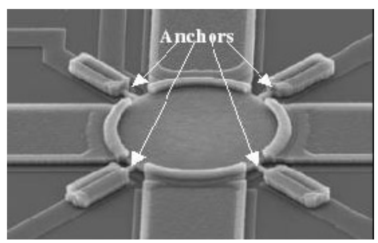
MEMS = Micro-Electro-Mechanical Systems

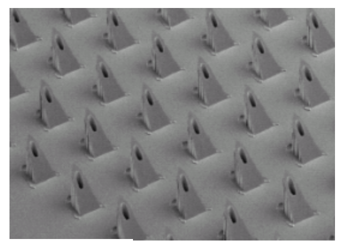
(include suspended and/or movable parts)

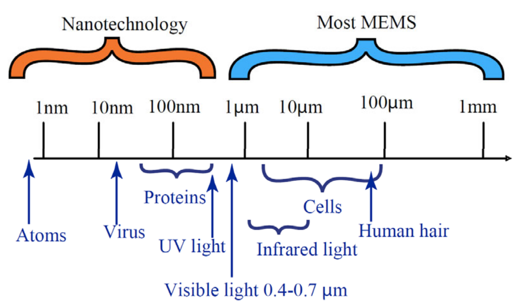
Microfluidics | Optical | Radio Frequency | Bio | Energy scavenging





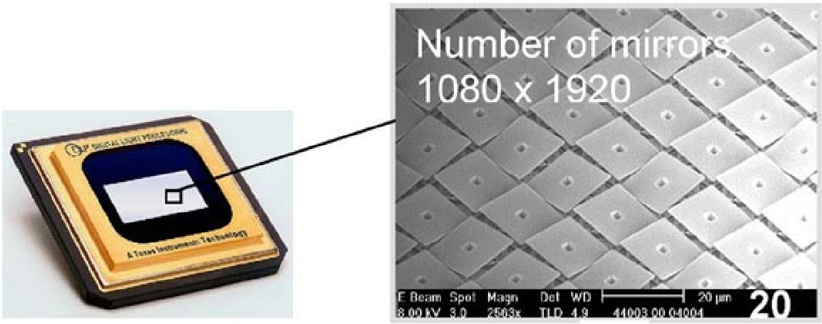






Information processing with MEMS short history

- 1967 - Invention of **surface micromachining** (Nathanson, Resonant Gate Transistor)
- 1970 - Micromachined **silicon pressure sensor** demonstrated (Petersen)
- 1970 - First **silicon accelerometer** demonstrated (Kulite)
- 1977 - First **capacitive pressure sensor** (Stanford)
- 1984 - First **polysilicon MEMS device** (Howe, Muller)
- 1988 - Rotary **electrostatic side drive motors** (Fan, Tai, Muller)
- 1989 - Lateral **comb drive** (Tang, Nguyen, Howe)
- 1991 - Polysilicon hinges developed (Pister, Judy, Burgett, Fearing)
- 1992 - **Multi User MEMS Process** (MUMPs) is introduced by MCNC, (now MEMSCAP)
- 1993 - First **surface micromachined accelerometer** (ADXL50) sold, (Analog Devices)
- 1998 - Demonstration of **DMD (Digital Mirror Device),** (Texas Instruments)



(a) (b)

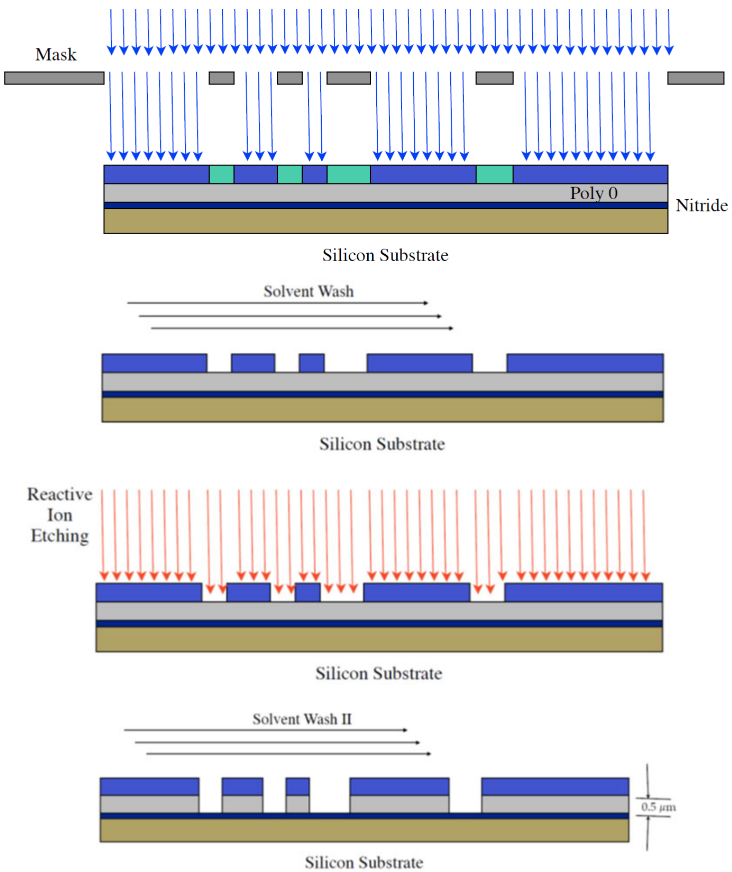
MEMS micro/nano fabrication

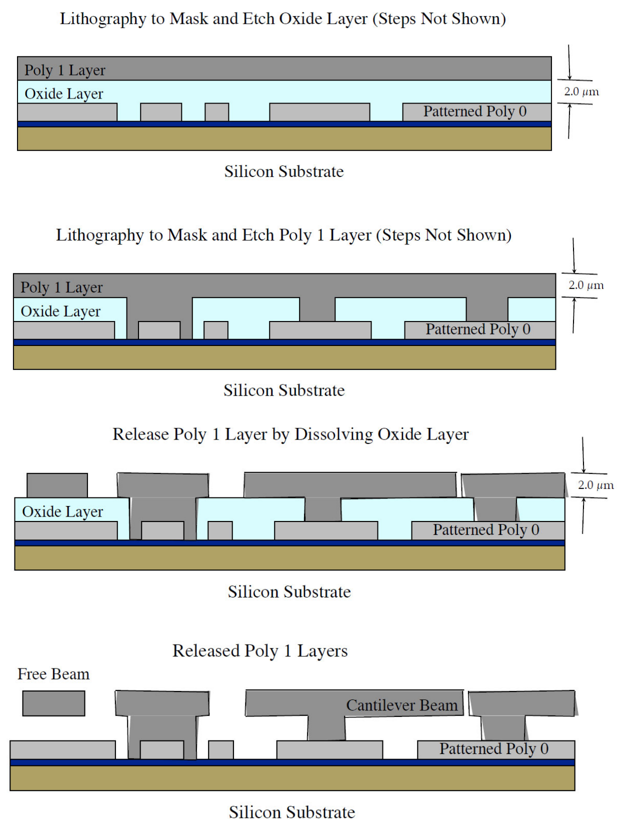
- MEMS are fabricated with a unique set of technologies collectively referred to as 'microfabrication' or 'micromachining'
- There are two main areas of micromachining:

❑ **Surface Micromachining**, which is based on the successive deposition and etching of thin films of material such as silicon nitride, polysilicon, silicon oxide and gold.

❑ **Bulk Micromachining**, which is based on the etching andbonding of thick sheets of material such as silicon oxides and crystalline silicon.

Example of surface micromachining microcantilever fabrication





MEMS actuation mechanisms

	Voltage (V)	Current (mA)	Power (mW)	Size	Switch time (μs)	Force (contact) (μN)
Electrostatic	1-100	~0	~0	Small	1-200	50-1000
Thermal	3-5	1-100	<500	Large	300-10'000	500-5'000
Magnetic	3-5	10-100	<500	Medium	300-1'000	50-200
Piezoelectric*	3-20	~0	~0	Medium	50-500	50-200

* Recent attention to quartz, GaAs, ZnO, PZT: $Pb(Zr_xTi_{1-x})O_3$): mechanical stress polarizes the material → electrical field, works also reversely!

Table adapted after Rebeiz [1]

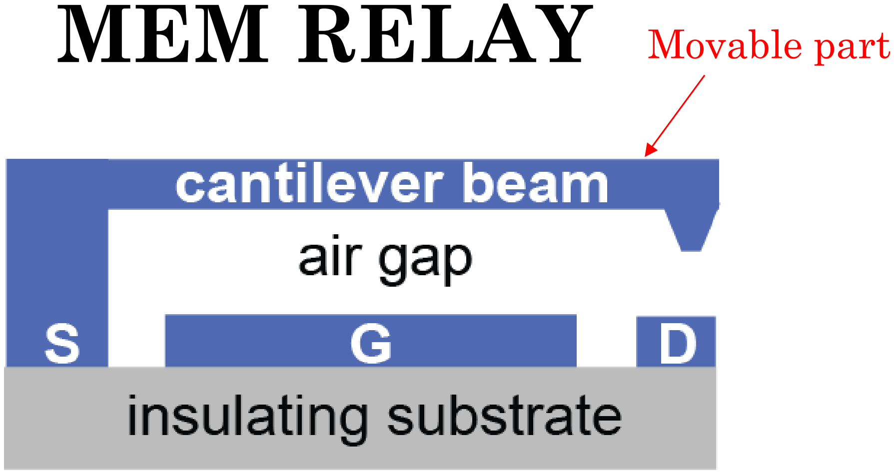
[1] Gabriel M. Rebeiz, RF MEMS: Theory, Design, and Technology. ISBN: 978-0-471-20169-4, Wiley, March 2003.

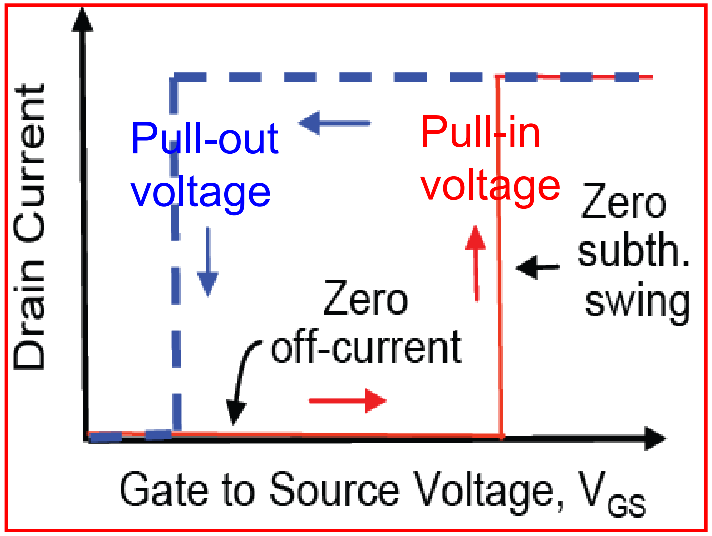
MEMS Switch/Relay

Electro-mechanical information processing:

as a **multi-state logic**, with the logic states dictated by a spatial configuration of movable objects

MEM RELAY





Electromechanical design of pull-in voltage

Pull-in / Pull-out electromechanical hysteresis of capacitive switch

$$g_o = \textit{zero-voltage gap spacing}$$

$$g = g_o - x$$

$$g_{eff} = g_o + \frac{g_\varepsilon}{\varepsilon_r} \approx g_o$$

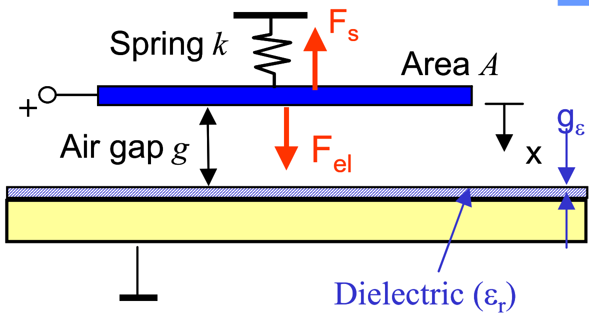
$$F_{el} = \frac{\varepsilon_0 A V^2}{2g^2}$$

$$F_s = k(g_o - g)$$

$$C_{up} = C(V=0) = \varepsilon_0 \frac{A}{g_{eff}}$$

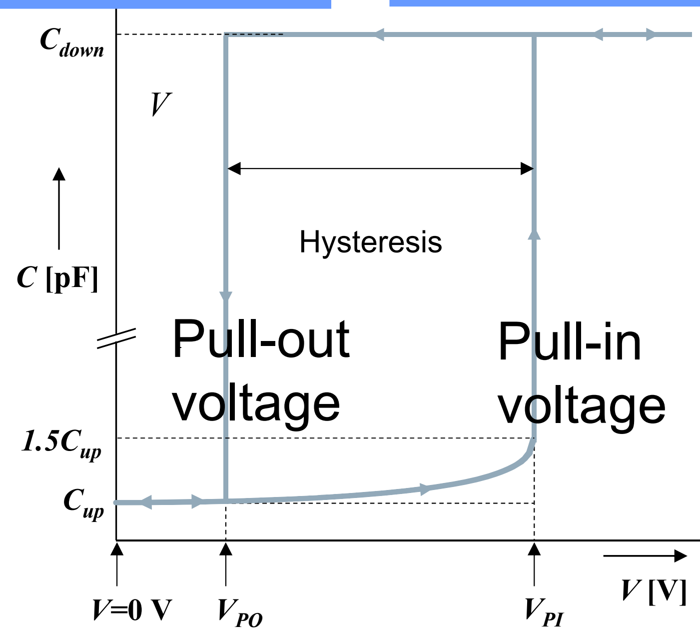
$$C_{down} = C(V > V_{PI}) = \varepsilon_0 \varepsilon_r \frac{A}{g_\varepsilon}$$

$$\frac{C_{down}}{C_{up}} = \frac{\varepsilon_r g_{eff}}{g_\varepsilon} \approx \frac{\varepsilon_r g_o}{g_\varepsilon}$$



$$V_{PO} = \sqrt{\frac{2 k g_o g_\varepsilon^2}{\varepsilon_r^2 \varepsilon_0 A}}$$

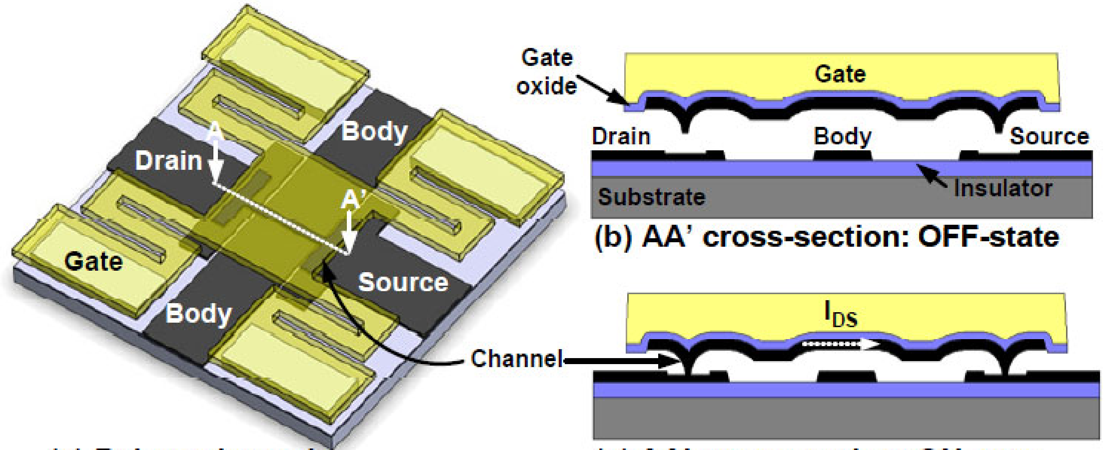
$$V_{PI} = \sqrt{\frac{8}{27} \frac{k g_{eff}^3}{\varepsilon_0 A}}$$



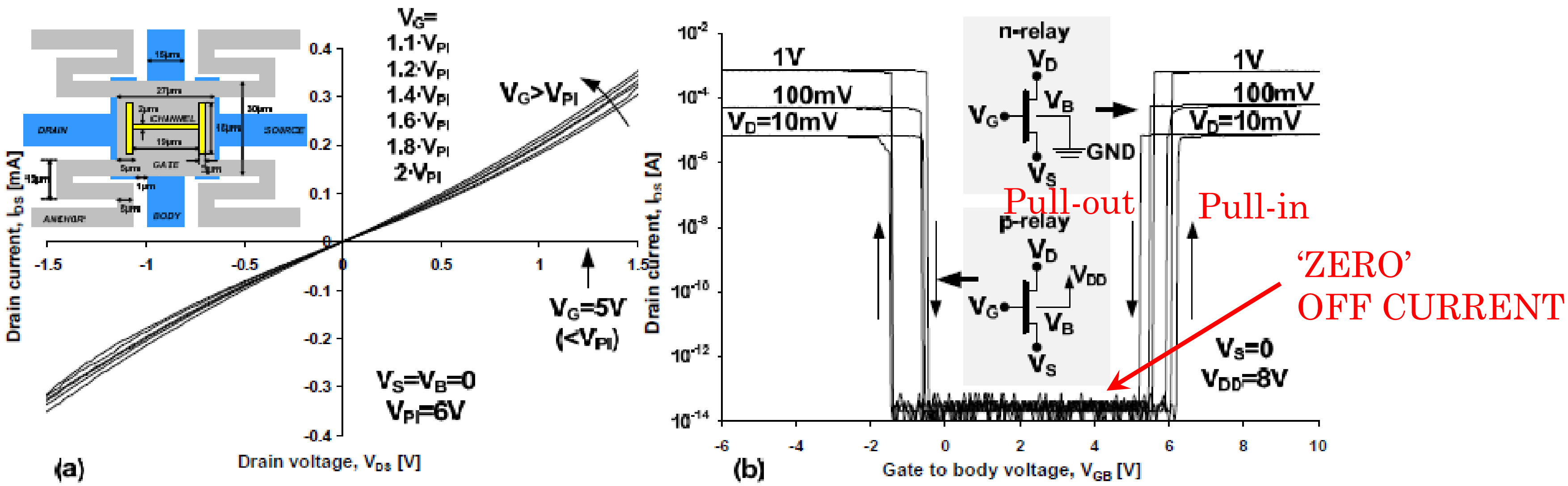
Pull-in @ 1/3 of the air gap!

Source: H. Tilmans, IMEC.

UC Berkeley's 4-terminal relay



(a) Relay schematic
(b) AA' cross-section: OFF-state
(c) AA' cross-section: ON-state



… and mechanical inverter operation

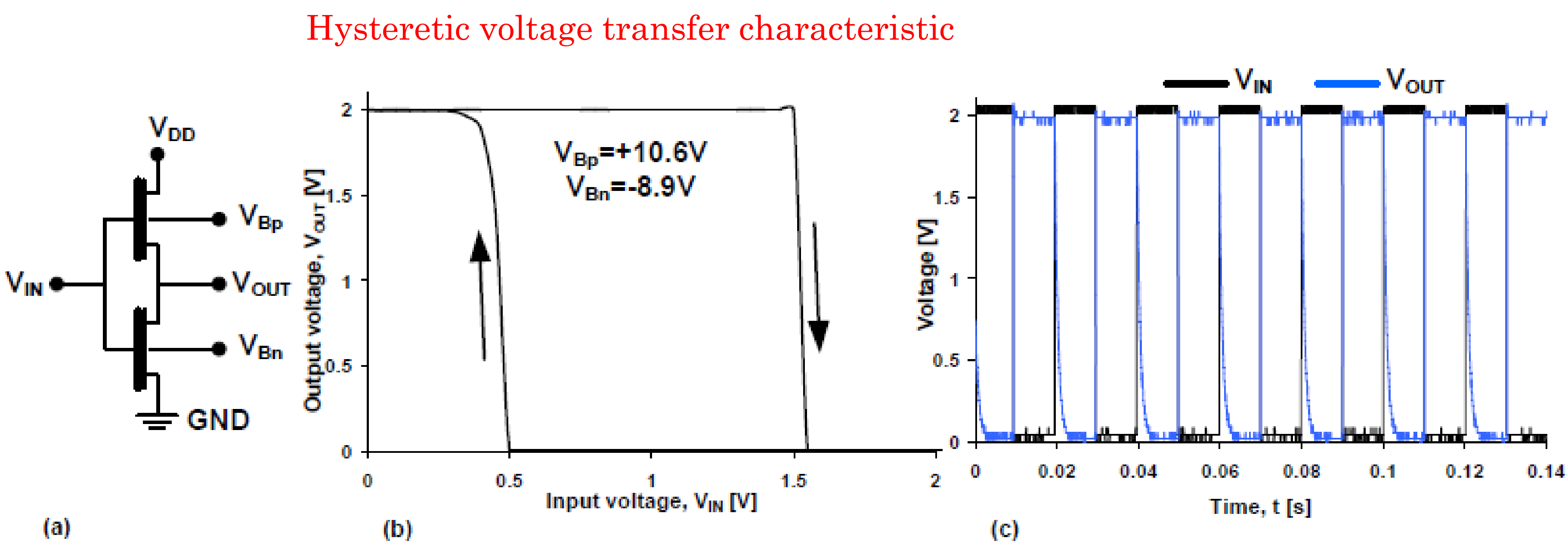
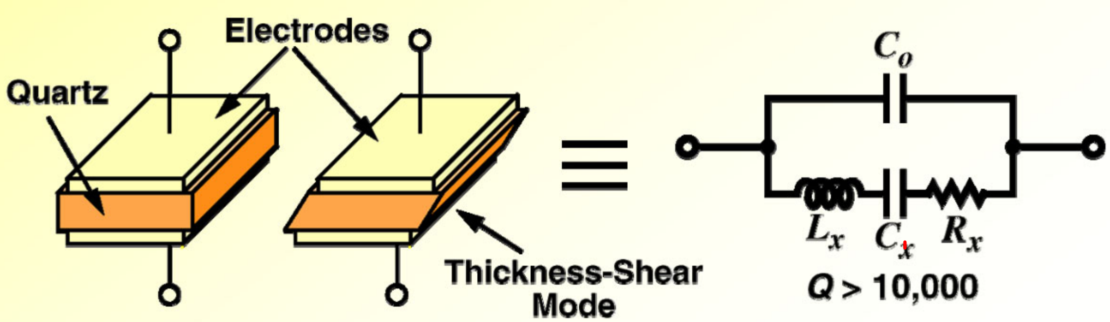


Fig. 6.18. (a) Relay inverter schematic. Two similar devices are operated in n-type and p-type modes. (b) Measured static and (c) dynamic characteristics [34]. V_{IN} is a f=50Hz square wave.

Rationale for MEMS resonators: High Quality factor, Q

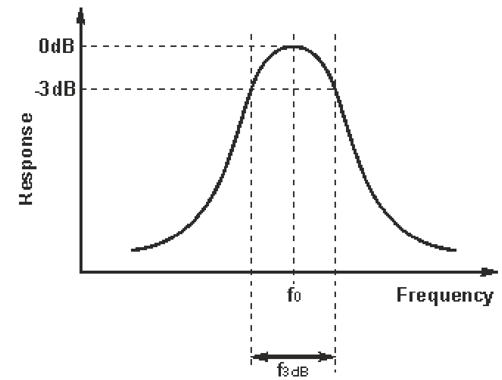
Information processing as **vibrational modes** of mechanical elements, based upon waves.

- ***Problem***: IC's cannot achieve *Q*'s in the thousands
  - transistors → consume too much power to get *Q*
  - on-chip spiral inductors → *Q*'s no higher than ~10
  - off-chip inductors → *Q*'s in the range of 100's
- ***Observation***: vibrating mechanical resonances → *Q* > 1,000
- ***Example***: quartz crystal resonators (e.g., in wristwatches)
  - extremely high *Q*'s ~ 10,000 or higher ($Q \sim 10^6$ possible)
  - mechanically vibrates at a distinct frequency in a thickness-shear mode



C. T.-C. Nguyen, FCS'05 Tutorial: "MEMS for Frequency and Timing References", 8/28/05

$$Q = \frac{F_0}{F_{3dB}}$$



Q of a tuned circuit with respect to its bandwidth

$$Q = \frac{E_{stored}}{E_{lost\ per\ cycle}}$$

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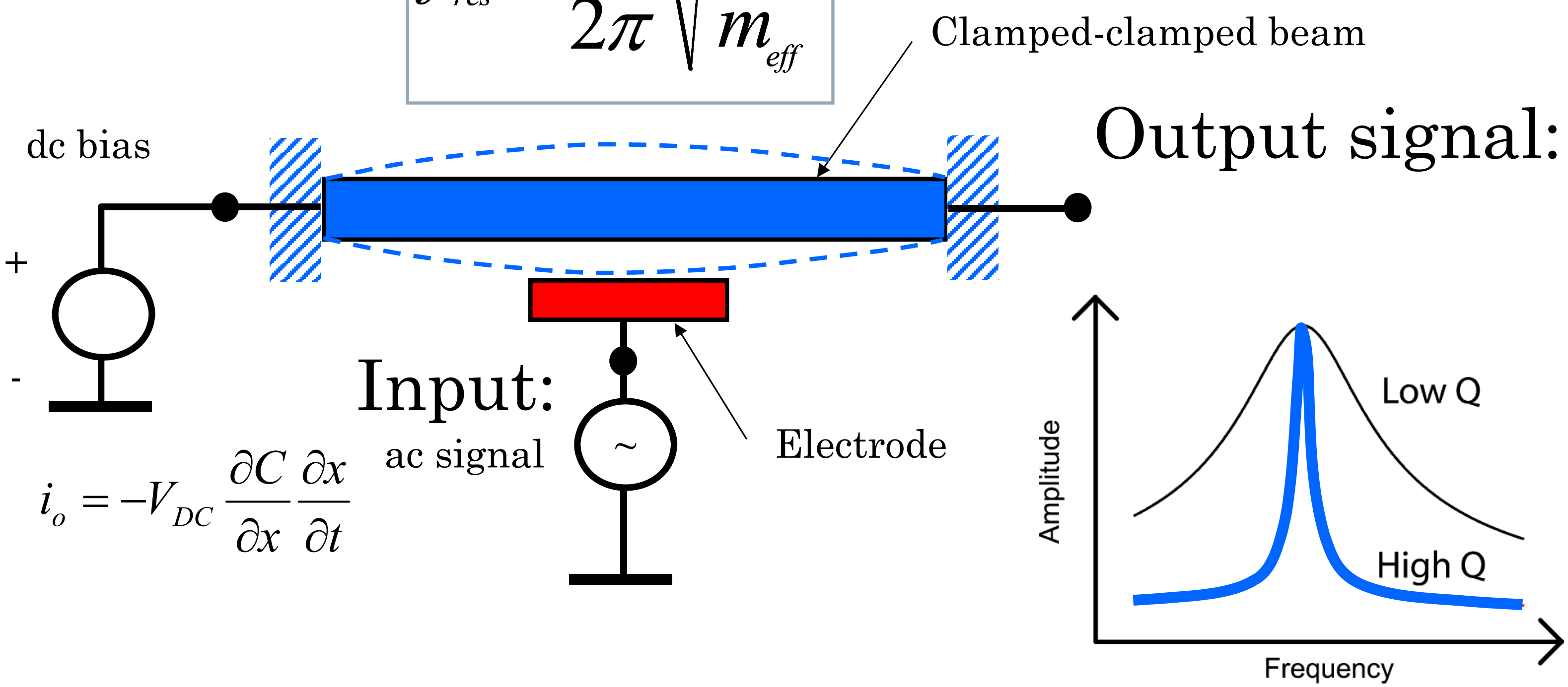
Principle

Micro-Electro-Mechanical resonator

Resonance frequency:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}}$$



$$i_o = -V_{DC}\frac{\partial C}{\partial x}\frac{\partial x}{\partial t}$$

MEM resonator is tuneable in frequency

Mechanical domain equations:

$$mx'' + bx' + kx = F$$

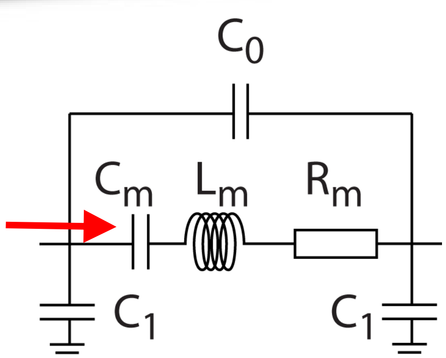
Electrical domain analogy:

$$Lq'' + Rq' + (1/C)q = V_i$$

L: motional inductance

R: Motional resistance

1/C: Stiffness



Tuning the resonance frequency: stiffness!

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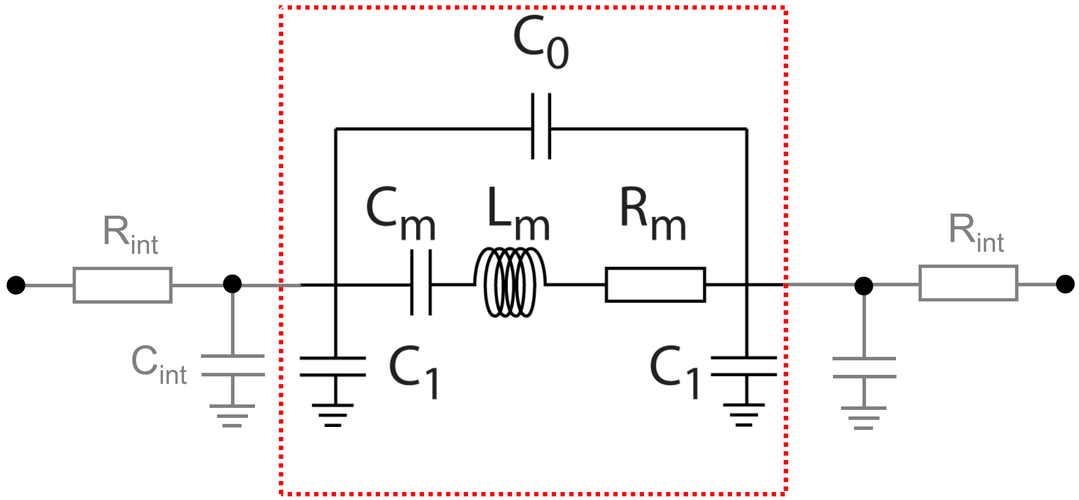
Motional to electrical equivalent parts and electrical small signal circuit

$$L_m = \frac{m_{eff}}{2V_{DC}^2\left(\frac{\partial C}{\partial x}\right)^2}$$

$$C_m = \frac{2V_{DC}^2\left(\frac{\partial C}{\partial x}\right)^2}{k_{eff}}$$

$$R_m = \frac{\omega m_{eff}}{2QV_{DC}^2\left(\frac{\partial C}{\partial x}\right)^2}$$



Motional resistance

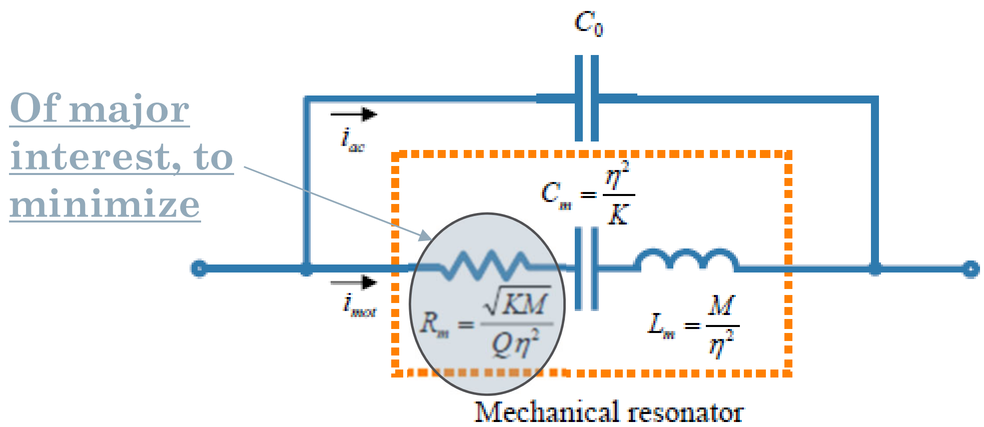
$$R_m = \frac{k_{eff}\, g^4}{\varepsilon_o^2 A^2 \omega Q V_{DC}^2}$$

Need for low motional resistance & nanogaps

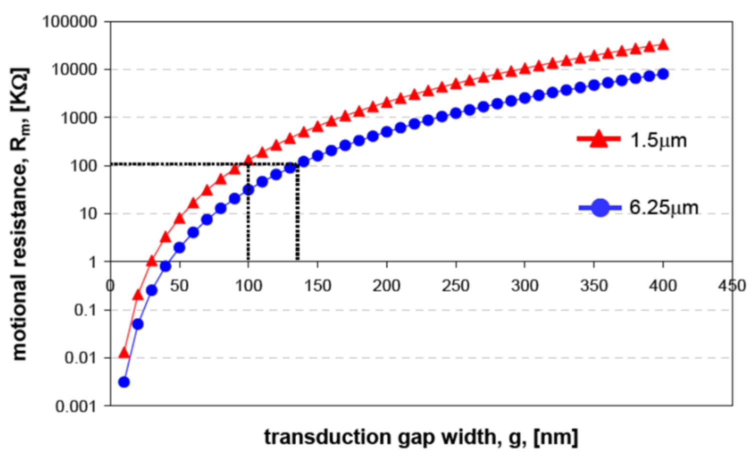
Motional resistance:

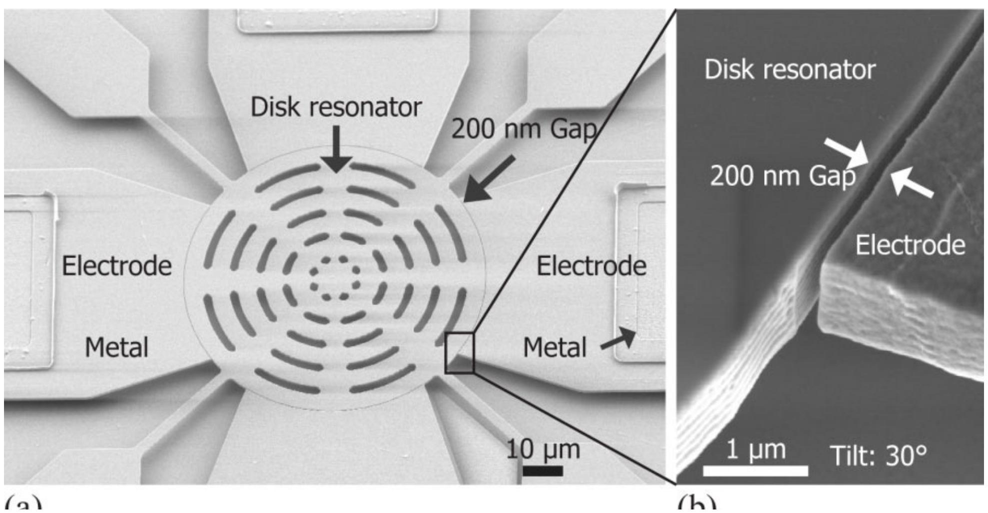
$R_m \sim gap^4/voltage^2$

(1/10 gap, 1/10'000 R_m)



Example:
f_{res}=31MHz, r=40um, t_{Si}=1.25um
Deep submicron gaps: 100-200nm,
Q>20'000, R_m=130kOhm





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Quality factor mechanisms

$$Q \equiv \omega * \frac{\overline{Energy\ stored}}{Energy\ loss/\sec} \equiv \frac{\omega_o}{\Delta\omega}$$

Mechanism #1:
Material defect losses

Mechanism #3: Gas damping (not an issue in vacuum or for bulk resonators)

$$\frac{1}{Q} = \frac{1}{Q_{defects}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{viscous}} + \frac{1}{Q_{support}}$$

Mechanism #2: Thermoelastic damping (TED)

Mechanism #4: Anchor losses, needs design optimization, important @ high frequency

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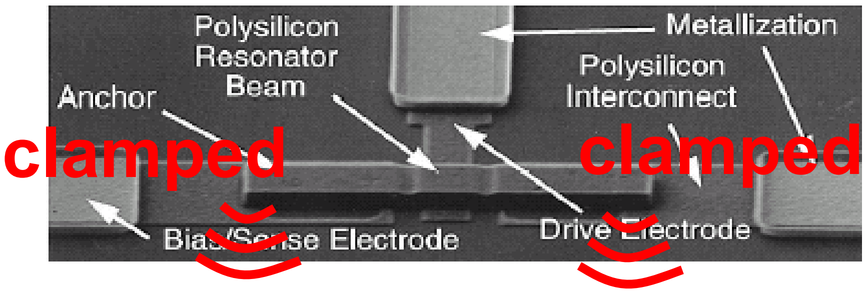
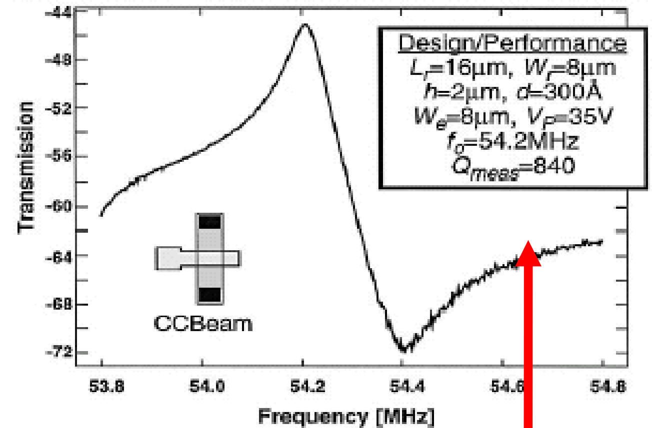
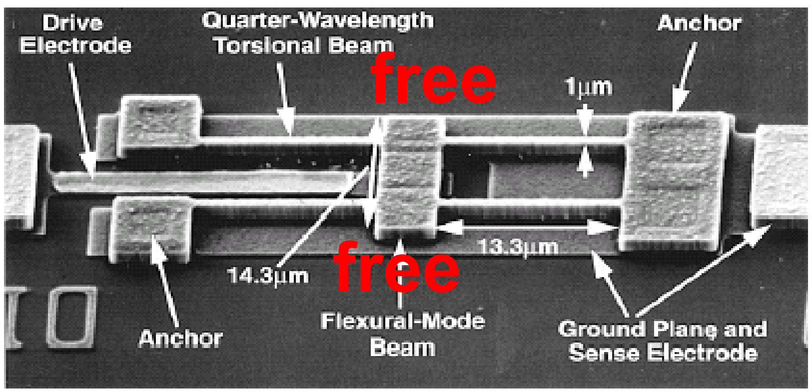
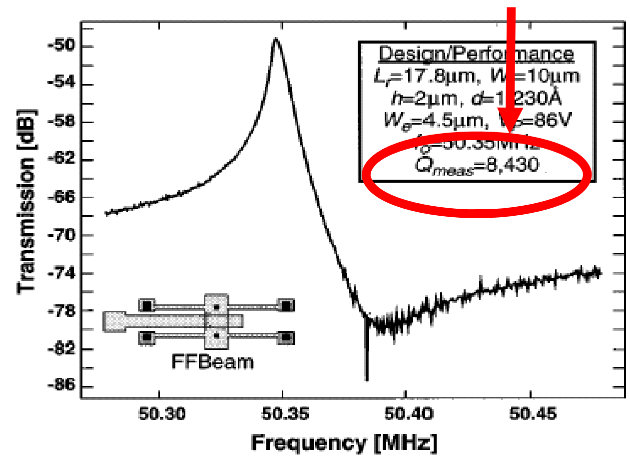
Quality factor: impact of anchor loss







Effect of energy anchor loss



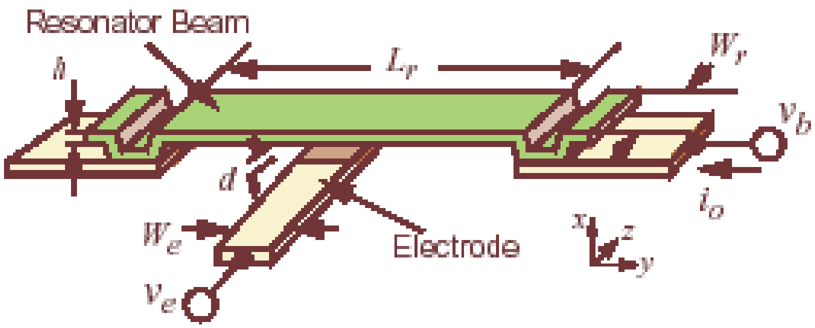
K. Wang, A.C. Wong, C.T. Nguyen, JMEMS, Vol. 9, Sept. 2000.

MEMS filters

Resonator beam: has two electrical inputs v_e $(=v_i)$ and $v_b(=V_P)$

$$F_d = \frac{\partial E}{\partial x} = \frac{1}{2}(v_e - v_b)^2 \frac{\partial C}{\partial x} = \frac{1}{2}\left(v_e^2 - 2v_e v_b + v_b^2\right)\frac{\partial C}{\partial x}$$

x= beam displacement and $\frac{\partial C}{\partial x} = -\frac{\varepsilon W_r W_e}{d_0^2}$



→ **filtering applications**

$v_b=V_P$ *(dc bias)*, $v_e=v_i=V_i \cos\omega_i t$

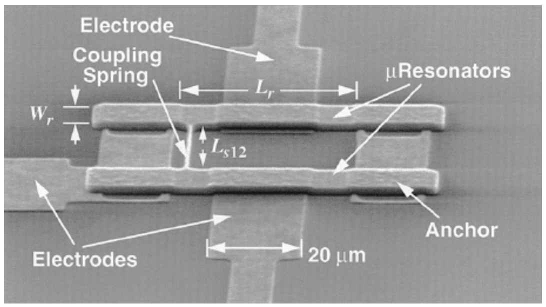
$$F_d = \frac{\partial C}{\partial x}\left(\frac{V_P^2}{2} + \frac{V_i^2}{4}\right) - V_P \frac{\partial C}{\partial x} V_i \cos\omega_i t + \frac{\partial C}{\partial x}\frac{V_i}{4}\cos 2\omega_i t$$

Off resonance dc force

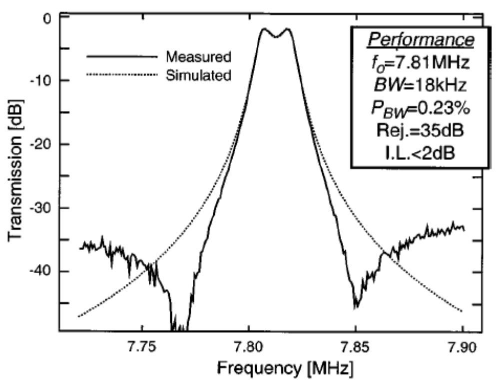
Component used in filtering

MEMS filters: examples

2-beam MEM filter

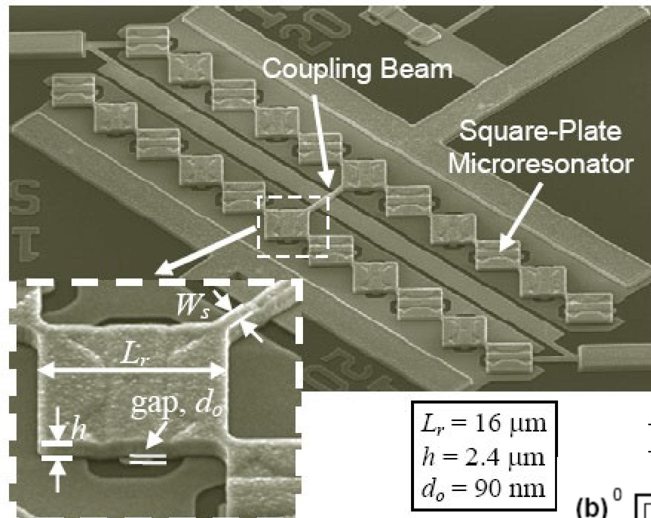


Band-pass filter



C.T.Nguyen, chapter in 'RF Technologies for Low Power Wireless Communications', Wiley, 2002.

Many coupled devices



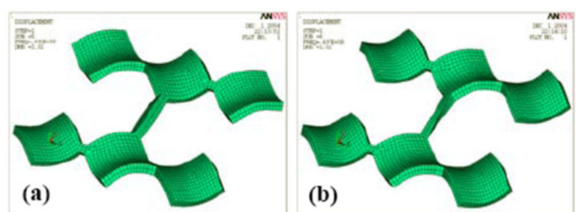
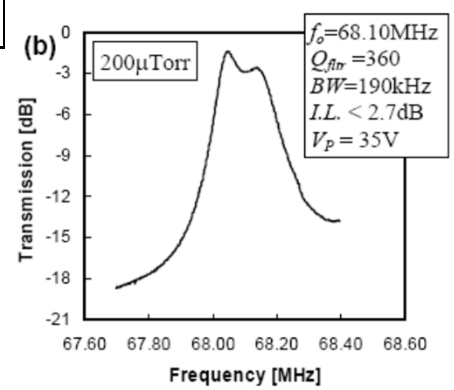


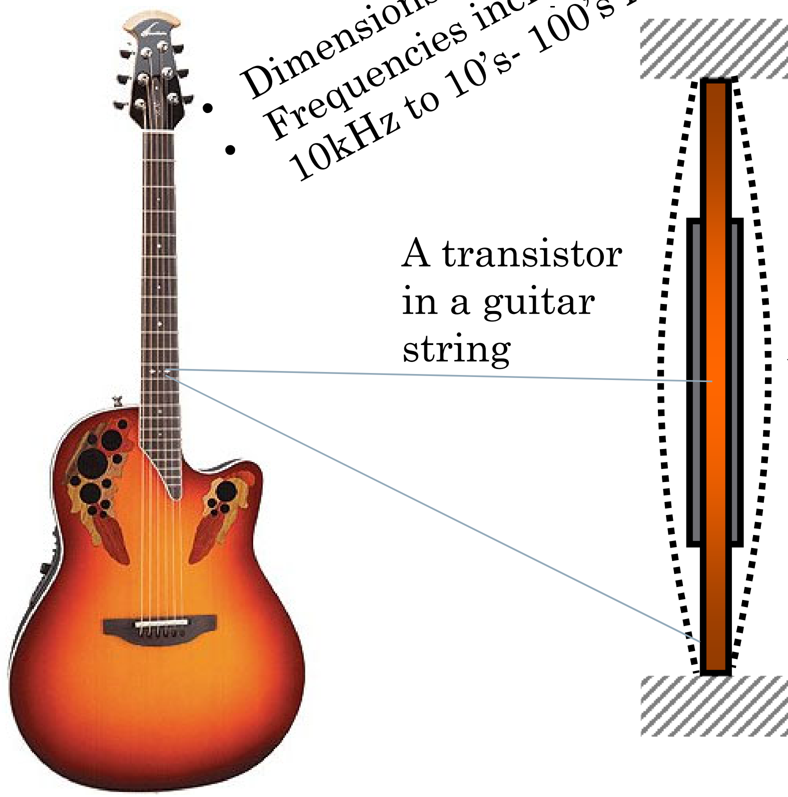
*Fig. 3: ANSYS-simulated **(a)** in-phase and **(b)** out-of-phase mode shapes of the coupled-array filter of Fig. 2.*

Band-pass filter



Resonant gate or body transistors: active MEMS resonators

- Dimensions reduced by more x10^5
- Frequencies increased from 10Hz - 10kHz to 10's- 100's MHZ



drain

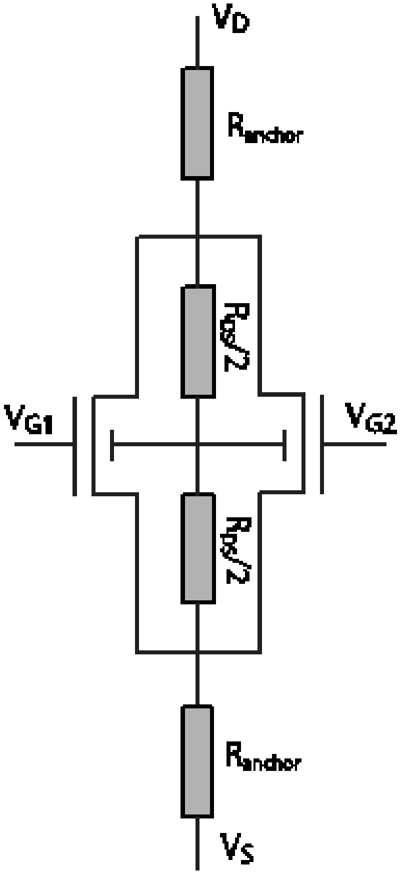
Vibration modulates the channel charge

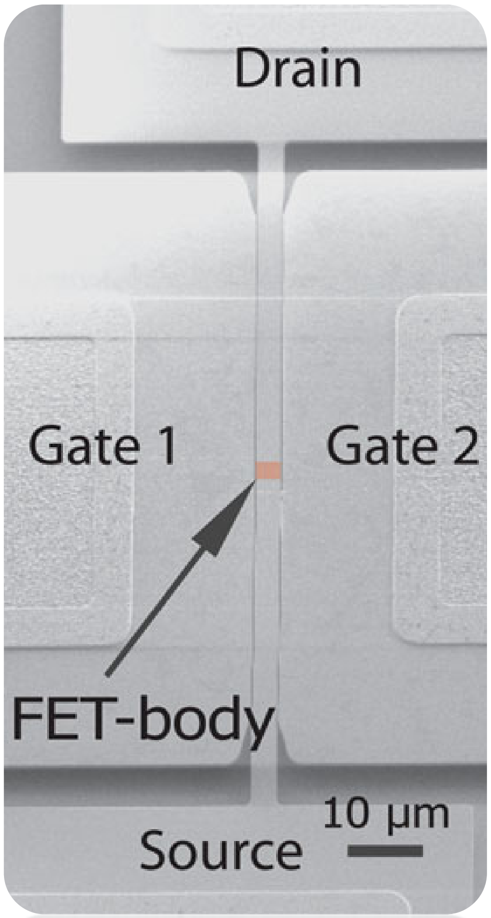
gate

Can potentially amplify the signal

source

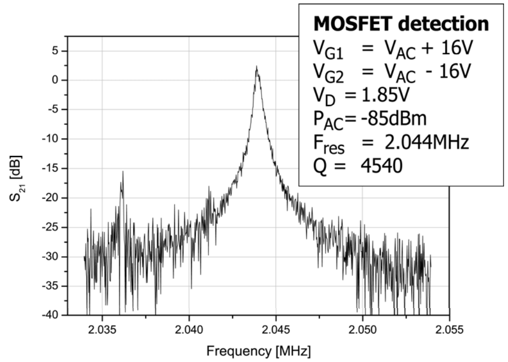
Vibrating body FET





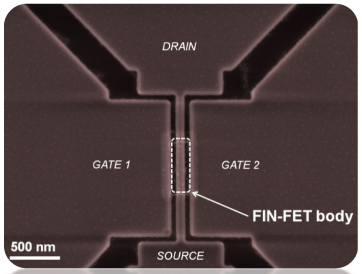
D. Grogg et al, IEDM 2008.

frez = 2MHz



R_m = -30Ω, amplifies!

Fully-depleted RB-FET:



frez = 70MHz

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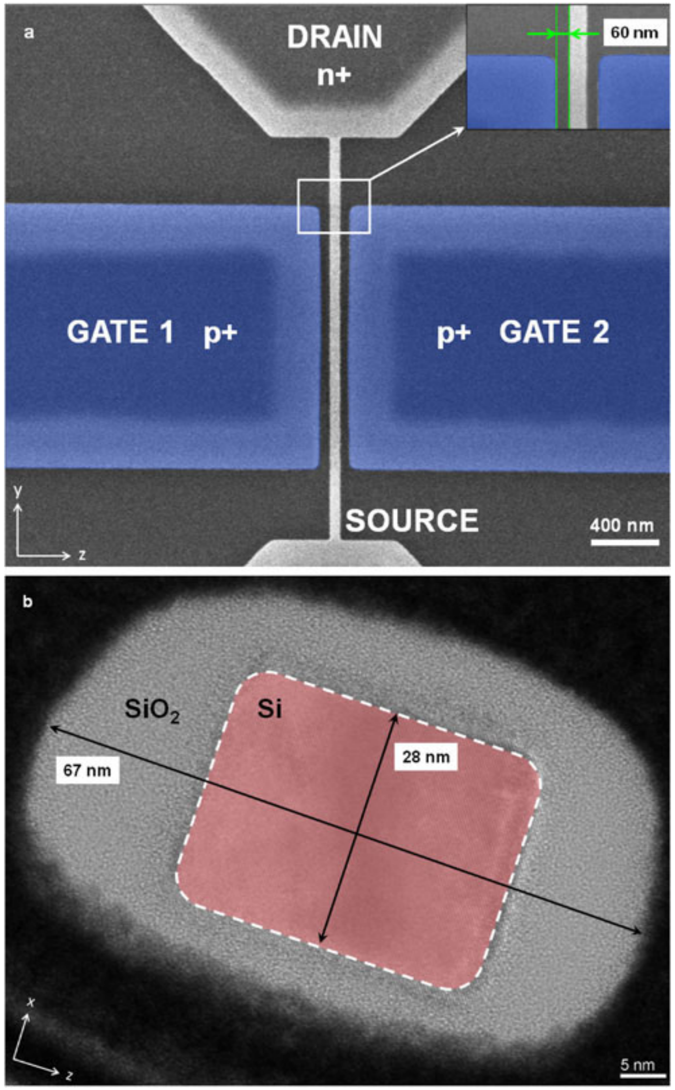
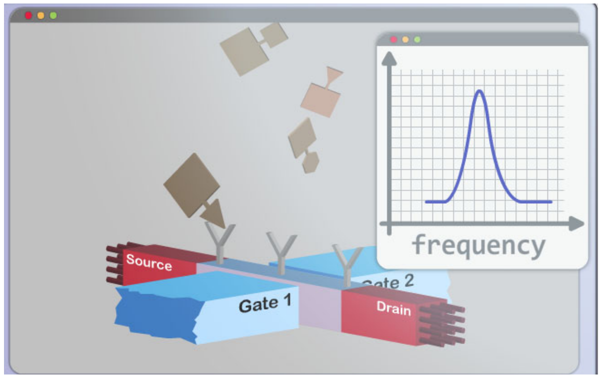


NEMS nanobalances for molecule/atom sensing

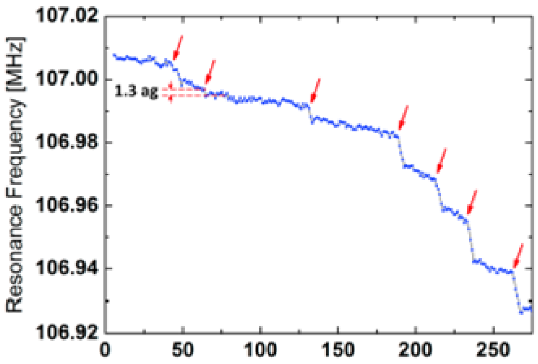
Ultra-scaled resonant transistor:
fres ~70 – 200MHz



$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}}$$

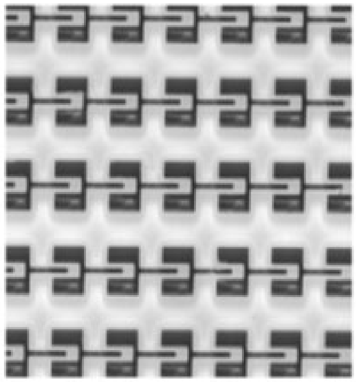
- Mass accretion of 1.3 ag (top) detected: corresponds to approx. 4000 gold atoms
- Scalable to detect ~10 atoms
- **Applications:**

✓ **biomarkers for early cancer detection**
✓ **integrated gas sensors**
✓ **integrated particle sensors**

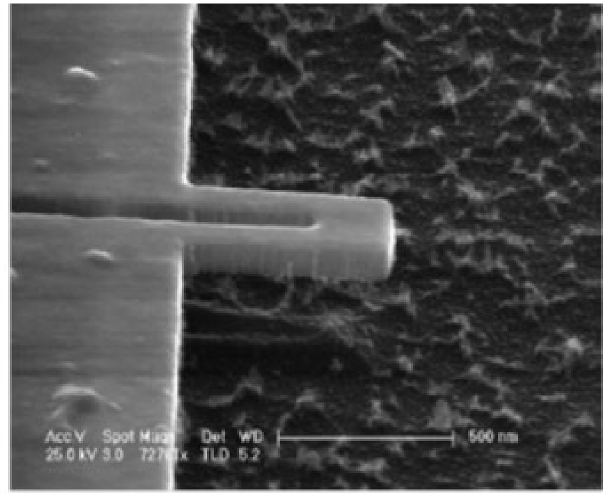


Gas sensors with NEMS (by Caltech)

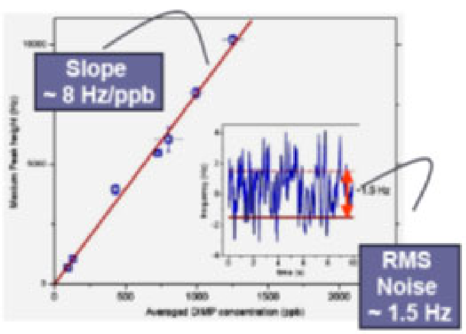
NEMS Array



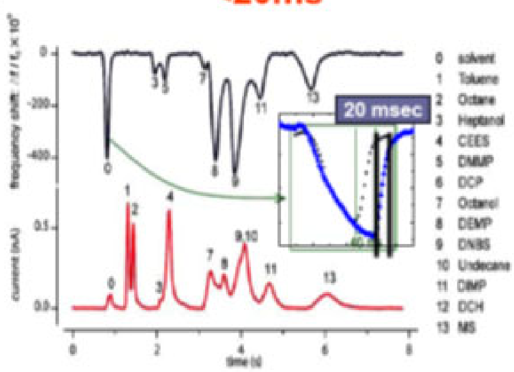
Cal Tech (Zeptogram Microresonators)		Achievement 8/25/07
Chemisorbing Resonator	Mass Responsivity	5 Hz/ag
	Mass Resolution	~10^{-19} g (100 zg)
	Operating Pressure	1 atm (760 torr)
Detector Response Time		< 20 ms
No. of Sensor Elements		25,000
Power Consumption		~100 mW
Size		< 1 cm^3



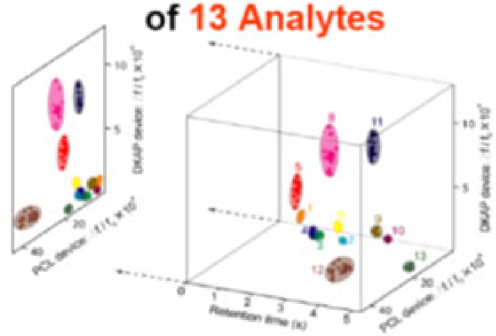
LOD – 200ppt DIMP
(single sensor, no preconc.)



Sensor Response Time
<20ms



Multisensor Discrimination
of 13 Analytes



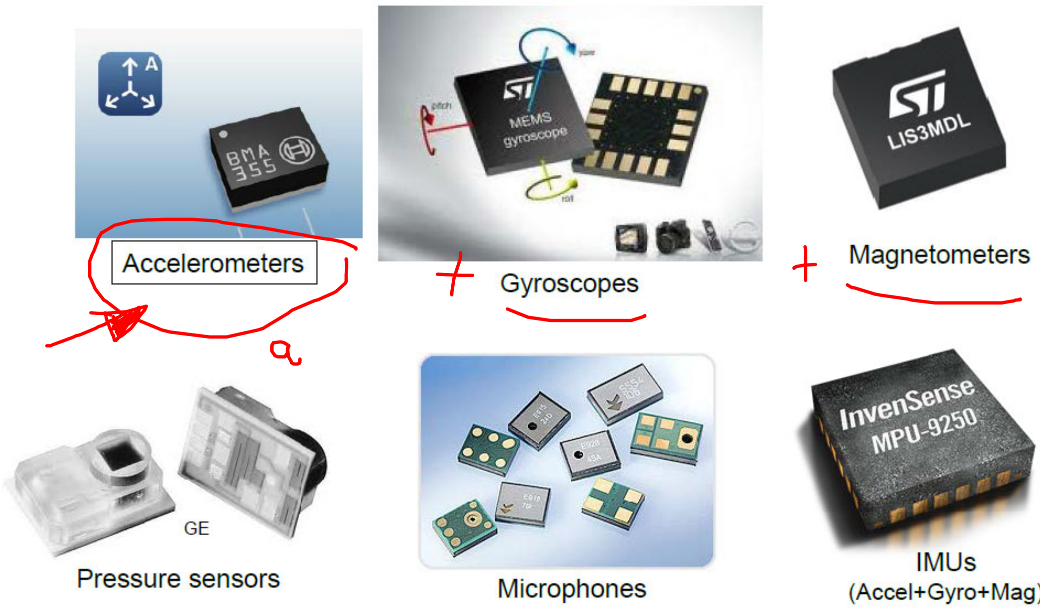
Conclusions: M/NEM resonators

- Large opportunities for **N/MEM resonators in enabling new low power analog/RF systems** (co-integration with silicon ICs) for filtering and mixing
- Future role of vibrant (resonant) FET devices for low power **integrated sensing**
- **NEM resonators**: key components for future advanced signal electro-mechanical processing, from analog/RF to sub-attogram sensing.

Micro-Electro-Mechanical Systems (MEMS) Motion Sensors

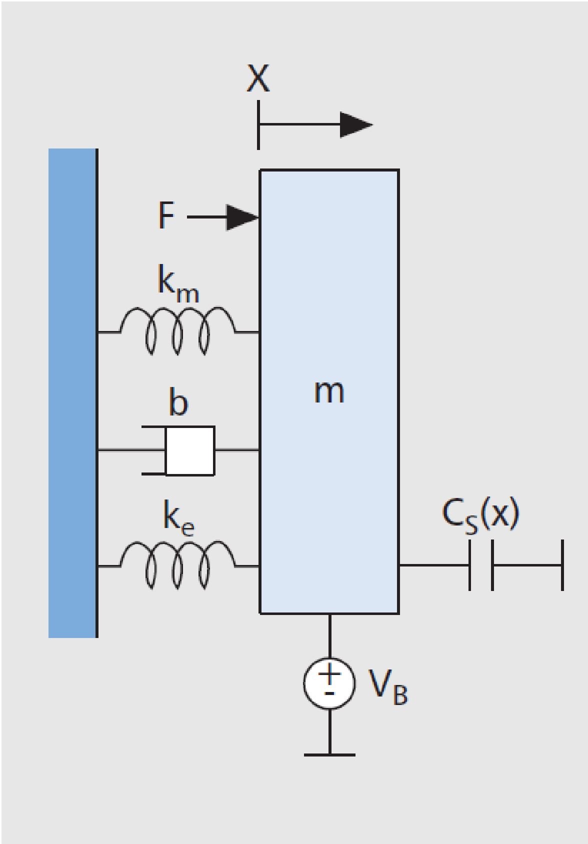
Growing Market for MEMS Motion Sensors

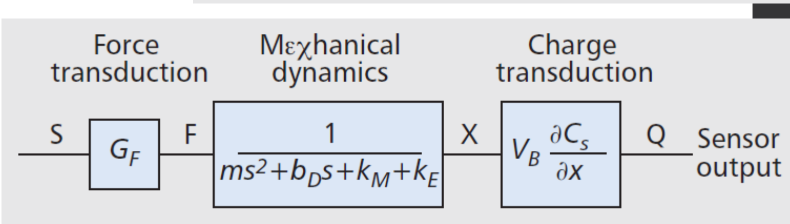
MEMS sensors in navigation systems



Case study: MEMS Inertial Sensors

- In any inertial system, a proof mass, m, is suspended on a mechanical frame by a spring, k_m, and responds to an input force, F, mirroring the quantity to be measured.
- The input force causes a displacement, x, of the mass, and the displacement is measured to sense the force coming from:
  - **acceleration of the mass**, as is the case in an **accelerometers**
  - from a **Coriolis acceleration**, resulting from angular rotation of the mass, as is the case in a **vibratory rate gyroscope**.
- Design optimization of inertial sensors aims at <u>**high transduction gain**</u>, while rejecting the effects of parasitic forces on the mass.
- The inertial MEMS sensors require analog/mixed-signal circuitry to process and digitize the sensor output.





Transduction mechanisms

Micro-Electro-Mechanical-Systems (MEMS) technology

$$\Delta Q(\Delta x) = \frac{\partial C_S(x)}{\partial x} V_B \Delta x. \qquad \Delta F(\Delta v) = \frac{\partial C_S(x)}{\partial x} V_B \Delta v.$$

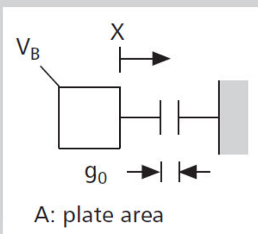
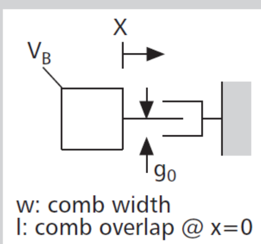
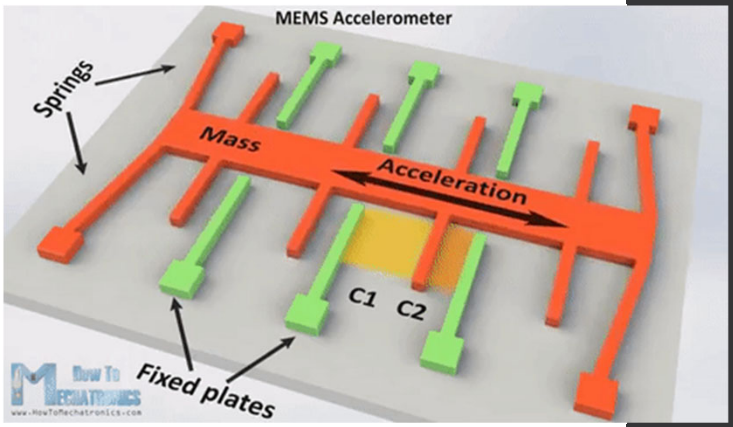
		Capacitance	Charge transduction	Force transduction	Spring constant
		C(x)	ΔQ(Δx)	ΔF(Δv)	k_E
Parallel-plate capacitor		$\frac{\varepsilon_0 A}{g_0 - x}$	$\frac{\varepsilon_0 A}{g_0^2} V_B \Delta x$	$\frac{\varepsilon_0 A}{g_0^2} V_B \Delta v$	$-\frac{\varepsilon_0 A}{g_0^3} V_B^2$
Comb-finger capacitor		$\frac{\varepsilon_0 w(l + x)}{g_0}$	$\frac{\varepsilon_0 w}{g_0} V_B \Delta x$	$\frac{\varepsilon_0 w}{g_0} V_B \Delta v$	0

Table 1. *Charge transduction, force transduction, and electrostatic spring constant for two common capacitor types.*

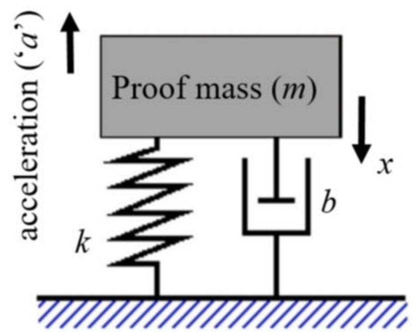


Basic equations

When an acceleration (a) is applied to proof mass (m) suspended by springs with a spring constant (k), and having a damping (b), then the force ($F_{applied}$) acting on the proof mass is given by:

$$F_{applied} - F_{spring} - F_{damping} = m\ddot{x}$$

$$m\ddot{x} + b\dot{x} + kx = F_{applied} = ma_{applied}$$



The transfer function $H(s)$ of the system is given by:

$$ms^2x(s) + bsx(s) + kx(s) = F(s) = ma(s)$$

$$s^2x(s) + \frac{b}{m}sx(s) + \frac{k}{m}x(s) = \frac{F(s)}{m} = a(s)$$

$$H(s) = \frac{x(s)}{a(s)} = \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}} = \frac{1}{s^2 + \frac{\omega_0}{Q}s + {\omega_0}^2}$$

$$\omega_0 = \sqrt{k/m}$$

$$Q = \frac{m\omega_0}{b}$$

Accelerometers work in the low frequency domain ($\omega \ll \omega_0$) with their mechanical sensitivity calculated by setting $s = 0$ in the transfer function $H(s)$ to get

$$\frac{x}{a} \sim \frac{m}{k} = \frac{1}{{\omega_0}^2}$$

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Sensitivity and cross-sensitivity

The sensitivity of an accelerometer is defined as the output voltage signal generated per unit input acceleration in 'g'. It is sometimes referred to as scale factor and denoted by 'S'. The general units are mV/g. For a triaxial accelerometer, the axial sensitivities are independent along the X, Y and Z axes are denoted by X_S, Y_S and Z_S.

$$X_S = \frac{Output\ Volage\ generated\ (\mathrm{mV})}{input\ acceleration\ along\ X - axis\ (\mathrm{g})}$$

$$Y_S = \frac{Output\ Volage\ generated\ (\mathrm{mV})}{input\ acceleration\ along\ Y - axis\ (\mathrm{g})}$$

$$Z_S = \frac{Output\ Volage\ generated\ (\mathrm{mV})}{input\ acceleration\ along\ Z - axis\ (\mathrm{g})}$$

$$(X_S)_{AY} = \frac{Output\ Volage\ generated\ (\mathrm{mV})}{input\ acceleration\ along\ Y - axis\ (\mathrm{g})}$$

$$(X_S)_{AZ} = \frac{Output\ Volage\ generated\ (\mathrm{mV})}{input\ acceleration\ along\ Z - axis\ (\mathrm{g})}$$

- Dynamic range and non-linearity

The dynamic range of the accelerometer is the maximum dynamic acceleration that can be measured accurately. It is given in '$\pm$g'.

$$\%\ Non\ linearity = \frac{Maximum\ deviation\ (\mathrm{g})}{Full\ scale\ range\ (\mathrm{g})} \times 100$$

Basics: displacement and acceleration

Displacement and acceleration are coupled together by a fundamental scaling law

- A higher resonant frequency implies less displacement
- high f & low sensitivity
- Measuring small accelerations requires floppier structures
- high sensitivity and low f

$$x = \frac{F}{k} = \frac{ma}{k}$$

$$\boxed{x = \frac{a}{\omega_0^2}}$$

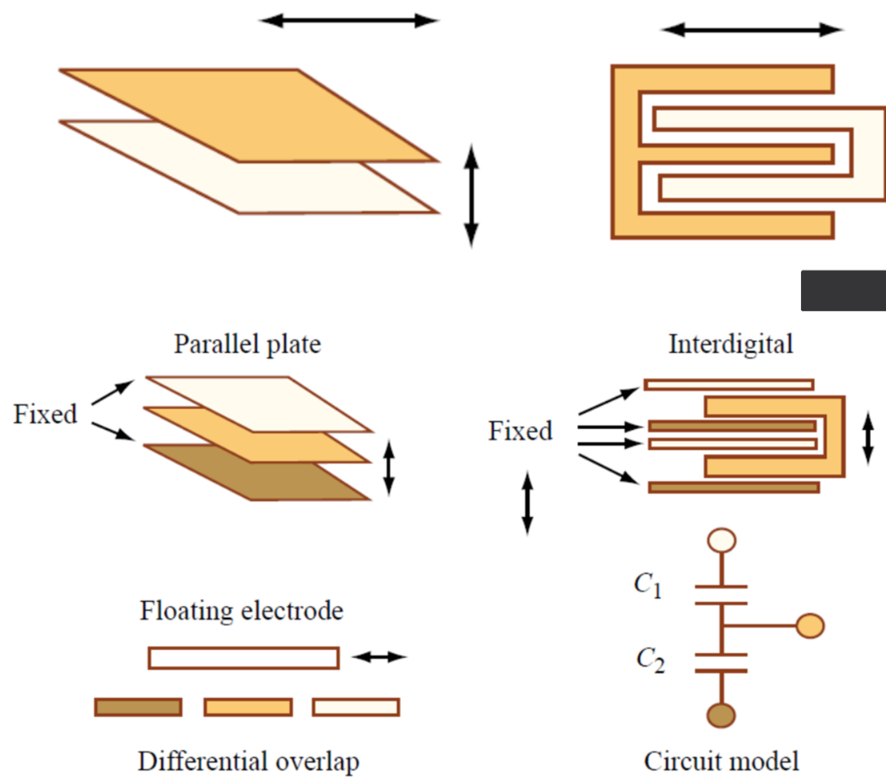
Fundamental low Limit of detection (LoD)

- Johnson noise in the damping mechanism

$$a_{n,rms} = \sqrt{\frac{4k_B T \omega_0}{mQ}}$$

How to use a MEM capacitor?

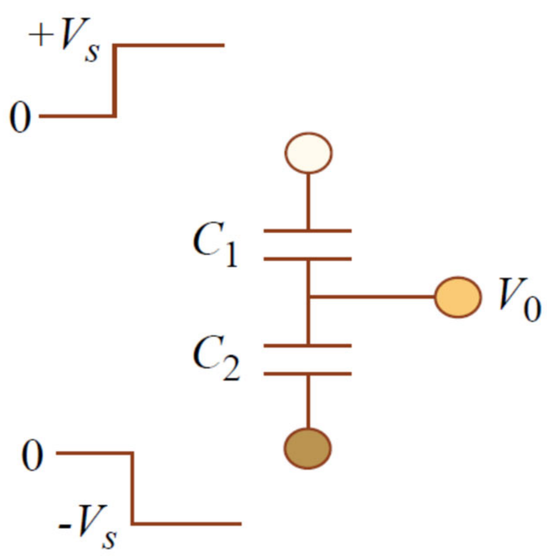
- **Single MEM capacitors:**
  - ❖ **Capacitance is function of gap or area**
  - ❖ **Can be nonlinear**
- **Differential capacitors**
  - ❖ **One capacitor increases while the other decreases**



Adapted from Figure 19.4 in Senturia, Stephen D. *Microsystem Design*. Boston, MA: Kluwer Academic Publishers, 2001, p. 501. ISBN: 9780792372462.

Using a differential capacitor

- **Differential drive creates sense signal proportional to capacitance difference**
- **Gives zero output for zero change**
- **Output linear with gap**



$$V_0 = -V_S + \frac{C_1}{C_1 + C_2}(2V_S) = \frac{C_1 - C_2}{C_1 + C_2} V_S$$

for parallel-plate capacitors where only g changes, this becomes

$$V_0 = \frac{g_2 - g_1}{g_1 + g_2} V_S$$

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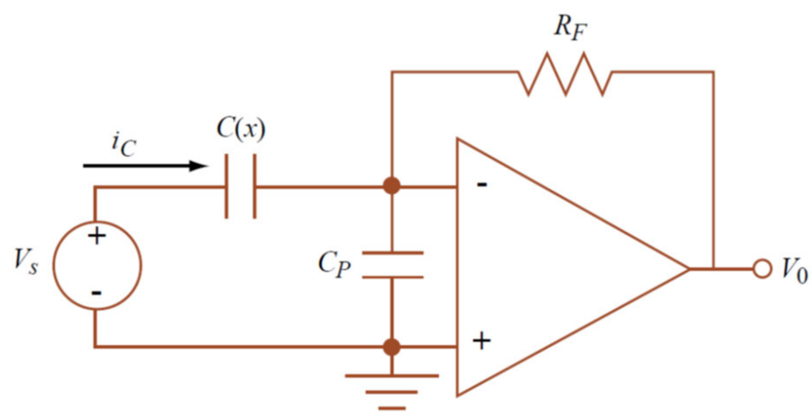
Transimpedance circuit (1)

- **The simplest type of circuit measures the displacement current in a capacitor using a transimpedance amplifier**
- **Transimpedance converts current to voltage**
- **Nulls out parasitic capacitance**
- **If source is DC, measure velocity of motion, not really what we want…**



$$V_0 = -R_F \underbrace{V_S \left.\frac{\partial C}{\partial x}\right|_{V_S}}_{\text{constant}} \frac{dx}{dt}$$

Inertial MEMS for human activity (1)

Engineering aspects:

- Design optimization of inertial sensors aims at **high transduction gain**, while rejecting the effects of parasitic forces on the mass.
- Inertial MEMS sensors require **analog/mixed-signal circuitry** to process and digitize the sensor output.
- Important aspects for the wearability: **low power consumption and the small size.**
- The energy efficiency of inertial sensors is currently evaluated by some specific figures of merit such as a power ratio of peak SNR to energy per conversion.
- Other practical aspects (packaging, cost, etc).

Inertial MEMS for human activity (2)

- **Status in MEMS for inertial measurement:**
  - major technology & package progress made by ST Microelectronics, Texas Instruments and InvenSense
  - ST Microelectronics (2014):
    - 3 Billions MEMS units, with manufacturing capacity larger than 3 Mu/day
    - include analog and digital accelerometer and gyroscope sensors with advanced power saving features for ultra-low-power applications.

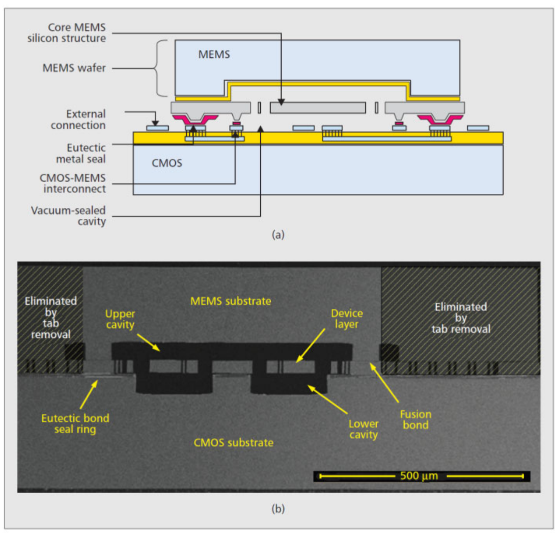
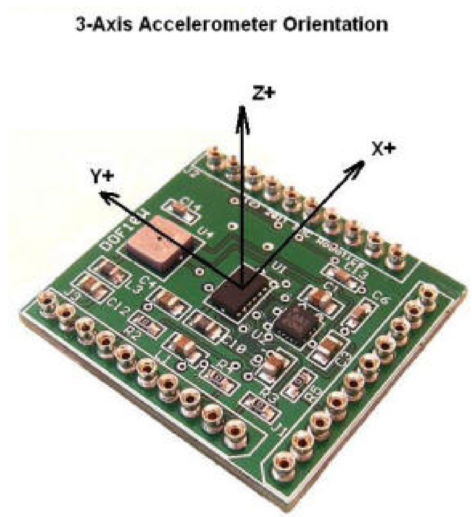
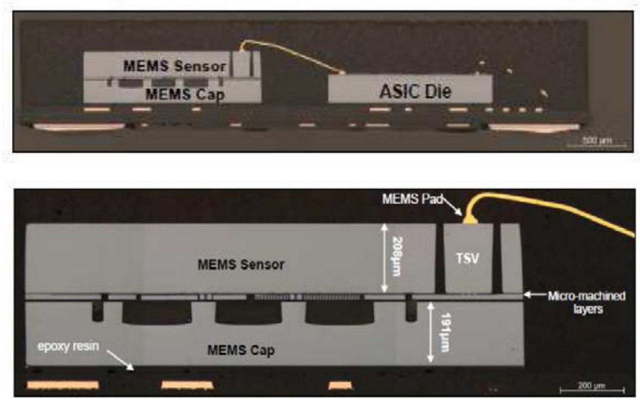


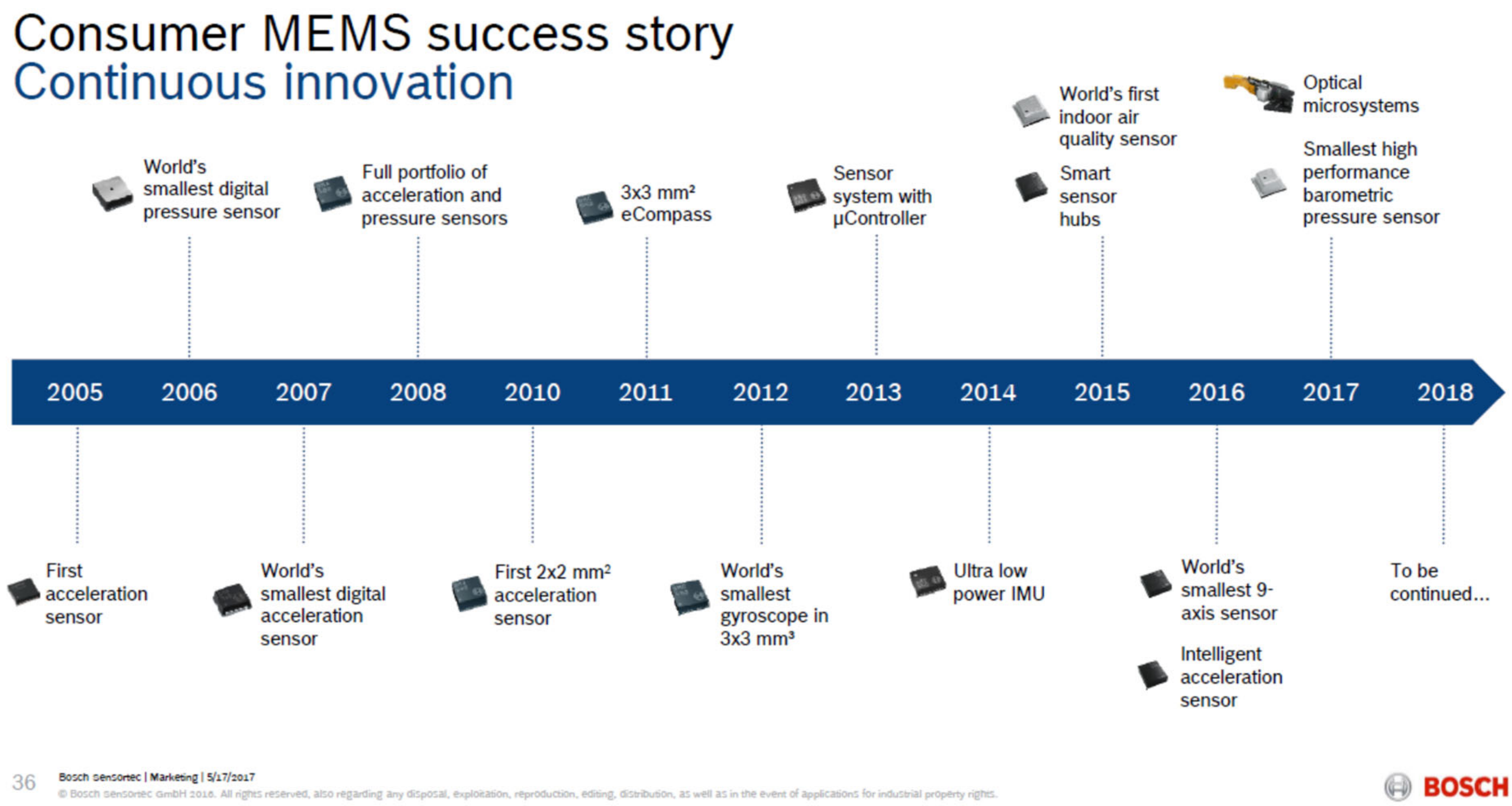
Figure 6. *InvenSense silicon MEMS/CMOS fabrication technology: a) assembly; b) device cross-section.*



ST Microelectronics



Commercial MEMS IMU's



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