Nanoscale CMOS and Beyond

Micro/Nano Electro Mechanical Systems (M/NEMS)

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Outline

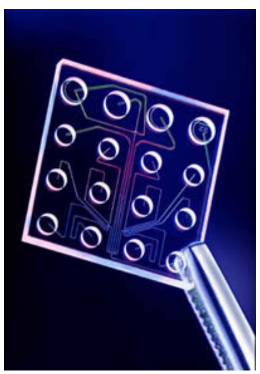
- **Introduction: Micro/Nano-Electro-Mechanical Systems**
- **M/NEM switches/relays for logic**
- **M/NEM resonators:**
  - Passive resonators, filters and mixers
  - Resonant gate or body transistors to amplify small signals **M/NEM inertial sensors:**
  - Accelerometers

Introduction

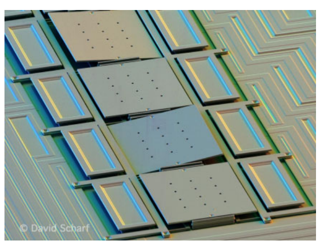
MEMS = Micro-Electro-Mechanical Systems

(include suspended and/or movable parts)

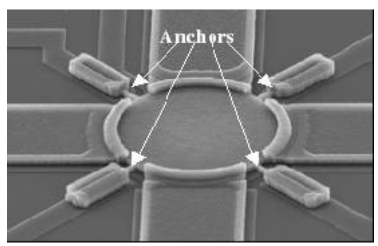
Microfluidics



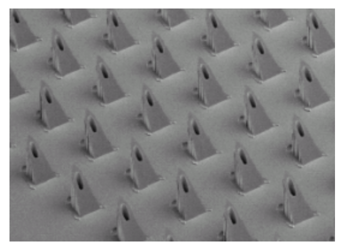
Optical



Radio Frequency



Bio

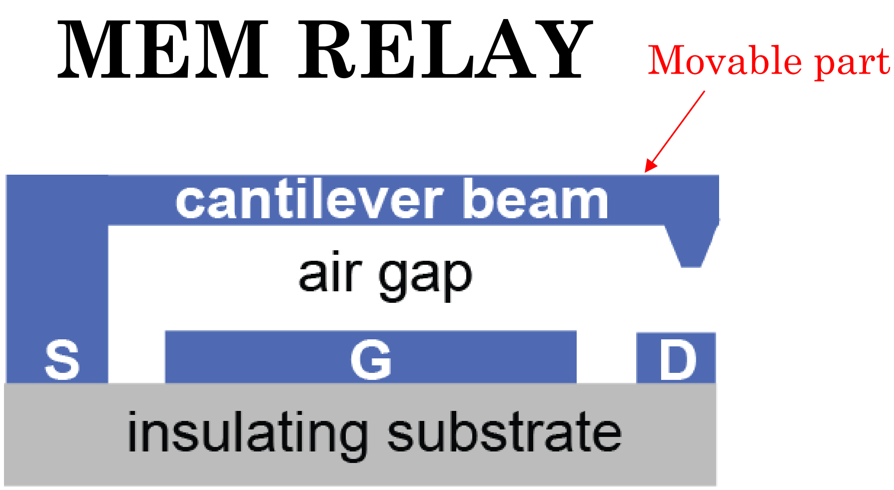


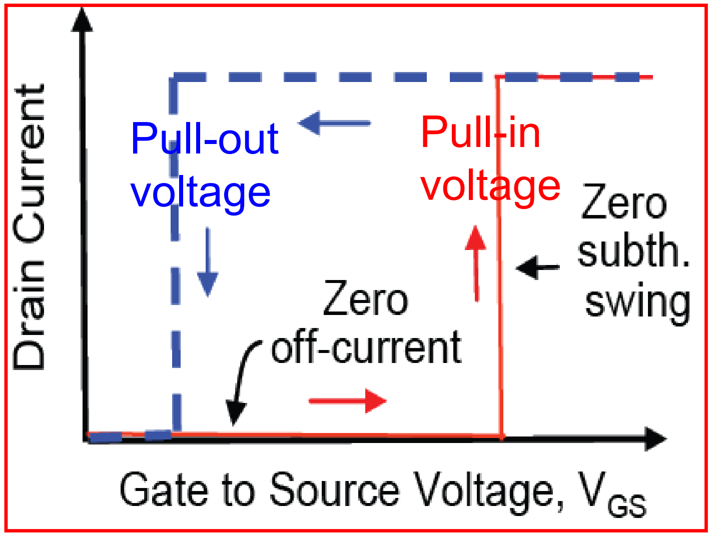
Energy scavenging

MEMS Switch/Relay

Electro-mechanical information processing:

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





Electromechanical design of pull-in voltage

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

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

$g = g_o - x$

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

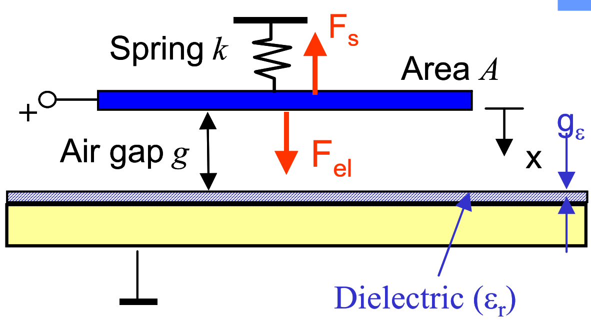
$F_{el} = \frac{\varepsilon_0 A V^2}{2g^2}$

$F_s = k(g_o - g)$

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

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

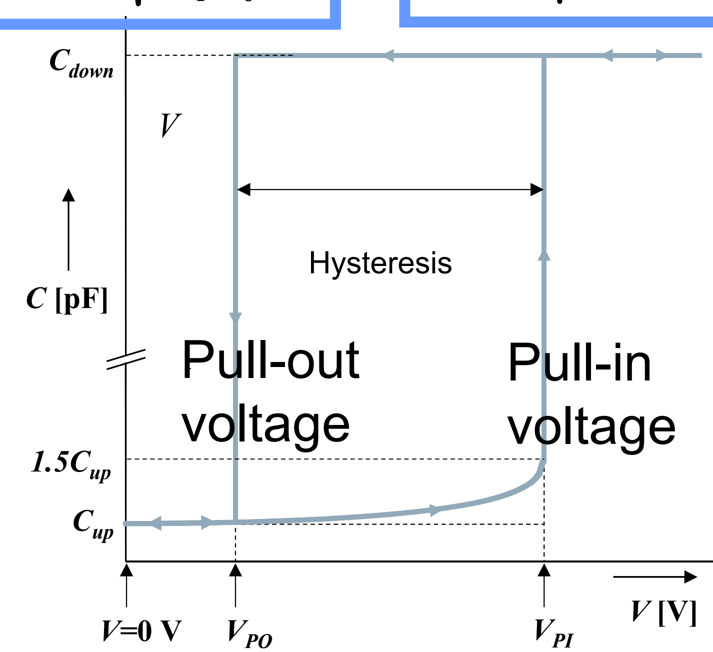
$\frac{C_{down}}{C_{up}} = \frac{\varepsilon_r g_{eff}}{g_\varepsilon} \approx \frac{\varepsilon_r g_o}{g_\varepsilon}$



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

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

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



Source: H. Tilmans, IMEC.

MEMS actuation mechanisms

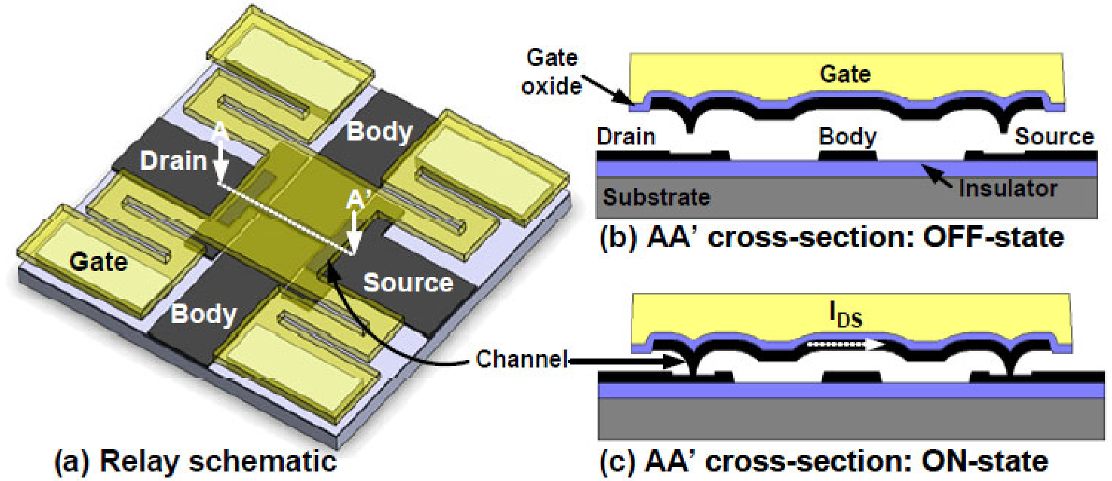
	Voltage (V)	Current (mA)	Power (mW)	Size	Switch time (μs)	Force (contact) (μN)
Electrostatic	1-100	~0	~0	Small	1-200	50-1000
Thermal	3-5	1-100	<500	Large	300-10'000	500-5'000
Magnetic	3-5	10-100	<500	Medium	300-1'000	50-200
Piezoelectric*	3-20	~0	~0	Medium	50-500	50-200

* 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.

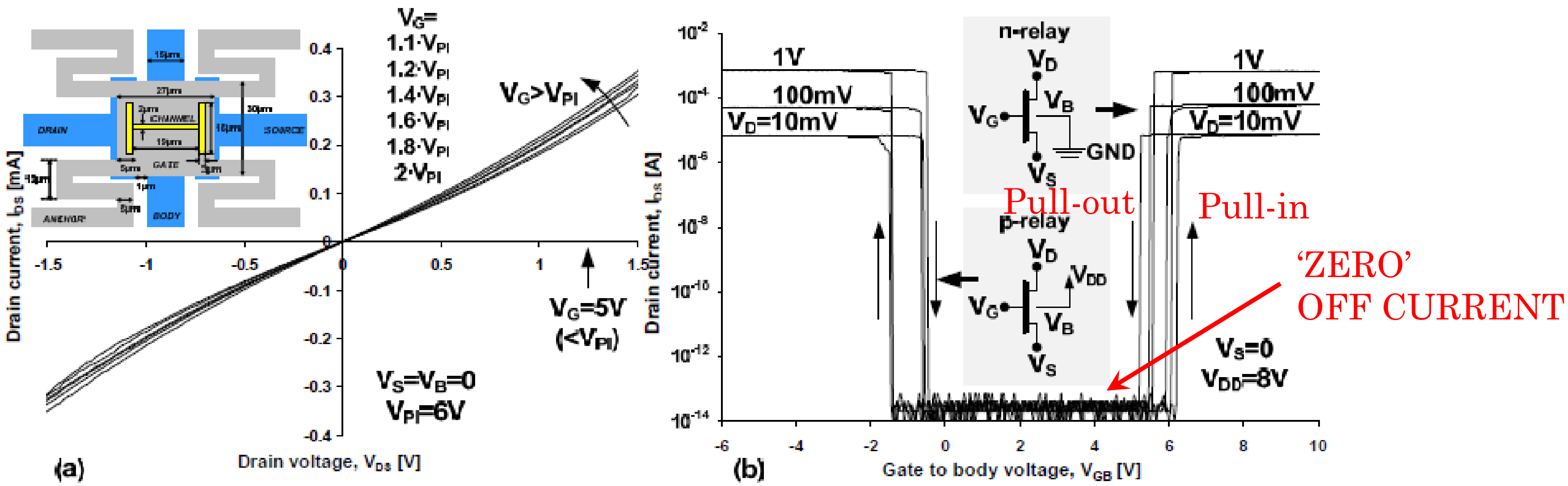
UC Berkeley's 4-terminal relay



(a) Relay schematic

(b) AA' cross-section: OFF-state

(c) AA' cross-section: ON-state



… and mechanical inverter operation

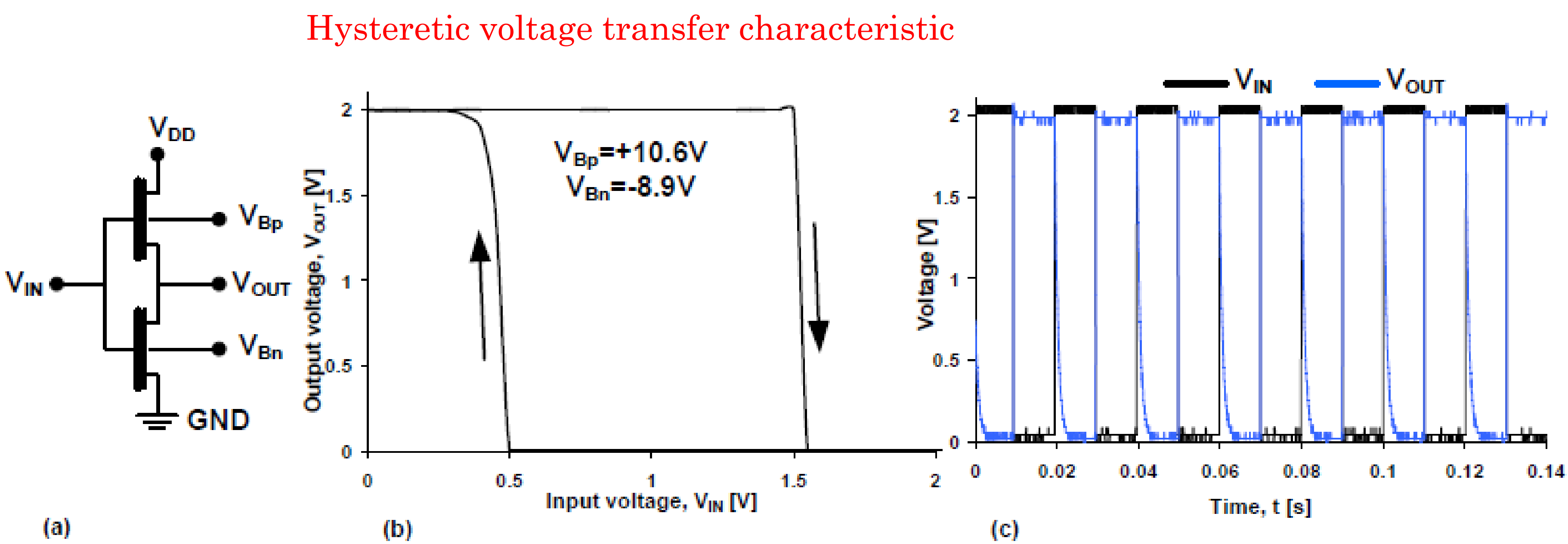
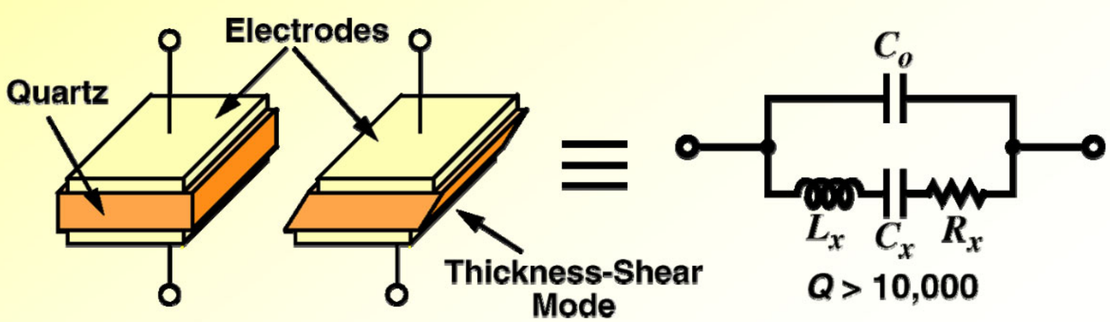


Fig. 6.18. (a) Relay inverter schematic. Two similar devices are operated in n-type and p-type modes. (b) Measured static and (c) dynamic characteristics [34]. V_{IN} is a f=50Hz square wave.

Rationale for MEMS resonators: High Quality factor, Q

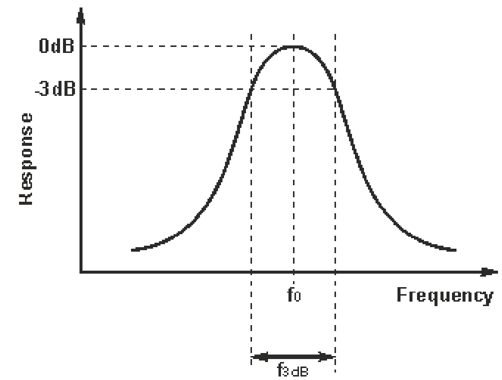
Information processing as **vibrational modes** of mechanical elements, based upon waves.

- ***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

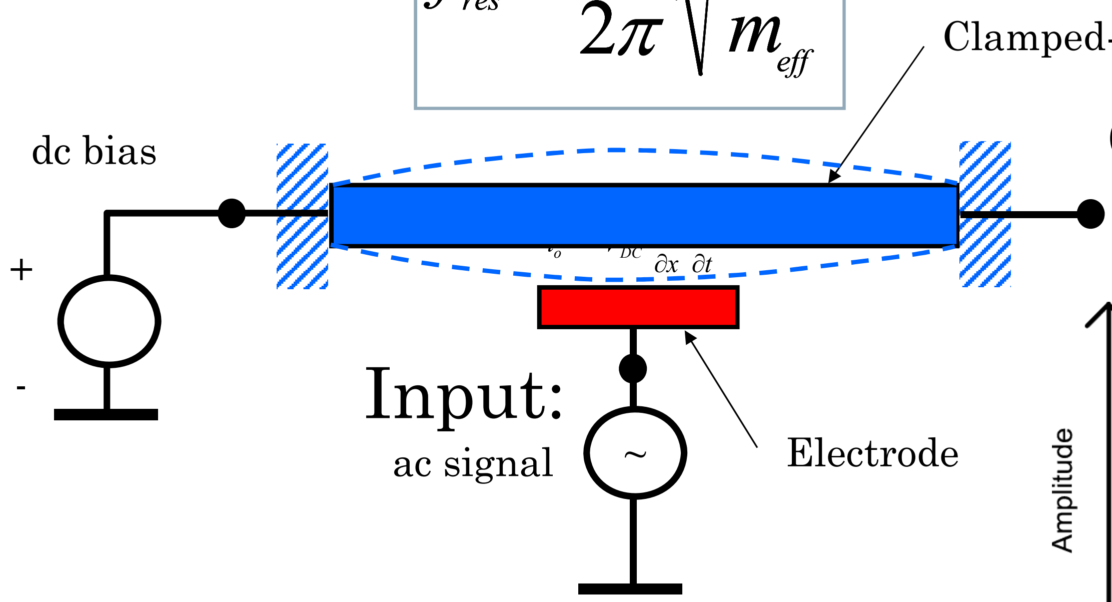
$$Q = \frac{E_{stored}}{E_{lost\ per\ cycle}}$$

Principle

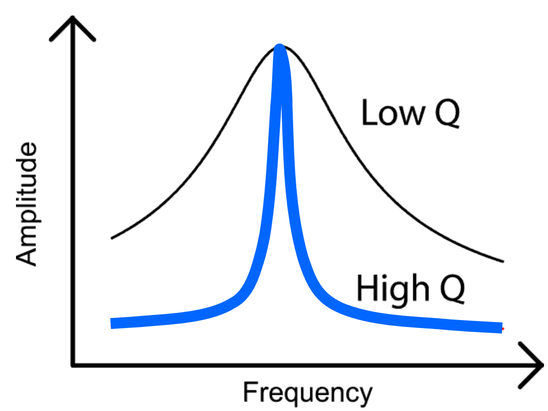
Micro-Electro-Mechanical resonator

Resonance frequency:

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



Output signal:



MEM resonator is tuneable in frequency

Mechanical domain equations:

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

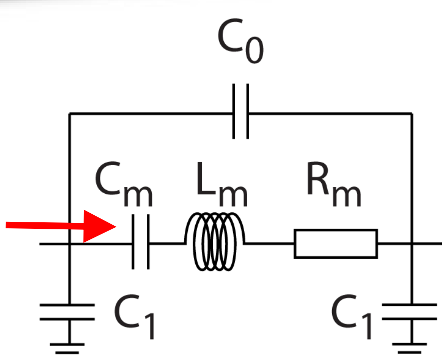
Electrical domain analogy:

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

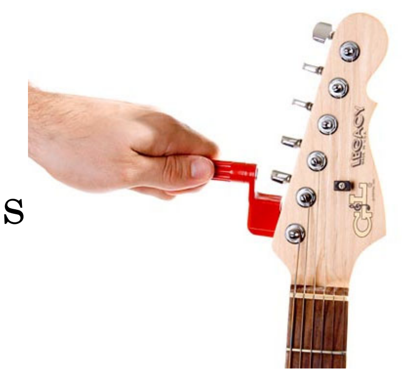
L: motional inductance

R: Motional resistance

1/C: Stiffness



Tuning the resonance frequency: stiffness!

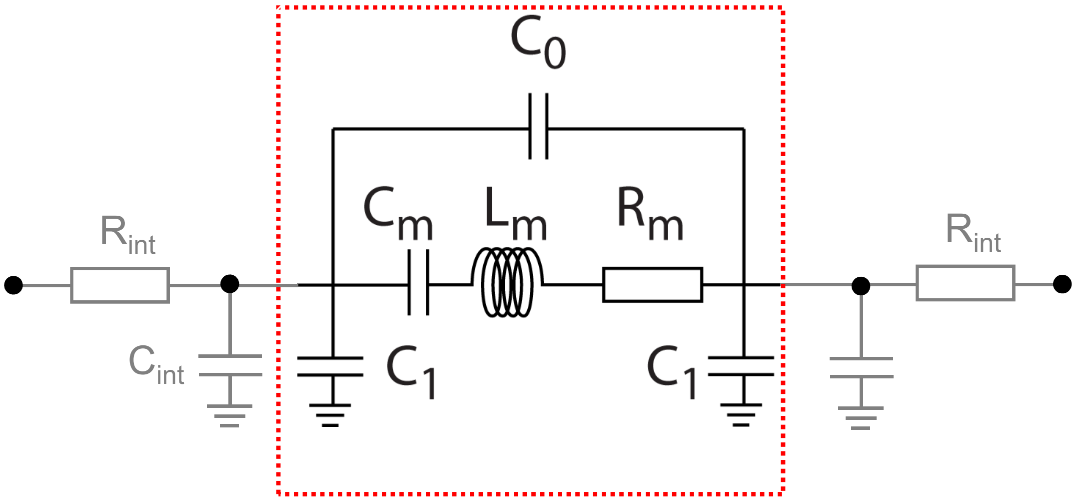


Motional to electrical equivalent parts and electrical small signal circuit

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

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

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



Motional resistance

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

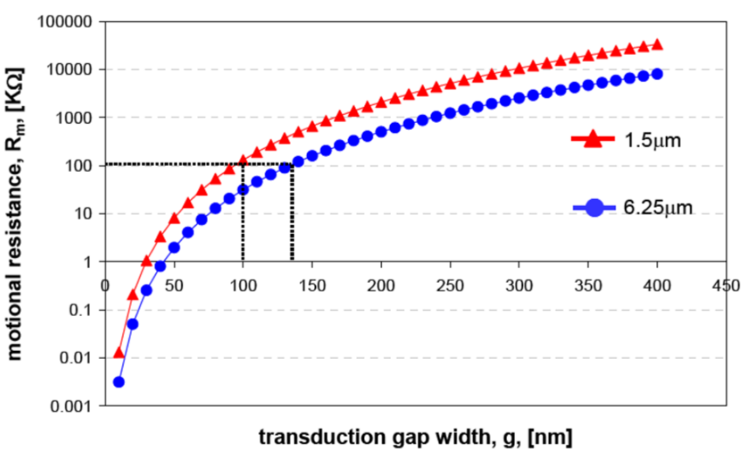
Need for low motional resistance & nanogaps

Motional resistance:

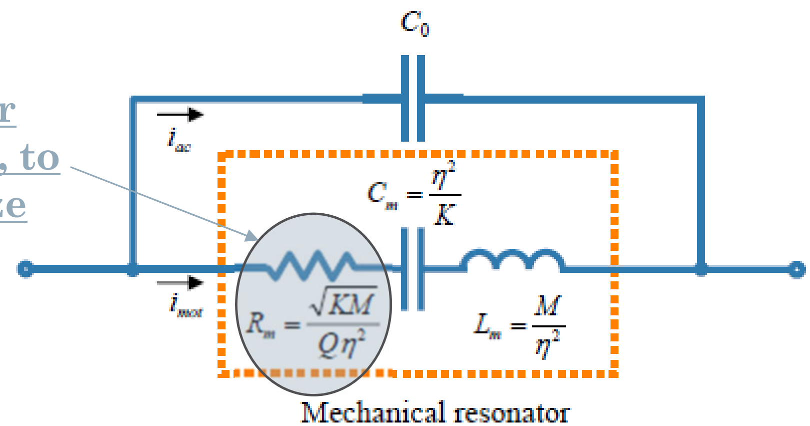
R_m ~ gap^4/voltage^2

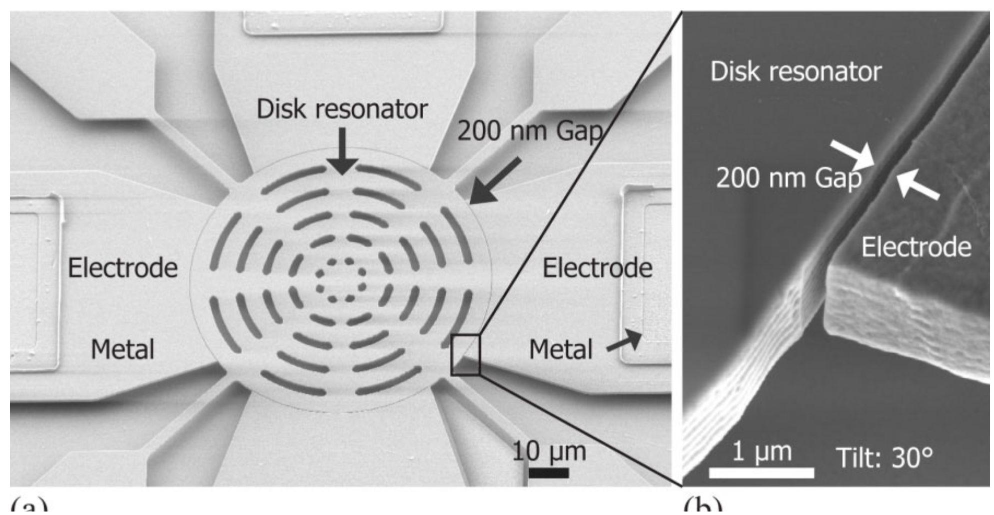
(1/10 gap, 1/10'000 R_m)

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



Of major interest, to minimize





Quality factor mechanisms

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

Mechanism #1:
Material defect losses

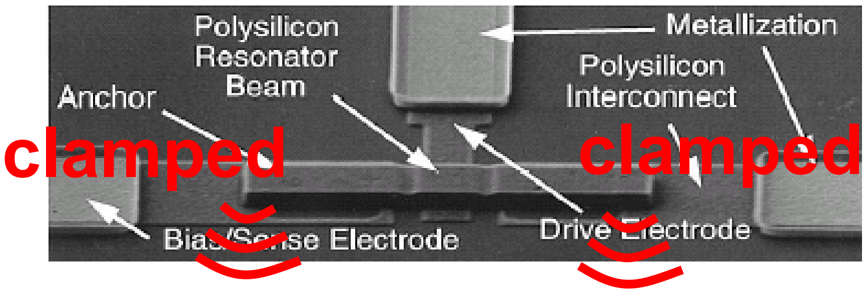
Mechanism #3: Gas damping
(not an issue in vacuum or
for bulk resonators)

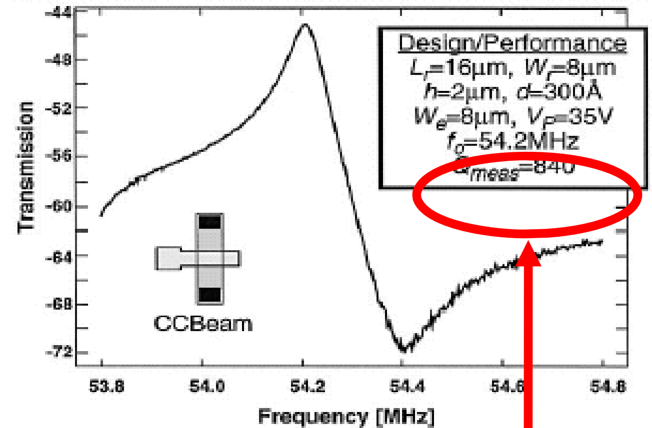
$$\frac{1}{Q} = \frac{1}{Q_{defects}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{viscous}} + \frac{1}{Q_{sup\ port}}$$

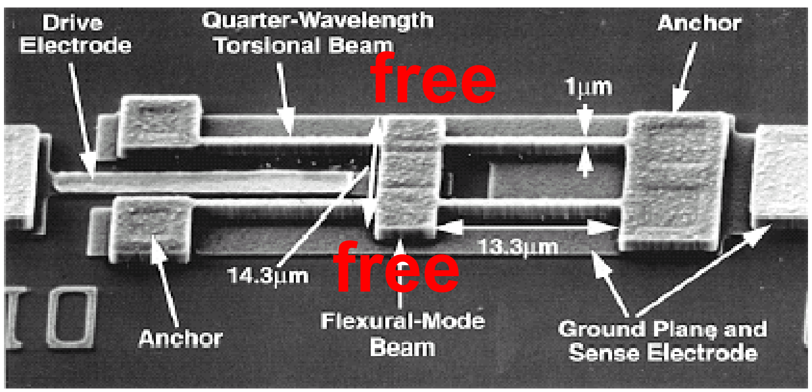
Mechanism #2: Thermoelastic
damping (TED)

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

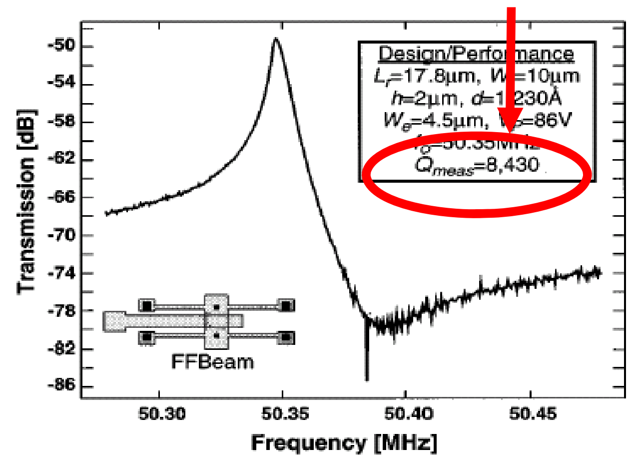
Quality factor: impact of anchor loss







Effect of energy anchor loss



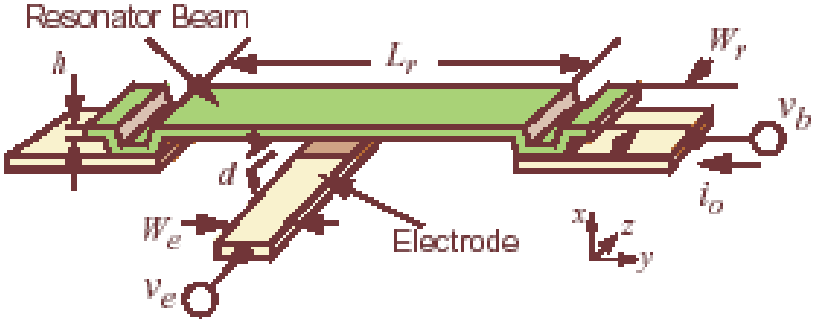
K. Wang, A.C. Wong, C.T. Nguyen, JMEMS, Vol. 9, Sept. 2000.

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), $v_e=v_i=V_i \cos\omega_i t$

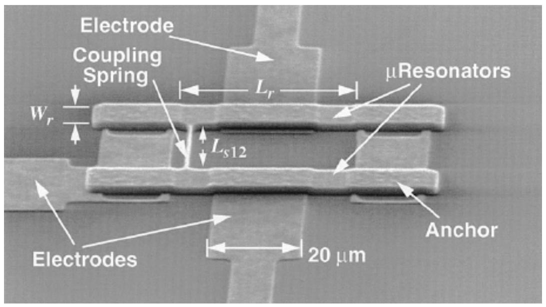
$$F_d = \frac{\partial C}{\partial x}\left(\frac{V_P^2}{2} + \frac{V_i^2}{4}\right) - V_P \frac{\partial C}{\partial x} V_i \cos\omega_i t + \frac{\partial C}{\partial x}\frac{V_i}{4}\cos 2\omega_i t$$

Off resonance dc force

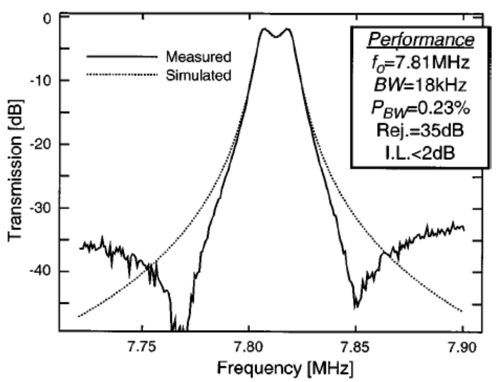
Component used in filtering

MEMS filters: examples

2-beam MEM filter

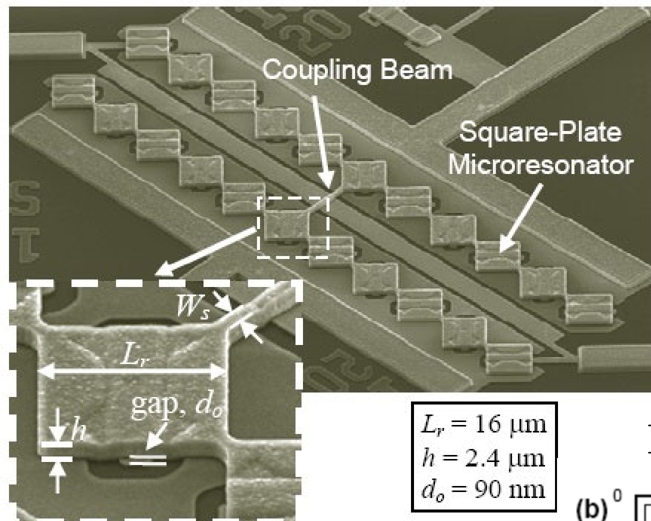


Band-pass filter



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

Many coupled devices



L_r = 16 μm
h = 2.4 μm
d_o = 90 nm

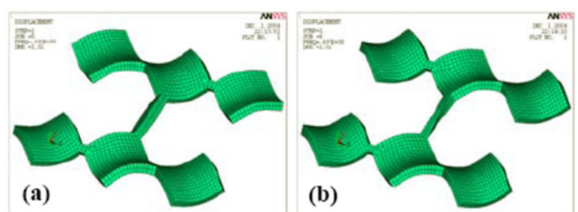
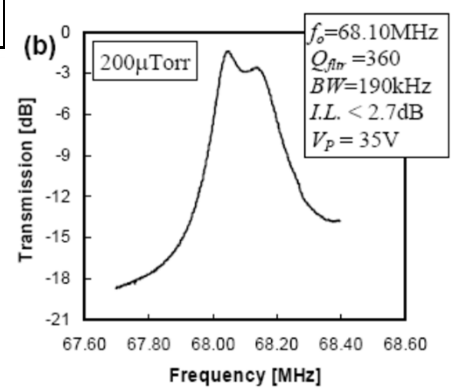


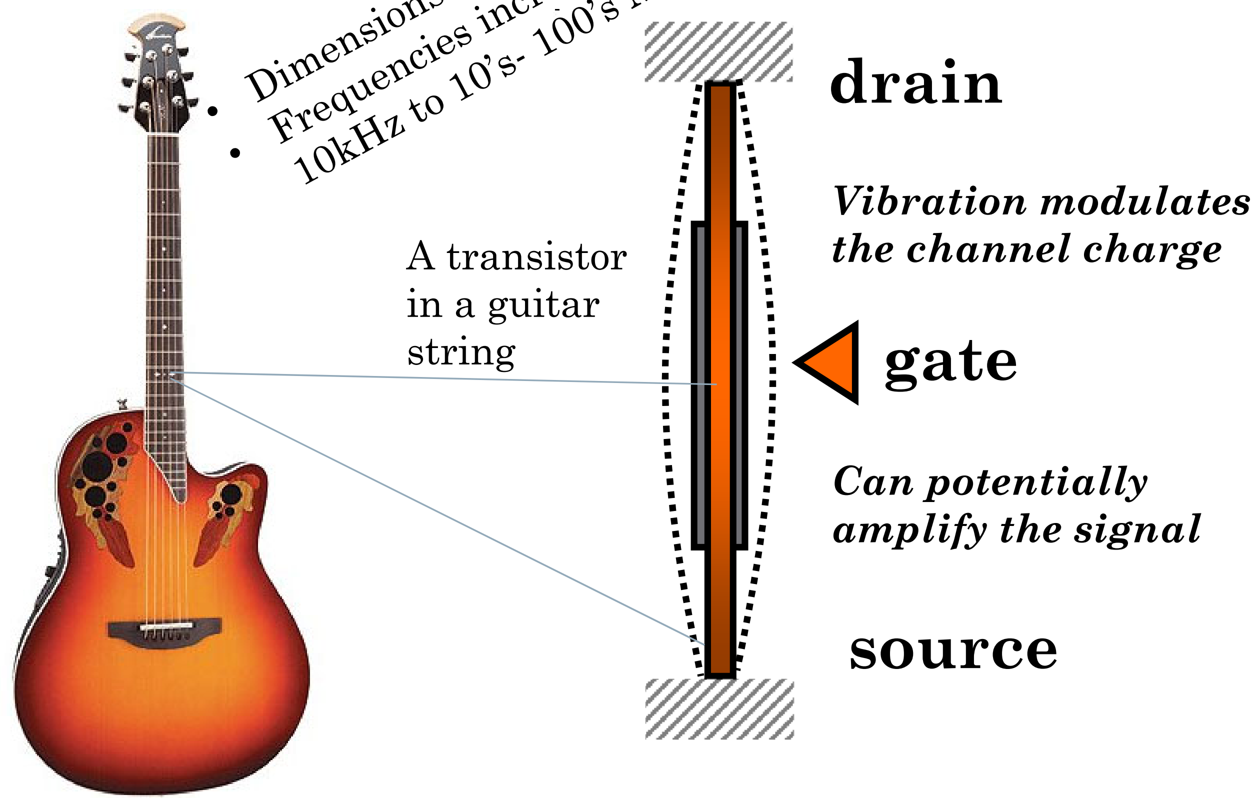
*Fig. 3: ANSYS-simulated **(a)** in-phase and **(b)** out-of-phase mode shapes of the coupled-array filter of Fig. 2.*

Band-pass filter



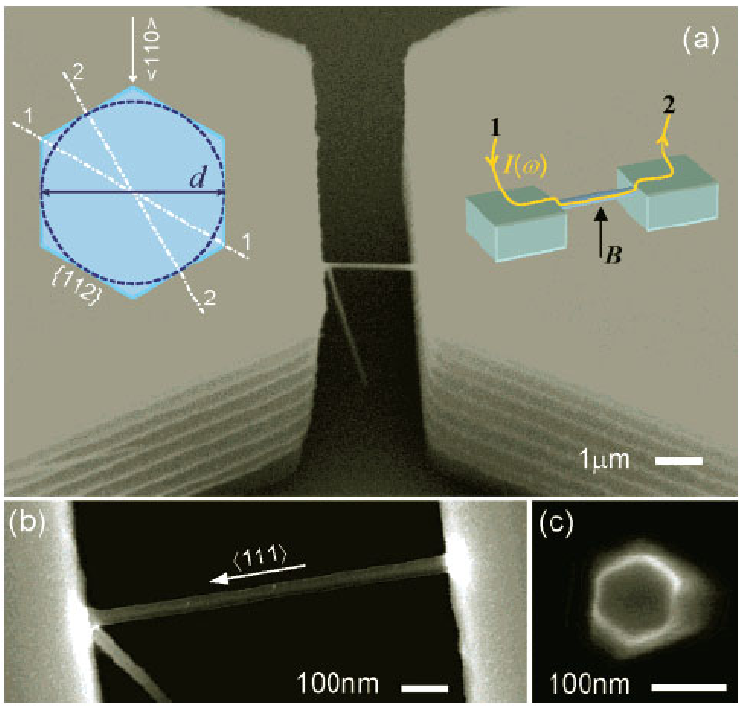
Resonant gate or body transistors: active MEMS resonators

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

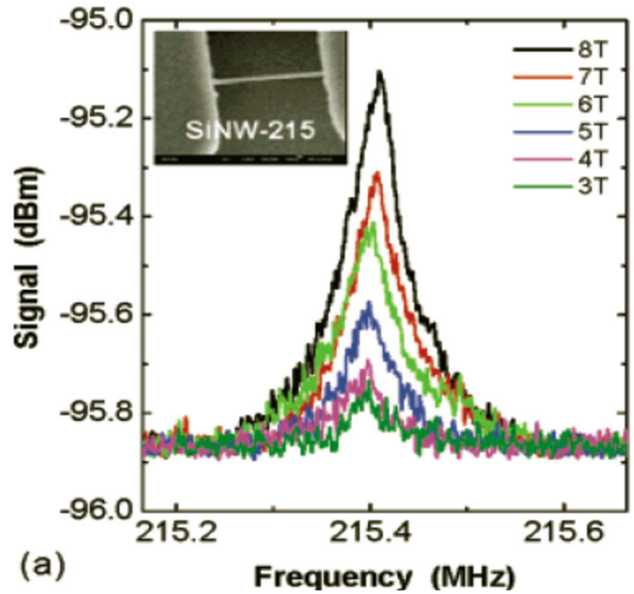


Nanowire resonators

Nanomechanical resonators based on single-crystal silicon nanowires (SiNWs) prepared by the bottom-up chemical synthesis – fres ~ 200 MHz , Q = 2'000 - 2'500.



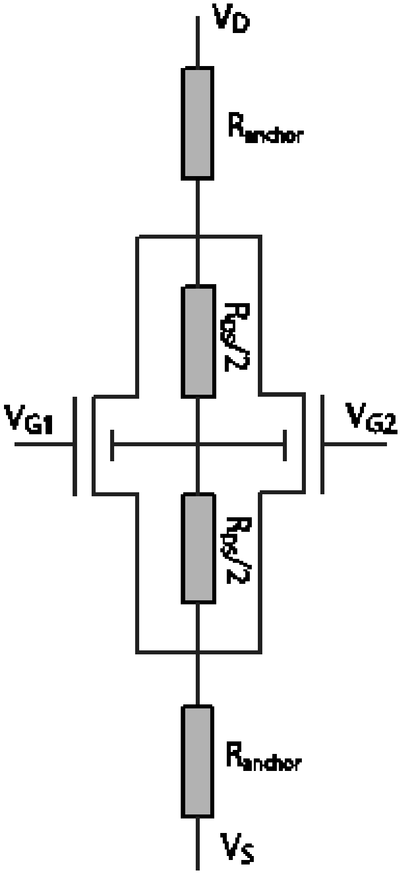
X.L. Feng et al, Nanoletts, Vol. 7, 2007.

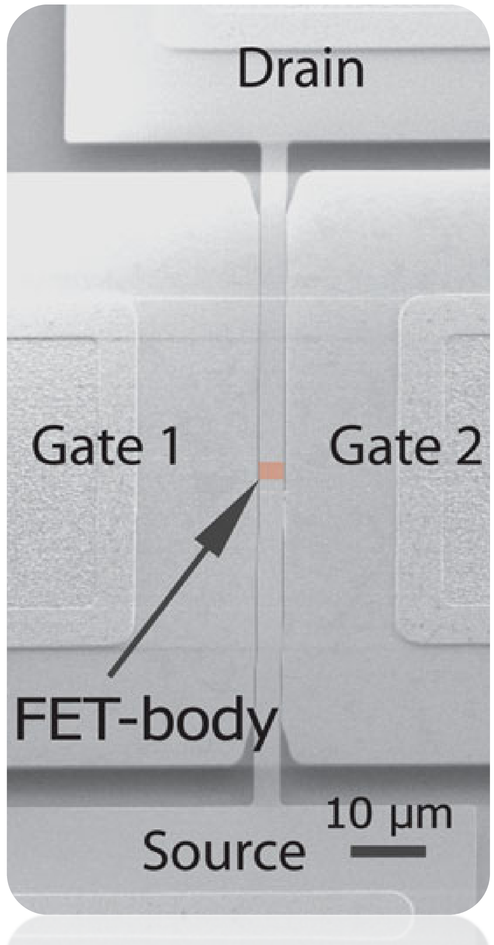


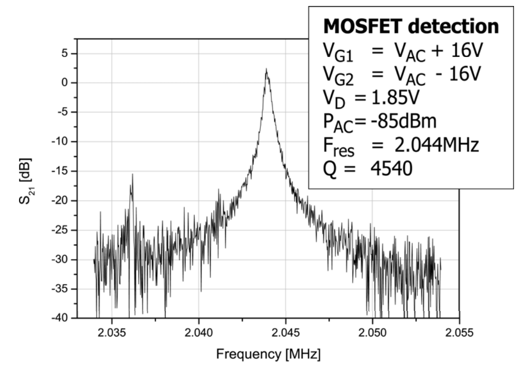
$$f_0 \equiv \frac{\omega_0}{2\pi} = 0.9395\,\frac{d}{L^2}\sqrt{\frac{E_Y}{\rho}}$$

Vibrating body FET

frez = 2MHz

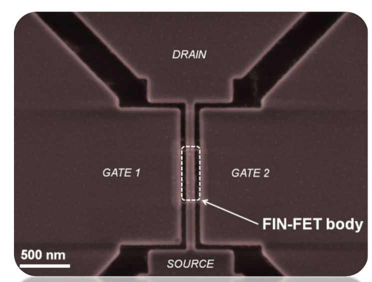






R_m = -30Ω, amplifies!

Fully-depleted RB-FET:

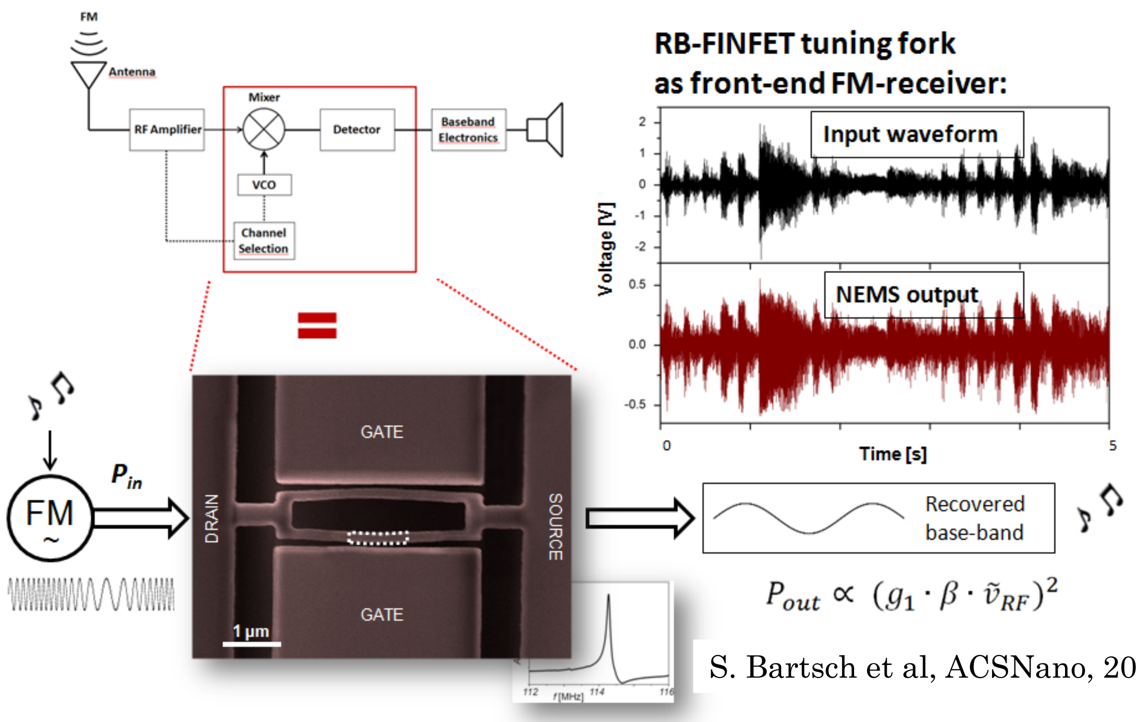


frez = 70MHz

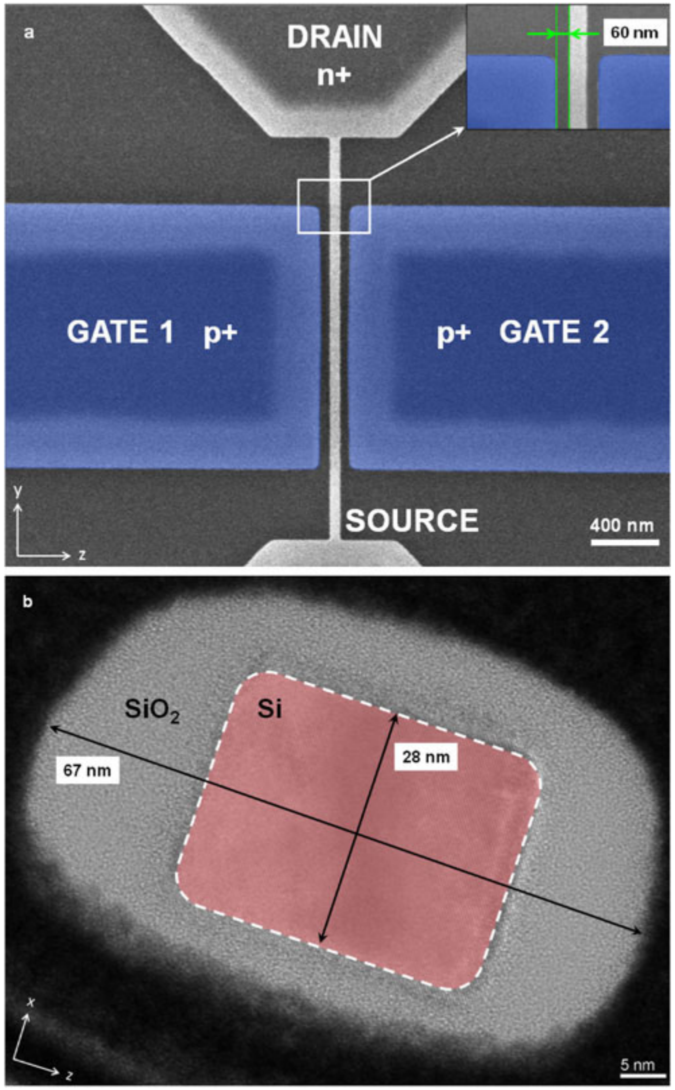
D. Grogg et al, IEDM 2008.

RF MEMS front-ends

- Ultra miniaturized single-device radios (RF front ends)



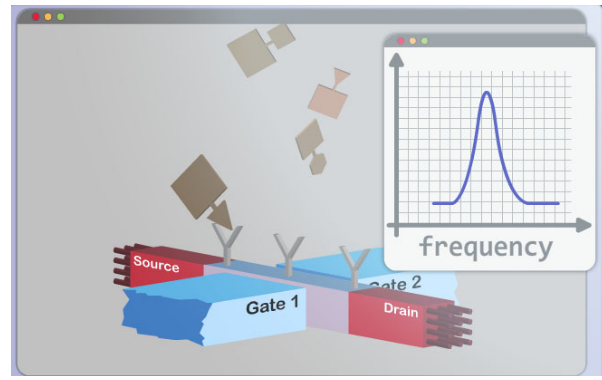
S. Bartsch et al, ACSNano, 2012.



NEMS nanobalances for molecule/atom sensing

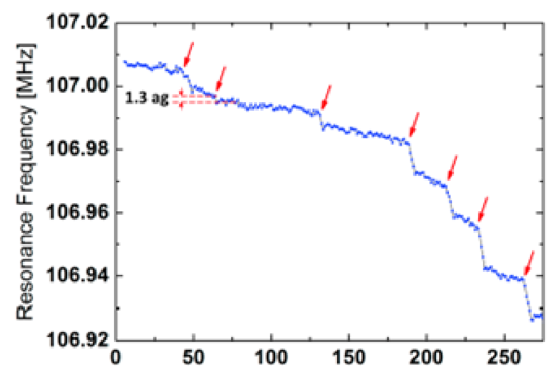
Ultra-scaled resonant transistor:
fres ~70 – 200MHz

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



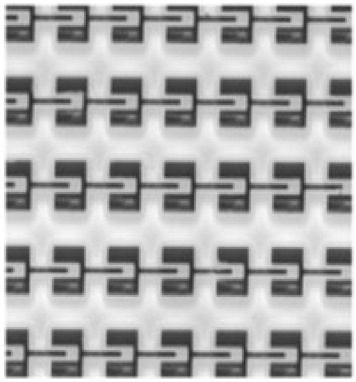
- Mass accretion of 1.3 ag (top) detected: corresponds to approx. 4000 gold atoms
- Scalable to detect ~10 atoms
- **Applications:**

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

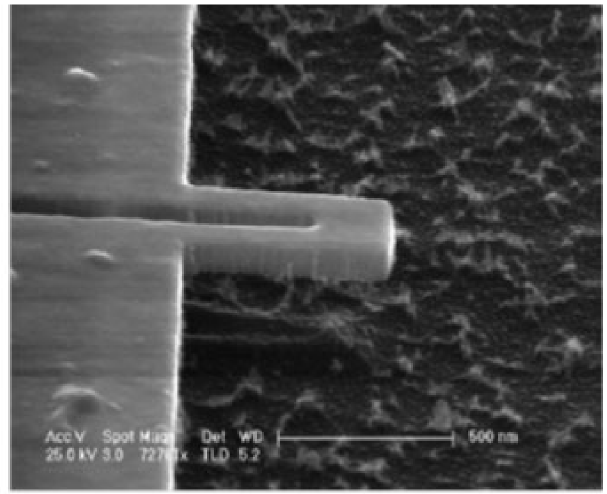


Gas sensors with NEMS (by Caltech)

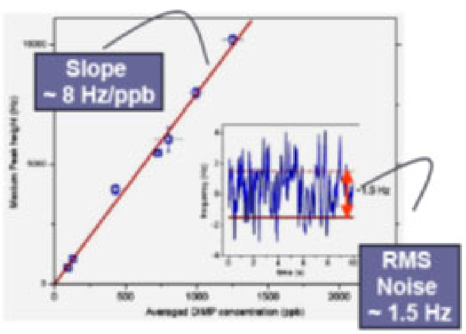
NEMS Array



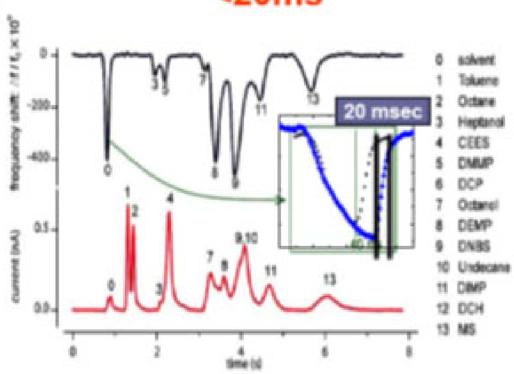
	Cal Tech (Zeptogram Microresonators)	Achievement 8/25/07
Chemisorbing Resonator	Mass Responsivity	5 Hz/ag
Chemisorbing Resonator	Mass Resolution	~10^{-19} g (100 zg)
Chemisorbing Resonator	Operating Pressure	1 atm (760 torr)
	Detector Response Time	< 20 ms
	No. of Sensor Elements	25,000
	Power Consumption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



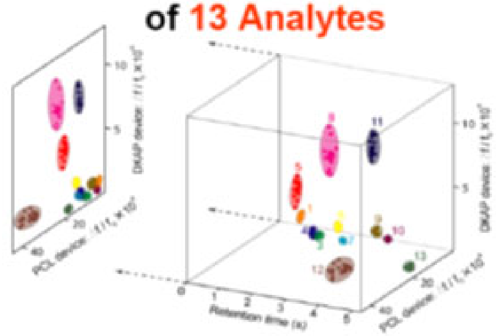
LOD – 200ppt DIMP (single sensor, no preconc.)



Sensor Response Time <20ms



Multisensor Discrimination of 13 Analytes

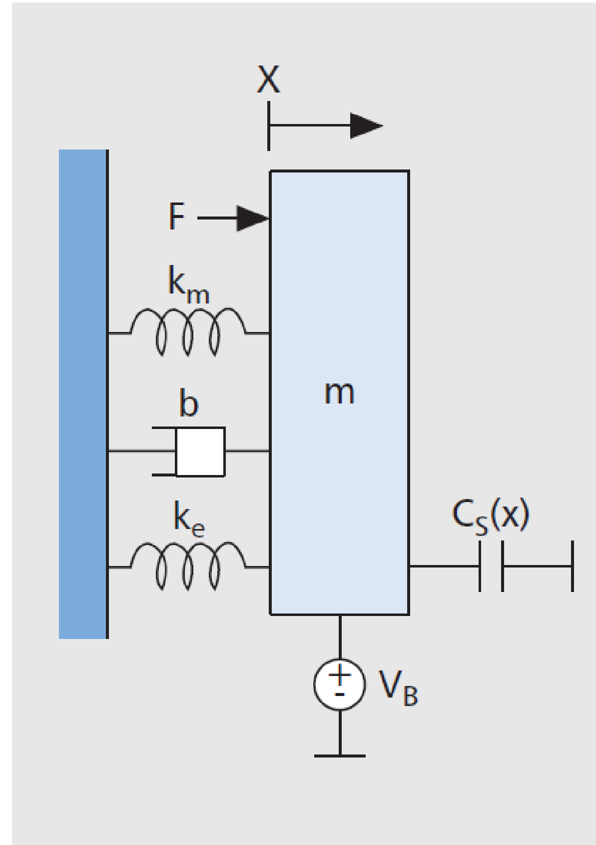


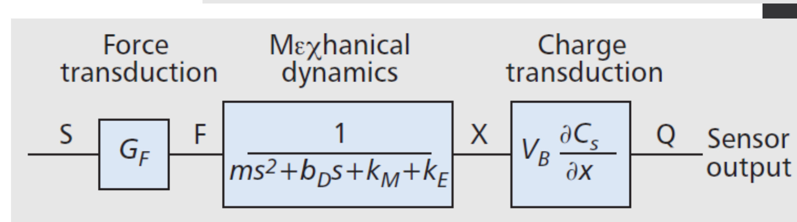
Conclusions: M/NEM resonators

- 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.

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

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

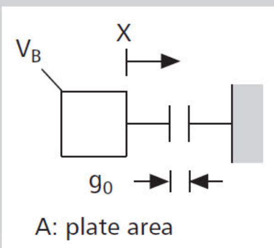
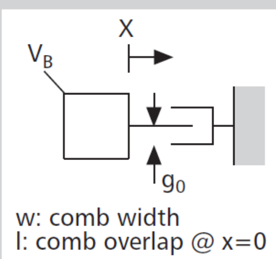
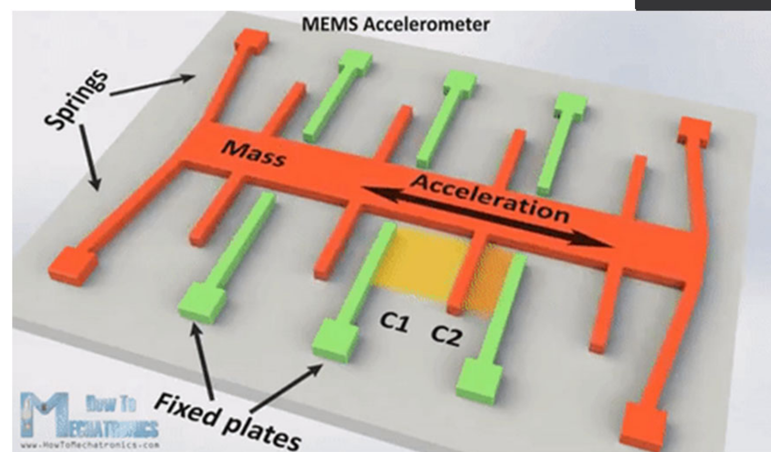
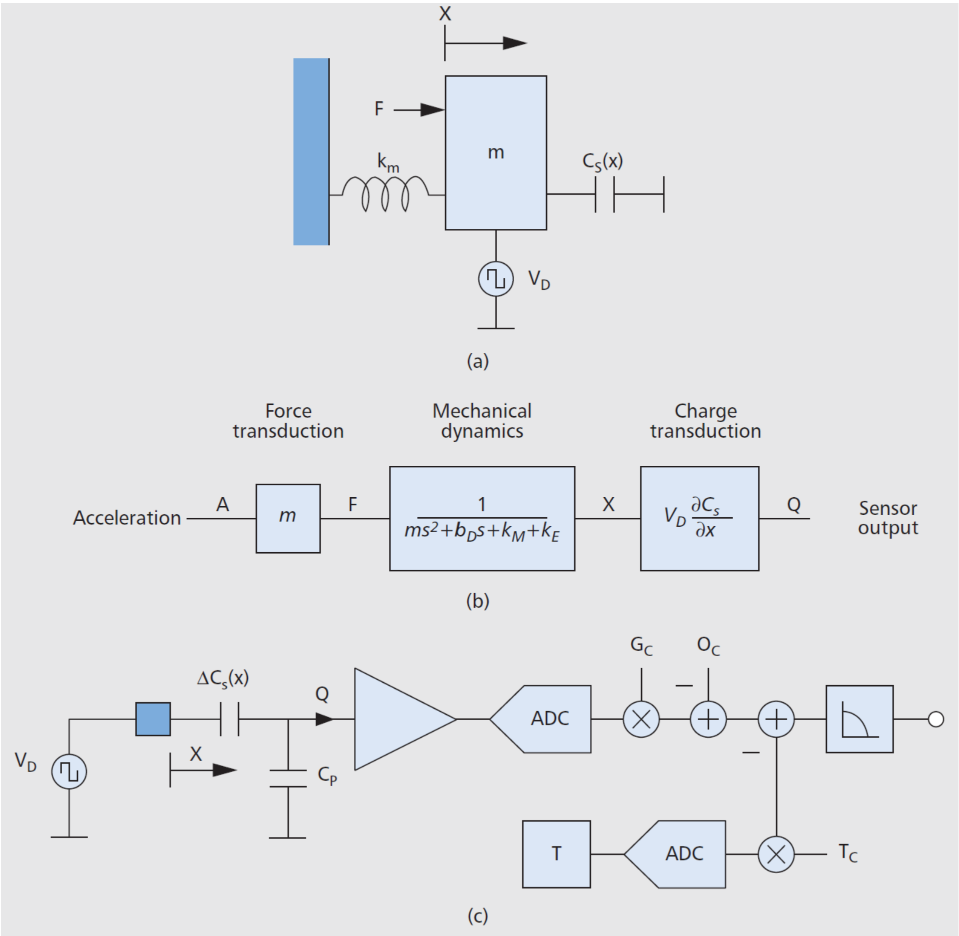
	Capacitance	Charge transduction	Force transduction	Spring constant
	C(x)	ΔQ(Δx)	ΔF(Δv)	k_E
Parallel-plate capacitor 	$\frac{\varepsilon_0 A}{g_0 - x}$	$\frac{\varepsilon_0 A}{g_0^2} V_B \Delta x$	$\frac{\varepsilon_0 A}{g_0^2} V_B \Delta v$	$-\frac{\varepsilon_0 A}{g_0^3} V_B^2$
Comb-finger capacitor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

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



Accelerometer system



Consumer applications

- Output data rates of a few kHZ
- Full-scale ranges of 16g
- 12–16 bit resolution
- DC accuracy over temperature and lifetime:

drift ~500 ppm levels (corresponding to, e.g., 10 mg for a 16g full-scale range), which implies that sub-nanometer displacements are significant for micron-scale gaps.

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.

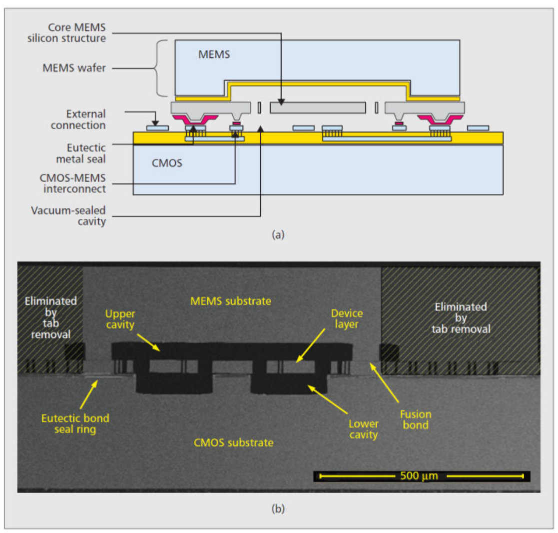
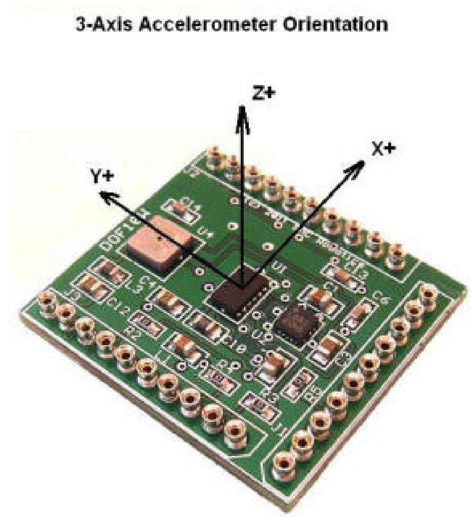
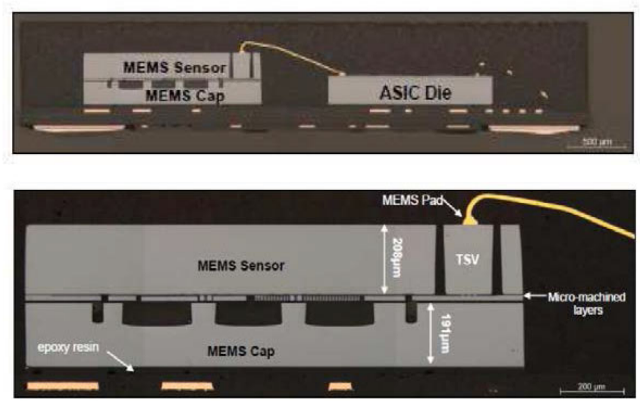


Figure 6. *InvenSense silicon MEMS/CMOS fabrication technology: a) assembly; b) device cross-section.*

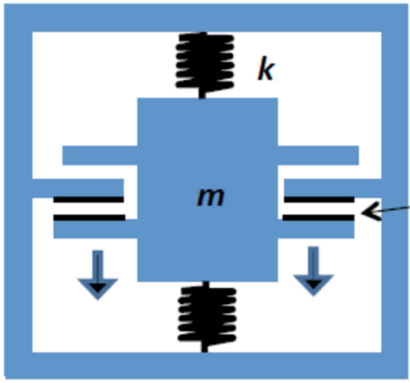


ST Microelectronics

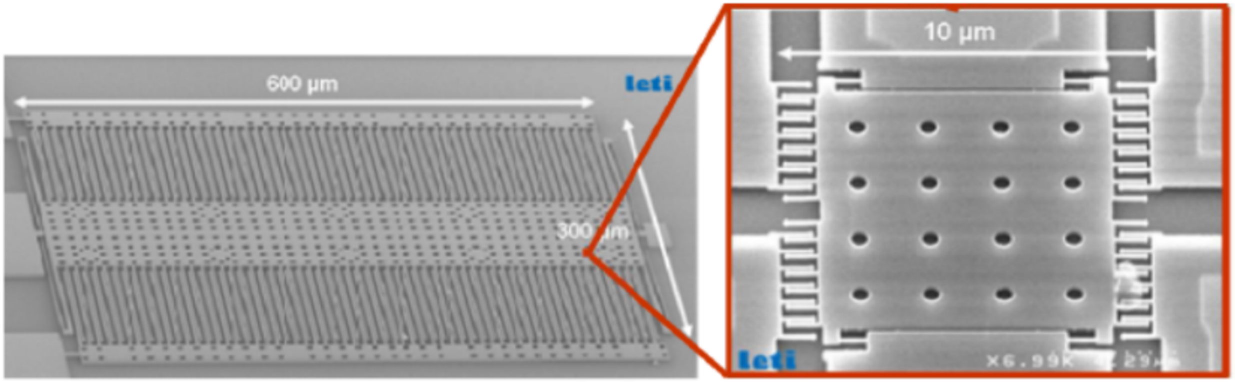


Ultra-low power NEMS-accelerometers

Applications : airbag (but no real need for miniaturisation), Ipod, videogames, mini-drones, etc.



$$I(t) = \frac{dQ}{dt} = \frac{\partial C}{\partial t} V$$



Micro-accelerometer

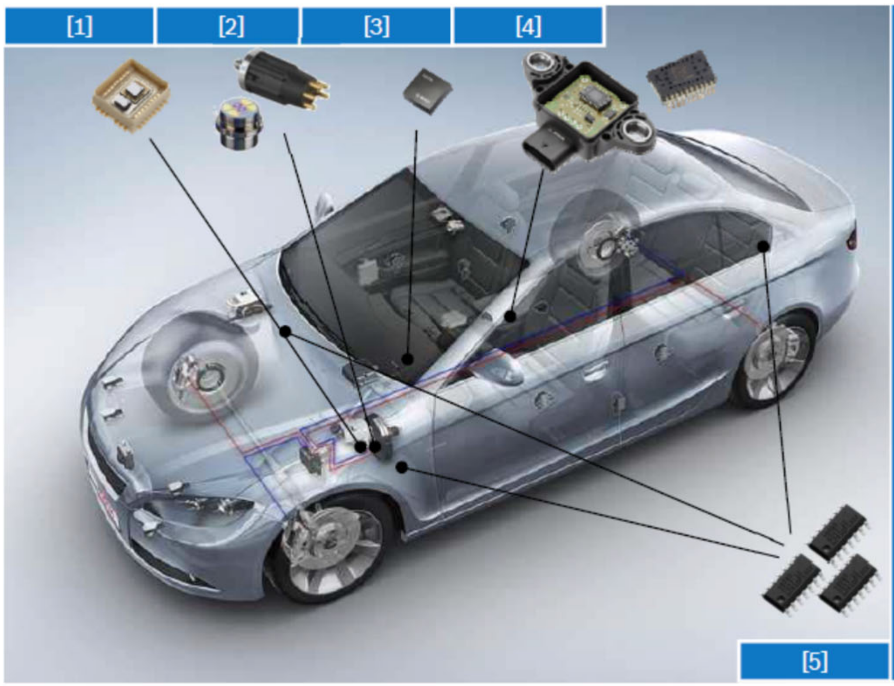
Nano-accelerometer

SEM images of micro and nano-systems fabricated at LETI-CEA (Grenoble)

Inertial sensors for automotive

Automotive sensors

MEMS sensors for vehicle dynamics control VDC



MEMS sensors for vehicle dynamics control VDC

[1] Inertial sensor
[2] High pressure sensor
[3] Inertial sensor
[4] Sensor cluster with yaw rate and acceleration sensor
[5] Low-g acceleration sensor for active suspension

Source: Bosch

Commercial MEMS IMU’s