Vibrating nanowires for advanced sensing

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Outline

- Electro-mechanical information processing
- NEMS technology
  - **Top-down versus bottom-up**
- MEMS/NEMS resonators
  - **Vibrating transistors**
- Vibrating nanowires for mass sensing:
  - **NEMSIC project**
- Conclusion

Electro-mechanical information processing

Electro-mechanical information processing:

(i) as a multi-state logic, with the logic states dictated by a spatial configuration of movable objects.

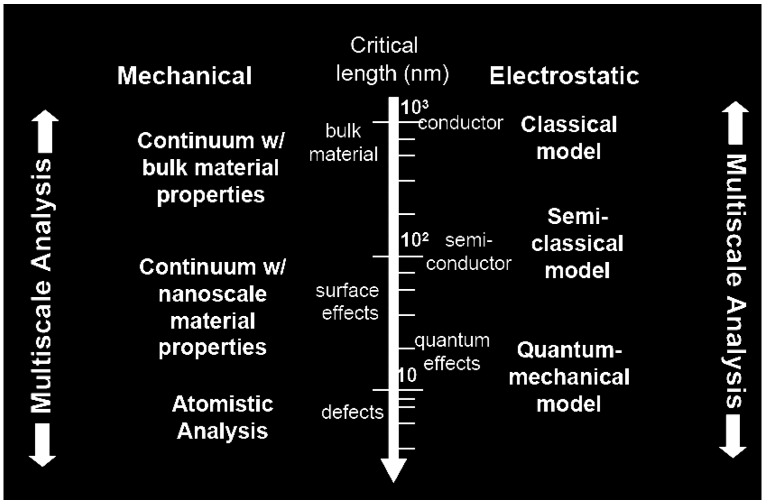
(i) as vibrational modes of mechanical elements, based upon waves.

Highly sensitive to mass loading.

Features of NEMS information processing

- Addresses some of the main limitation of dense digital computation with CMOS such as **standby power**.
- High potential of NEMS for analog computation and sensing; resonant nanostructures embed today full equivalent circuit functions: **filtering or frequency refs**.
- Nanometer small size generates supplementary interest for **collective information processing**.
- Extreme mass reduction: increases resonance frequency **beyond the GHz** and mass sensitivity **below the attogram**.
- Poor signal-to-noise ratio: **new detection schemes**.
- Size reduction at nanoscale may be **not a panacea for all the applications**.

NEMS simulation and modeling



NEMS technology

- NEMS technology requires the fabrication of nano-objects combined with surface micromachining
- The fabrication techniques capable of making nanostructures can be grouped into two three main categories:
  - top-down
  - bottom-up
  - hybrid bottom-up/top-down

Top-down nanofabrication

- **MEMS top-down** processing: based on the optical lithography and etching batch-type processing of semiconductor industry, which gives high volumes and high productivity on silicon wafers
- **NEMS top-down** processing: research, many fabrication techniques explored

Top-down fabrication techniques	Minimum feature size	Advantages and Issues
DUV (optical litho)	~30nm	Batch processing, robust, controlable, complex
e-beam litho	~5nm	Low-throughput, High resolution
Nanoimprinting	~10nm	High-throughput, low-cost, alignment issues
Nanostenciling	~50nm	High-throughput, low-cost, alignment issues (~1μm)
Spacer or side-wall	~20nm	High-throughput, Some limitation in design
Scanning probe litho	~5nm	Fast prototyping of individual devices with very small size
Reactive ion etching	~50nm	Free of wet etching restrictions, Suitable for mass production, Profile and uniformity control needed at nano scale
Metal lift-off	~10nm	Removing metals hard to etch, surface microfabrication
Focused ion-beam	~30nm	Versatile, fast, ion contamination issues

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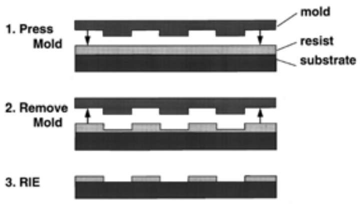
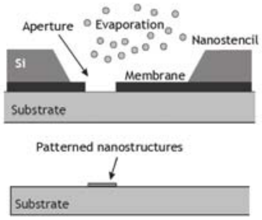
Nanostructure top-down fabrication

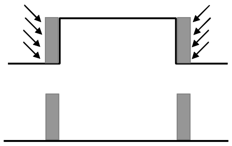
Nanoimprinting



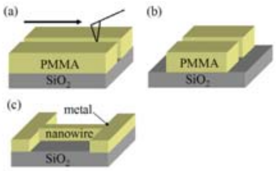
Nanostenciling



Side-wall

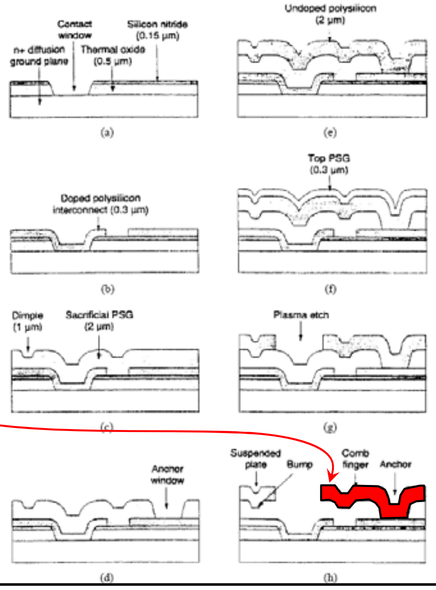


AFM nanoscratching



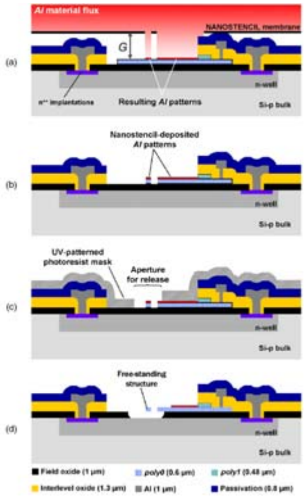
Surface micromachining

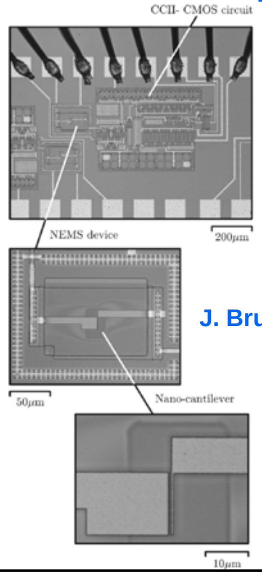
- possibility of suspending and anchoring parts of the fabricated nanostructures based on deposited thin films
- a free-standing structure is obtained by using a sacrificial layer that is selectively etched



Bustillo, J.M.; Howe, R.T.; Muller, R.S., Surface micromachining for microelectromechanical systems, Proceedings of the IEEE Volume 86, Aug. 1998 Page(s):1552 – 1574.

Example: Si NEMS fabrication





J. Brugger, EPFL.

Bottom-up processing

- Key bottom-up nano-structures used to fabricate NEMS processed by a non-lithographical method: growth or self-assembly processing that can provide feature size much smaller than the resolution offered by the lithography
- Silicon nanowires (SiNWs) and carbon nanotubes (CNTs) are typical nano-structures than can be realized by bottom-up techniques with cross sections smaller than 50nm
- issues concerning SiNWs controlability, variability, forming contacts and interfaces with desired electronic properties and leveraging of existing Si-CMOS process infrastructure needs further efforts and exploration of bottom-up and top-down SiNW fabrication alternatives

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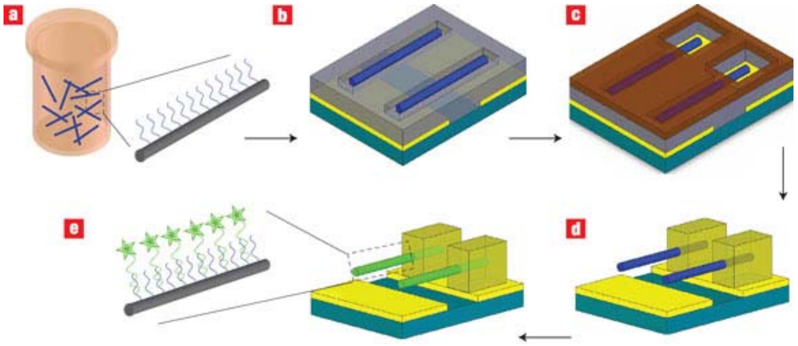
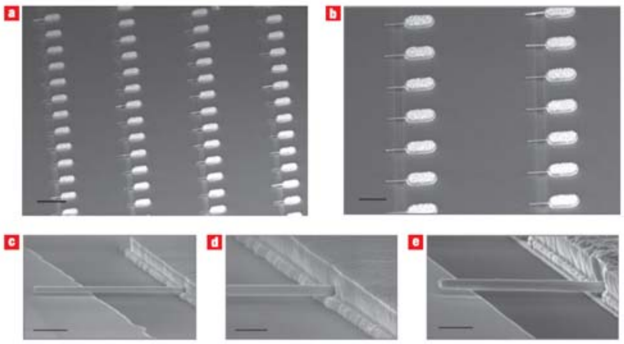
Example 1: bottom-up Rh and Si NW resonator arrays (1)

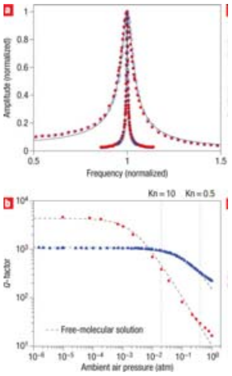


a) Molecules are attached to the NWs. b) dielectrophoresis is used to preferentially align single NWs in wells patterned in a sacrificial photoresist layer. c) Individual clamp windows are defined in a second photoresist layer. d) Metal clamps are electrodeposited around the NW tips. e) NWs are exposed to fluorescently labelled complementary and non-complementary targets to confirm detection selectivity.

M. Li et al., Nature Nanotechnology 3, 88 - 92 (2008)

Example 1: bottom-up Rh and Si NW resonator arrays (2)

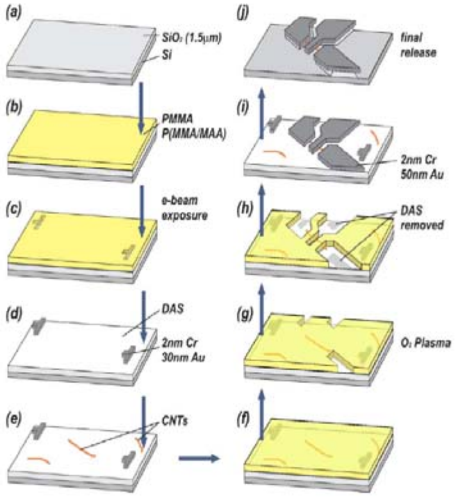


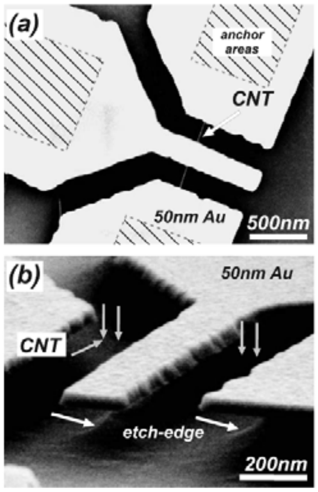


Fabricated Si- and RhNW resonator arrays

FE-SEM images: RhNW resonator arrays showing a high yield of single NWs positioned at predefined locations (a,b); cantilevered SiNW resonator clamped with electrodeposited Au (right), and suspended 300 nm above the Au electrode (left) (c,d); cantilevered RhNW resonator (e).

Example 2: CNT NEMS fabrication





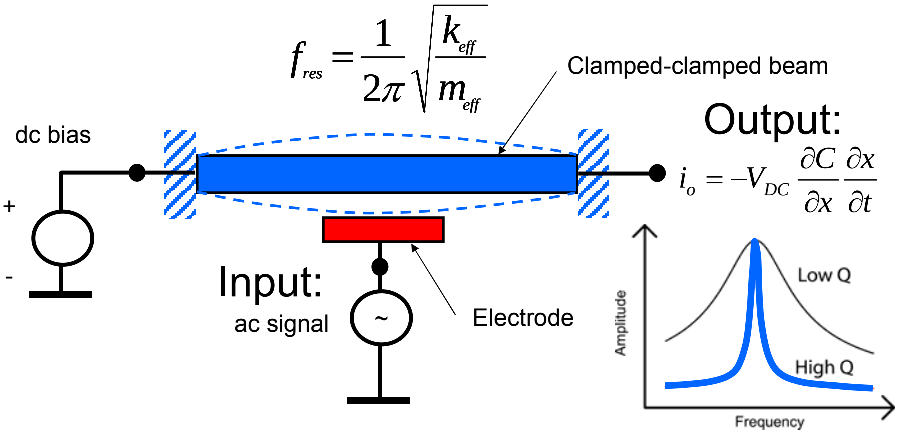
C. Hierold, ETHZ.

M/NEMS for analog/RF and sensing

- Device and system **miniaturization**
- **Co-Integration** with ICs (above- and in-IC, 3D)
  - lower costs
- **Power savings** (low power operated devices)
- **Novel functionality**
  - re-configurable RF ICs
- **High performance at RF**
  - mobile communication systems
- **High sensitivity/resolution** of sensors
- NEMS: **collective low power signal processing**

Principle of MEM resonator

- Micro-Electro-Mechanical resonator



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

Output:

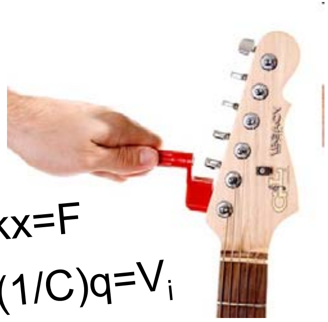
$$i_o = -V_{DC}\frac{\partial C}{\partial x}\frac{\partial x}{\partial t}$$

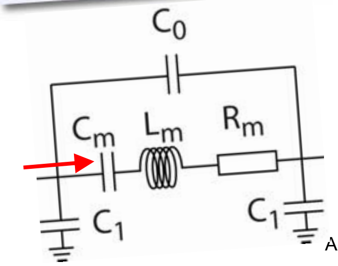
Input:

ac signal

MEM resonator is tuneable

Tuning the resonance frequency: stiffness!





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

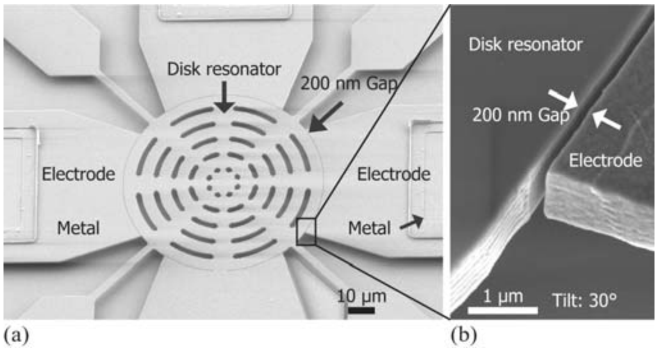
$Lq''+Rq'+(1/C)q=V_i$

Stiffness ~1/C

MEM resonator needs nanogap

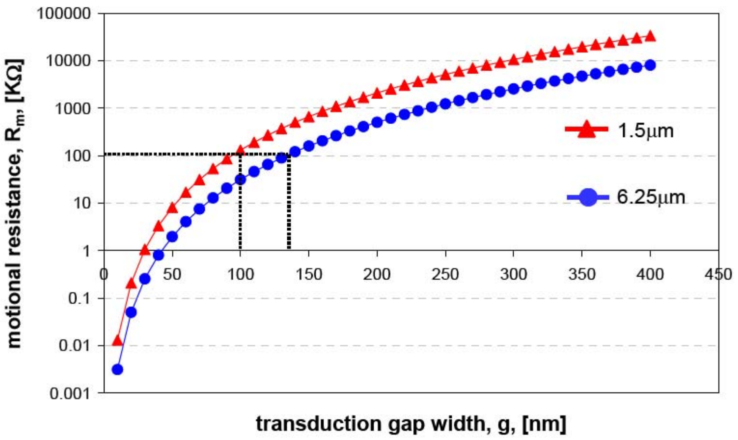
$R_m \sim gap^4/voltage^2$ (1/10 gap, 1/10'000 R_m)

f_{res}=31MHz, r=40um, t_{Si}=1.25um
Non-lithographic gap=200nm, Q>20'000, R_m=130kOhm.

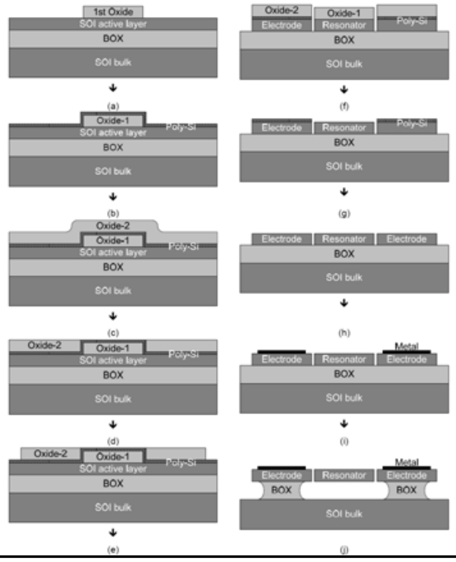


(a) (b)

R_m versus nanogap

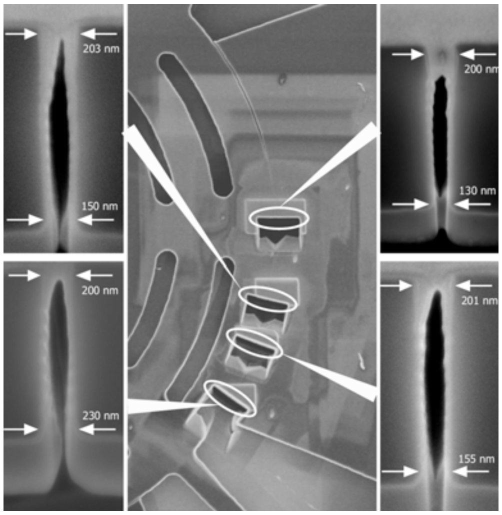


SOI resonator with non-lithographic gap definition: 4-mask process

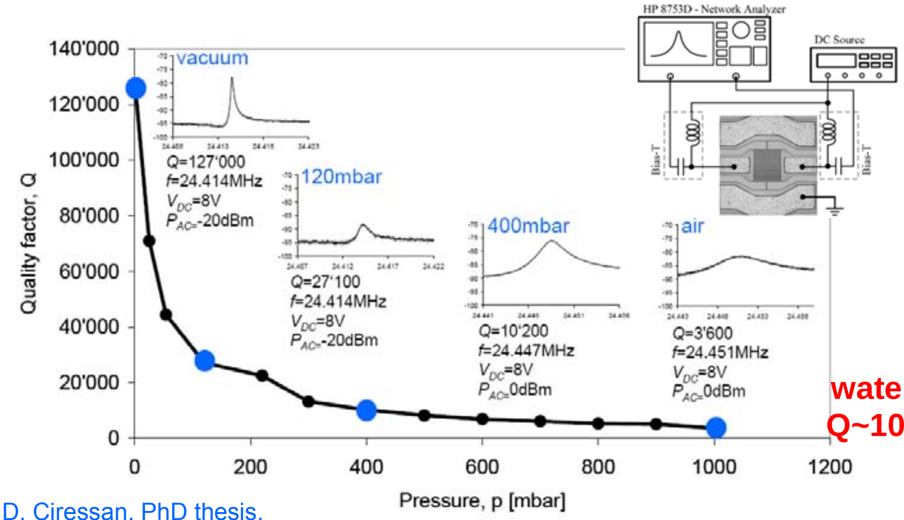


(a) TEOS deposition and mask 1: patterning
(b) deposition of the thin polysilicon gap spacer
(c) deposition of the second oxide layer
(d) CMP and BHF back-etch of the second oxide to reveal the polysilicon layer
(e) mask 2: patterning of electrodes
(f) transferring the hard mask into the silicon film by dry etch
(g) mask oxide removal
(h) mask 3: opening of contacts
(i) mask 4: metal deposition and patterning
(j) release

Gap control @ nm scale



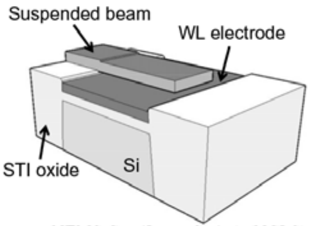
High-Q resonator needs vacuum



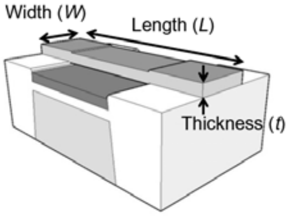
water
Q~100

D. Ciressan, PhD thesis.

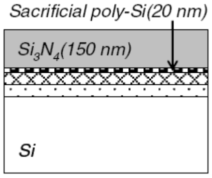
20nm gap in top-down NEM switch



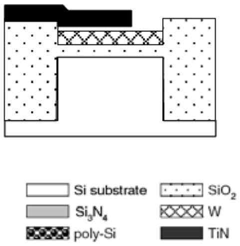
NEMS CantiLever Switch (NCLS)

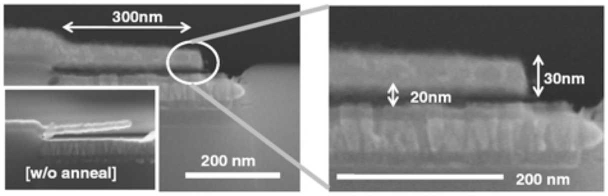


NEMS Clamp Switch (NCS)



poly-Si release





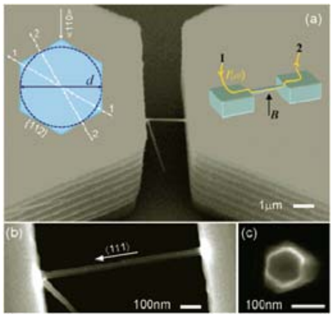
[Cantilever-type]

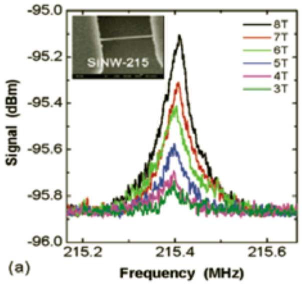
[Magnified view]

W.W. Jang et al, Solid-State Electronics 52 (2008) 1578–1583.

Nanowire and nanotube resonators

(VHF) 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.

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

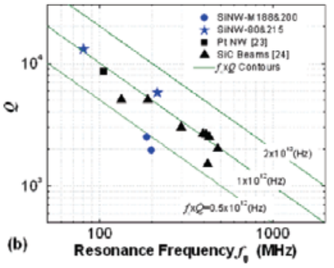
NW resonance frequencies

Table 1. Characteristics and Performance Specifications of VHF SiNW Resonators[a]

	SiNW-M200	SiNW-M188	SiNW-215	SiNW-80
L (μm)	2.25	2.1	1.69	2.77
d (nm)	142	118	81	74
metallization	30 nm Al + 5 nm Ti			
resistance (Ω)	~50	~50	3.2 k	3.6 k
f_0 (MHz)	199.68	187.86	215.40	80.57
Q	2000	2500	5750	13 100
$f_0 \times Q$ (Hz)	3.99×10^{11}	4.70×10^{11}	1.24×10^{12}	1.06×10^{12}
M_{eff} (fg)	70.1	45.2	17.1	23.4
k_{eff} (N/m)	110.3	62.9	31.4	6.0
E_Y (GPa)	182	187	152	184

[a] The SiNWs are named by their nominal resonance frequency in MHz, with "M" denoting the metallized ones

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



'Nano' added value

Vibrating cantilever: uniform scaling of all dimensions

$$w = a\ell,\ t = b\ell,\ L = c\ell$$

- Scaling of frequency:

$$f_0 \approx \alpha\sqrt{E/\rho}\,\frac{t}{L} \propto \frac{1}{\ell}$$

↑ with decreasing ℓ

- Scaling of compliance:

$$k_{eff} \approx \beta E w\left(\frac{t}{L}\right)^3 \propto \ell$$

↓ with decreasing ℓ

- Scaling of thermomechanical noise:

$$S_F^{1/2} = \left(4k_B T k_{eff}/(\omega_0 Q)\right)^{1/2} \propto \ell$$

↓ with decreasing ℓ

Sensing by resonator mass-loading

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

Mass sensitivity influenced by:
- resonator mass
- quality factor
- resonance frequency

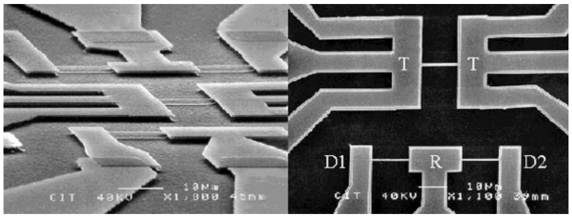
Minimum detectable mass:

$$\boxed{\delta m \cong 2 m_{eff}\sqrt{\frac{\Delta f}{Q \cdot 2\pi f_{res}}} \cdot 10^{-\frac{DR}{20}}}$$

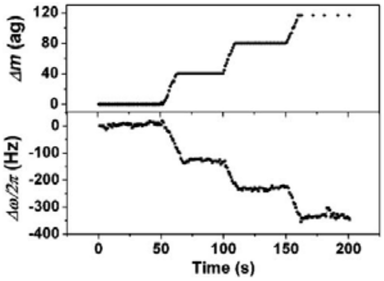
$$DR(dB) = 10 \cdot log\left(\frac{E_c}{k_B T}\right) \qquad E_c = m_{eff} \cdot (2\pi f_{res})^2 \cdot \langle x_c^2 \rangle$$

- Δf is the measurement bandwidth
- Q is the quality factor of the resonator
- DR is the dynamic range
- Ec is the kinematic energy of the resonator when driven at a constant mean square amplitude

Example 1: SiC resonators



K. L. Ekinci, X. M. H. Huang, and M. L. Roukes, “Ultrasensitive nanoelectromechanical mass detection”, Applied Physics Letters, vol 84, 2004.

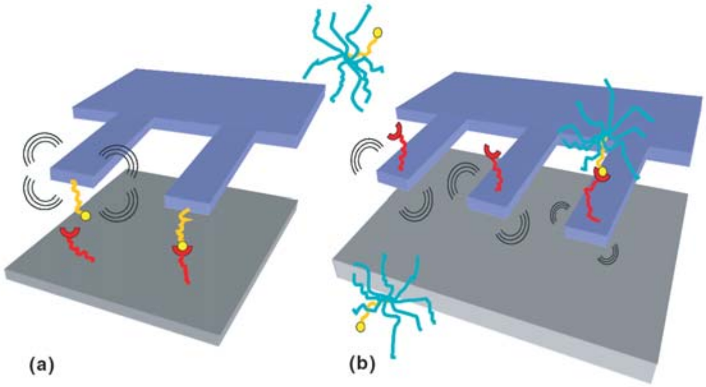


- Measured frequency shifts: Δ*f* (bottom) induced by sequential gold atom adsorption upon the CC beam resonator
- Mass of gold atoms, Δ*m*, in the upper plot is measured by a separate quartz crystal detector

Example 2a:

- Detection based upon a **change in device compliance**

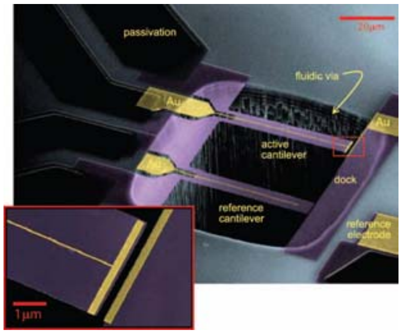
- Detection based upon a **change in device damping**



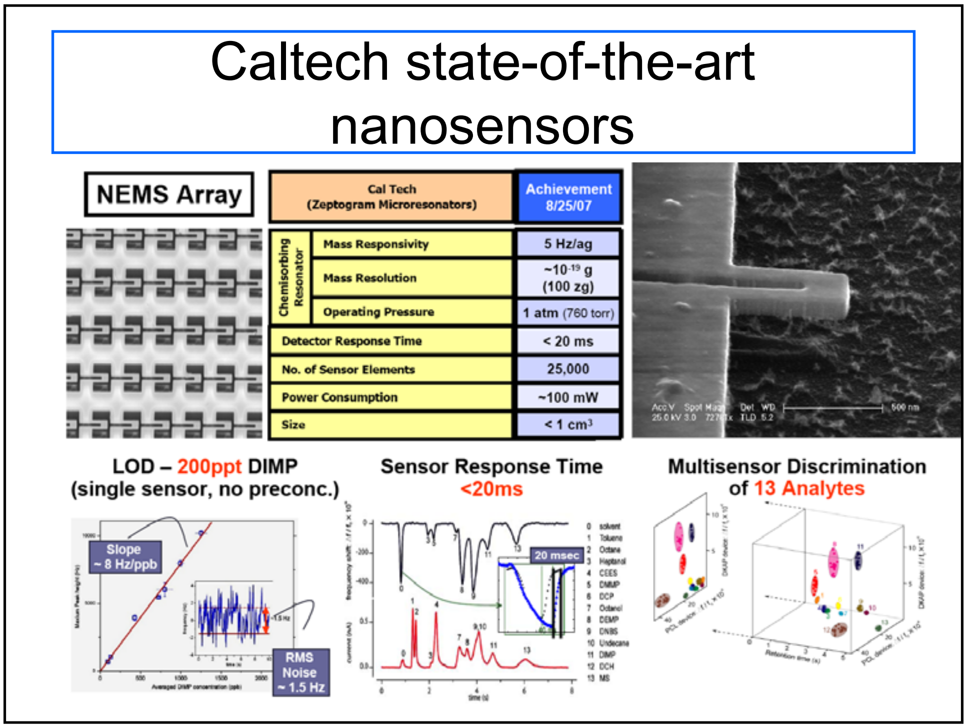
Example 2b:

- Bio-NEMS detection based on a change in device compliance

• the fine gold lines at the cantilever tip and along the dock in the vicinity of the tip are **functionalized with a receptor specific to the analyte**
• binding of an analyte across the gap leads to a **change in the cantilever's effective spring constant** (compliance)



Arlett JL, Paul MR, Solomon JE, Cross MC, Fraser SE, Roukes ML
BioNEMS: Nanomechanical Systems for Single-Molecule Biophysics
Lect. Notes Phys. **711,** 241-270, 2007.



Caltech state-of-the-art nanosensors

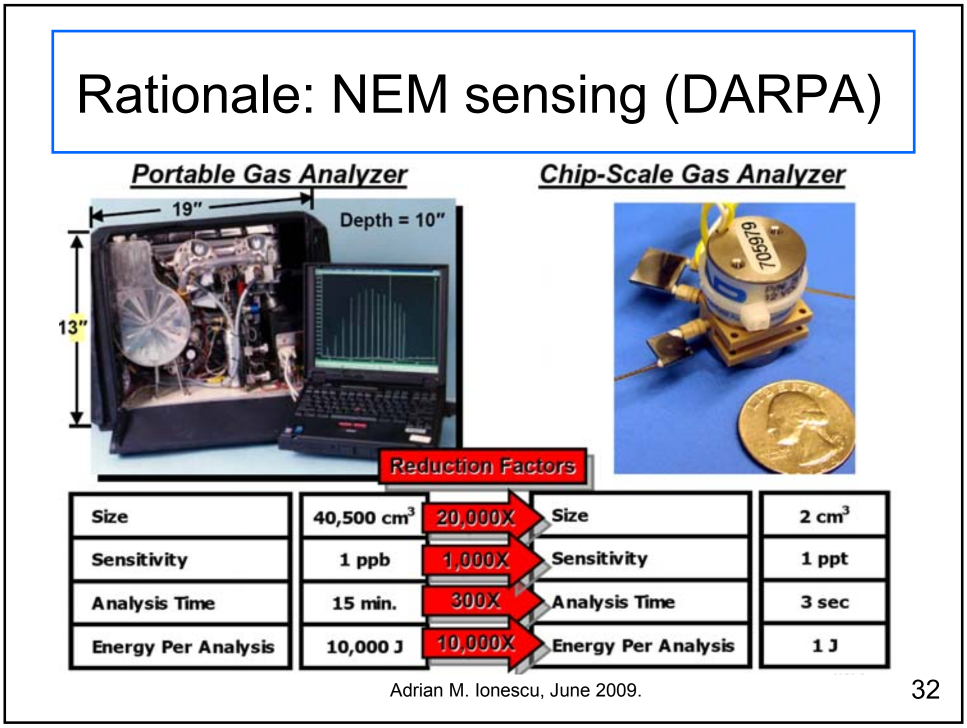
NEMS Array

		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



Rationale: NEM sensing (DARPA)

Portable Gas Analyzer

Chip-Scale Gas Analyzer

Reduction Factors

Size	40,500 cm^3	20,000X	Size	2 cm^3
Sensitivity	1 ppb	1,000X	Sensitivity	1 ppt
Analysis Time	15 min.	300X	Analysis Time	3 sec
Energy Per Analysis	10,000 J	10,000X	Energy Per Analysis	1 J

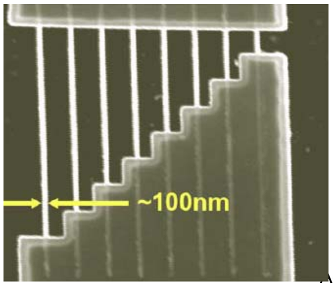
NEM-semiconductor hybrids

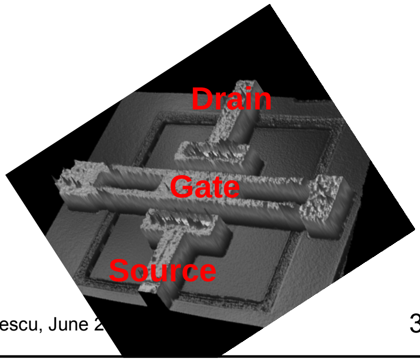
Pure M/NEM devices:
- micro/nano movable parts
- passive device operation

Ex: suspended nano-beams

Hybrid M/NEM devices:
- micro/nano movable parts
- solid state semiconductor device involved in operation

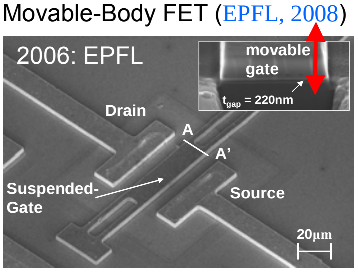
Ex: suspended-gate FETs



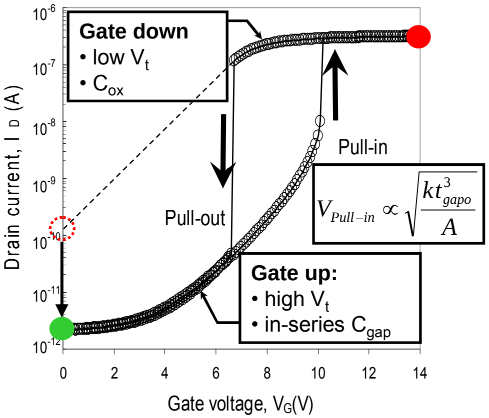


FET with movable parts

- Resonant-Gate FET (Nathanson,1966)
- Suspended-Gate MOSFET (EPFL 2001, 2005 & 2006)
- Nano-Electro-Mechanical FET (UC Berkeley, 2005)
- Movable-Body FET (EPFL, 2008)

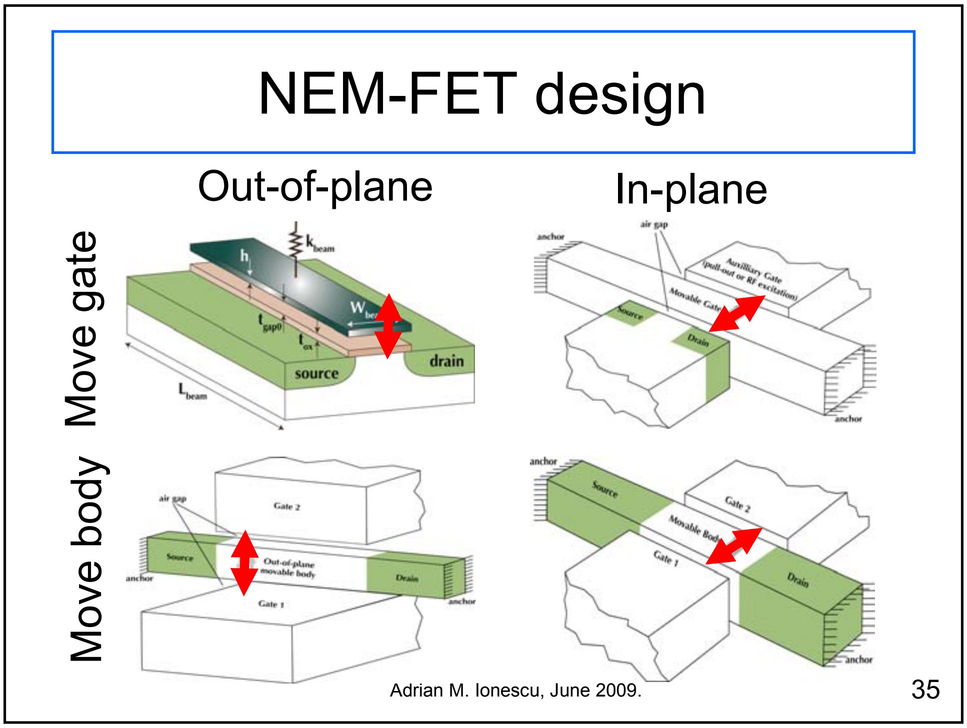


Out-of-plane movable gate

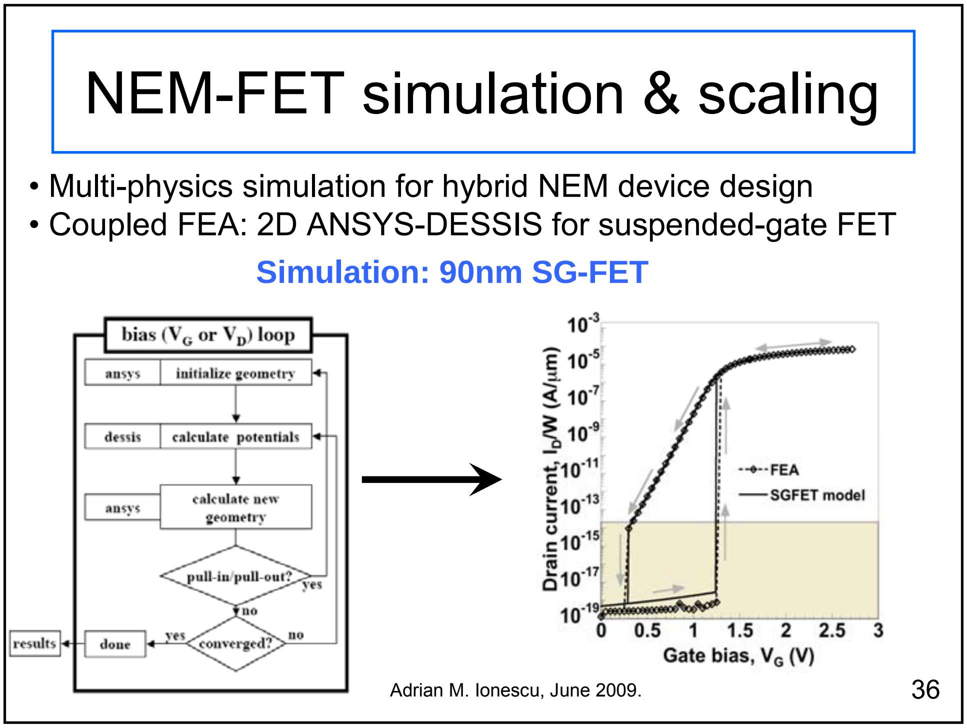


Applications: power management, low power logic, memory

Sensing?



NEM-FET design

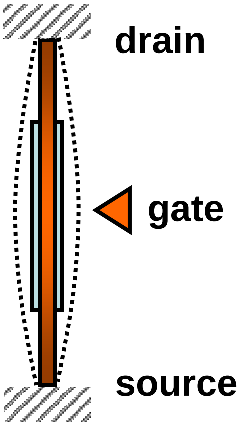


NEM-FET simulation & scaling

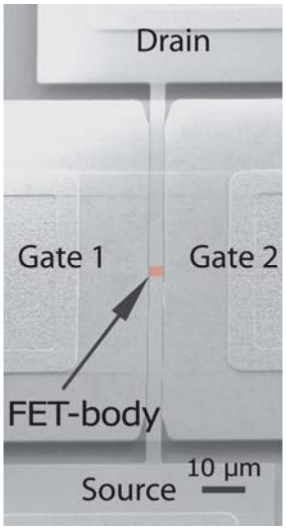
- Multi-physics simulation for hybrid NEM device design
- Coupled FEA: 2D ANSYS-DESSIS for suspended-gate FET

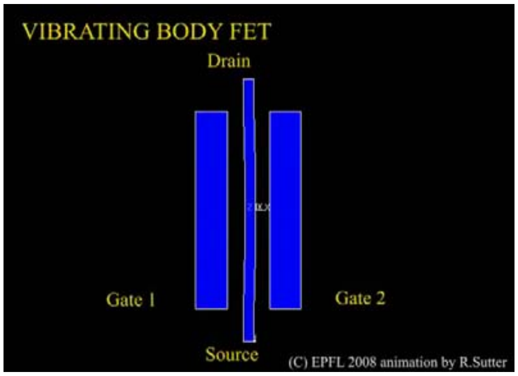
Simulation: 90nm SG-FET

A transistor in a guitar string

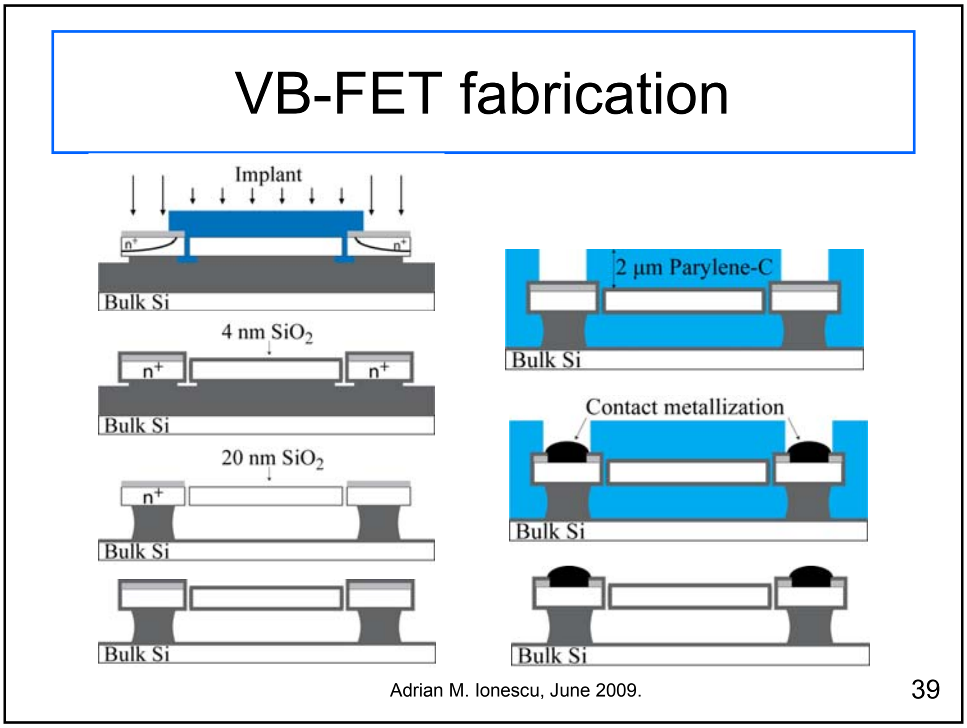


Vibrating-body (string FET)



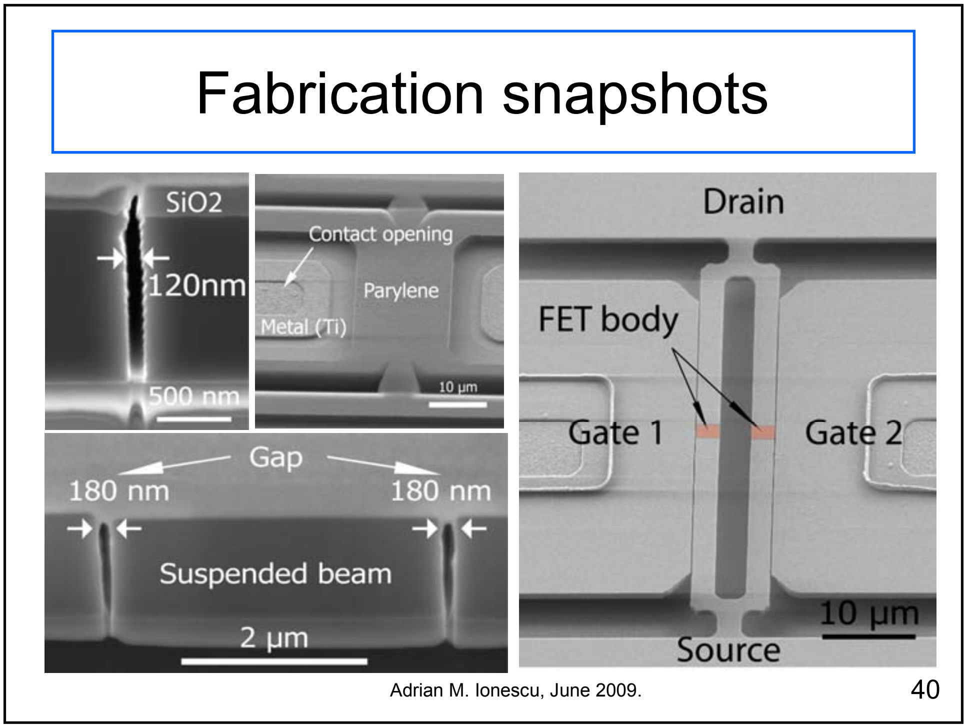


- charge
- piezoresistive modulations



VB-FET fabrication

Adrian M. Ionescu, June 2009.

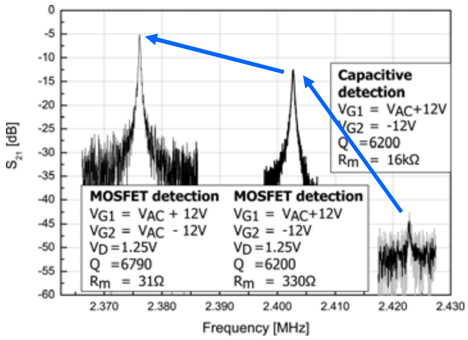


Fabrication snapshots

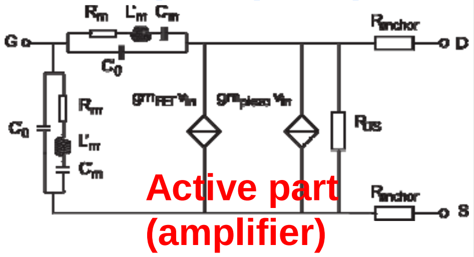
Adrian M. Ionescu, June 2009.

MEM resonator with intrinsic gain

1 VB-FET resonator



MEM part (filter)



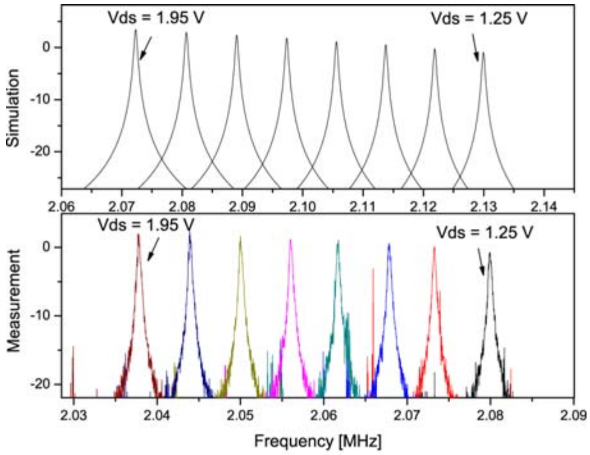
Active part (amplifier)

VB-FET is a filter-amplifier low power device.

Tuning the VB-FET

Model

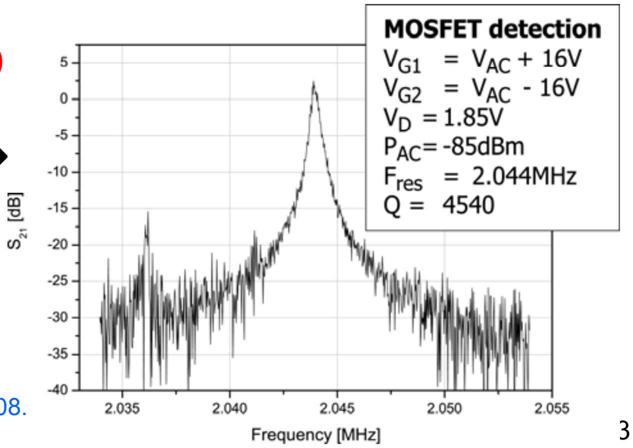
Experiment



Intrinsic signal amplification

+ 3dB signal gain measured on a 50Ω VNA

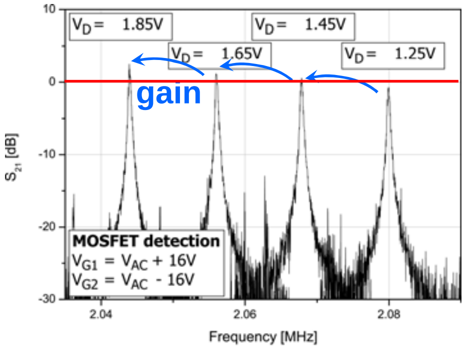
- R_m = -30Ω (negative res!)
  - Impedance mismatch ➔ Higher gain expected in a matched device



D. Grogg et al., IEDM 2008.

10micro-Watt single FET oscillator

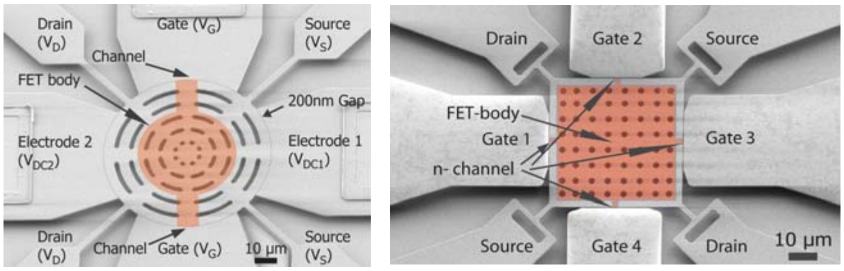
10µW single-device oscillator!



EPFL's VB-FET technology:

- Voltage operation:
  - Vd=1-2V.
  - Vg1=Vg2=8-16V.
- Resonance frequency:
  - 1MHz – 100MHz.
- Tuning range: ~1000ppm.
- Thermal drift: ~10ppm/°C.

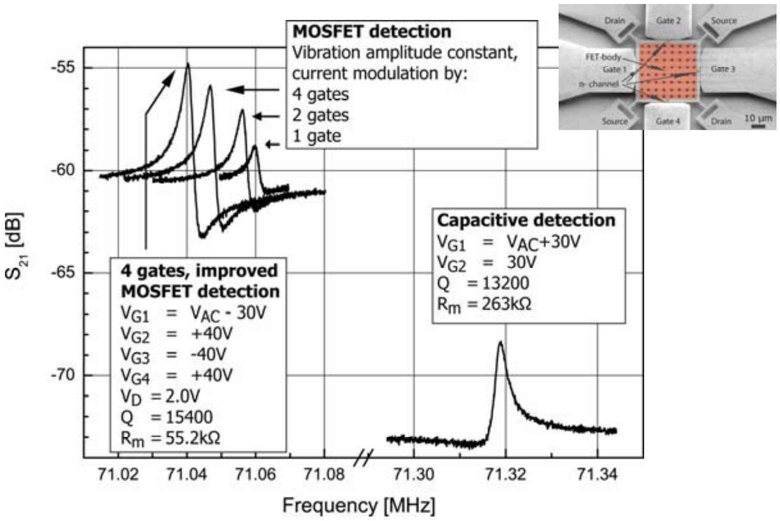
High frequency: multi-gate VB-FET



Grogg & Ionescu @ IEDM 2008 & VLSI TSA 2006.

- Frequency (experimental) 24 to 71 MHz
- Multi-gate configuration

Experiment multi-gate VB-FET

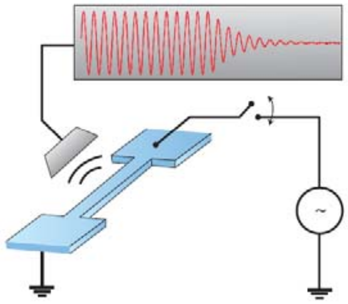


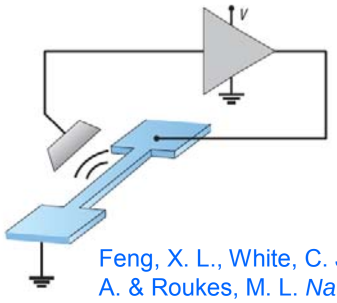
NEMS and feedback loop

NEM resonator operation require an external oscillator, such as an applied a.c. voltage, to compensate for losses.

Self-sustaining (?) nanoelectromechanical oscillator without an external oscillator

But that’s not a true self-oscillation!

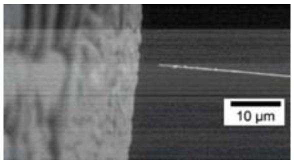


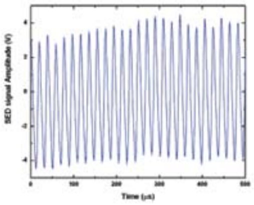


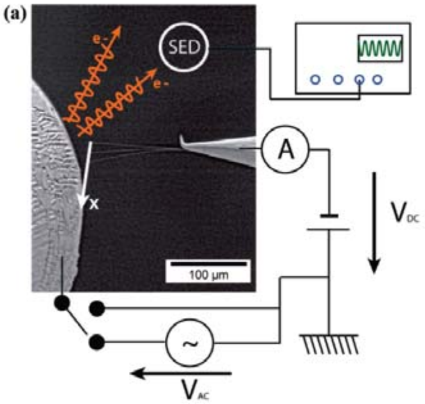
Feng, X. L., White, C. J., Hajimiri, A. & Roukes, M. L. *Nature Nanotech.* **3,** 342–346 (2008).

True self-sustained NEM oscillation

Self-Oscillations in Field Emission Nanowire Mechanical Resonators



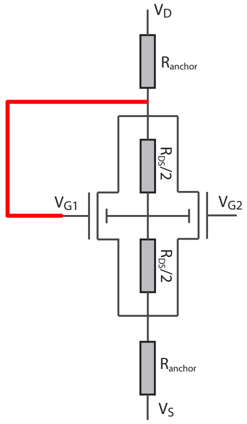


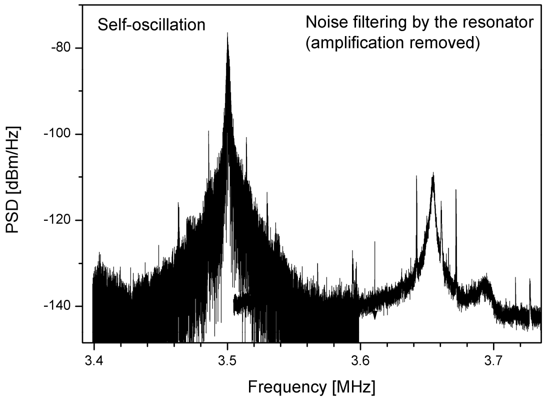


A. Ayari et al., NANOLETTERS 2007, Vol. 7, No. 8.

Self-oscillations in VB-FET

- Enabling future single-device nW oscillators

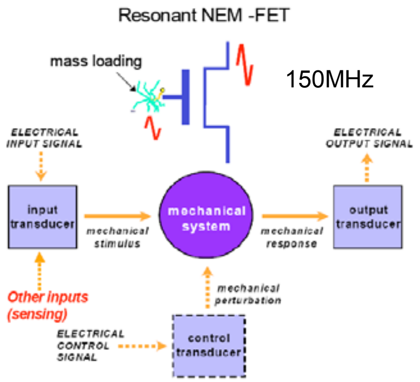




D. Grogg, A.M. Ionescu, submitted to IEDM 2009.

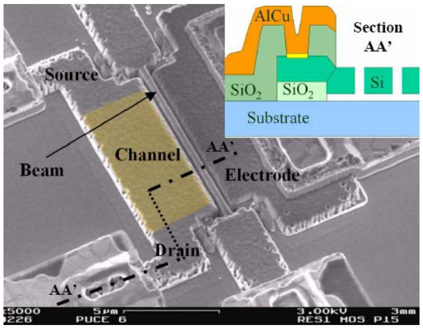
NEMSIC project

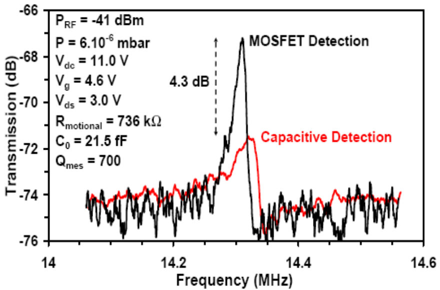
- Hybrid Nano-Electro-Mechanical / Integrated Circuit Systems for Sensing and Power Management



NEMSIC: resonant gate & body transistors for gas and bio-sensing

- **Lateral MOS transistor**, detection in drain current
- +4.3dB experimental gain demonstrated compared to capacitive detection using same structure

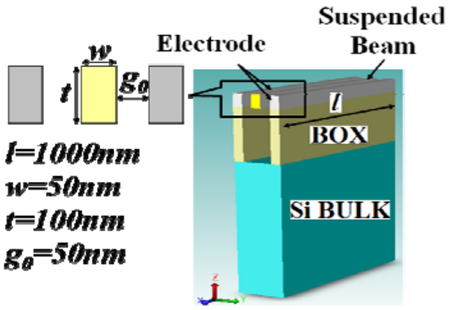




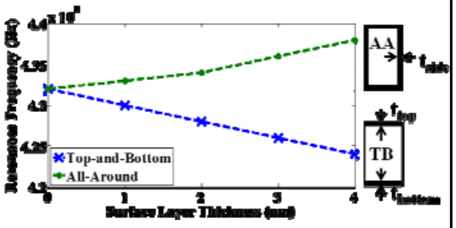
- low Q
- high motional resistance
- limited gain

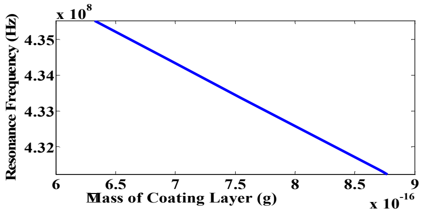
C. Durand et al., IEEE EDL 2008.

Resonant device in NEMS-IC



l=1000nm
w=50nm
t=100nm
g$_0$=50nm

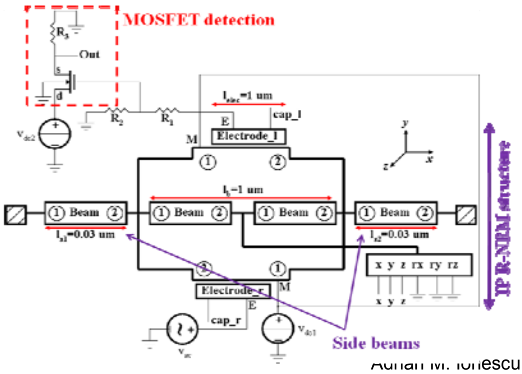


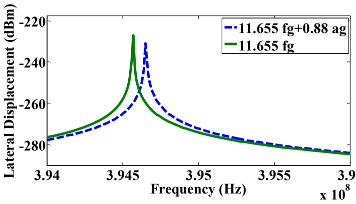


In-Plane Resonant NEM Sensor for Sub-Attogram Mass-Detection

Reference: quartz crystal microbalance (QCM) biosensor features a detection area of 0.049 cm2 and a mass detection limit of 100 pg with a sensitivity of 30 pg/Hz

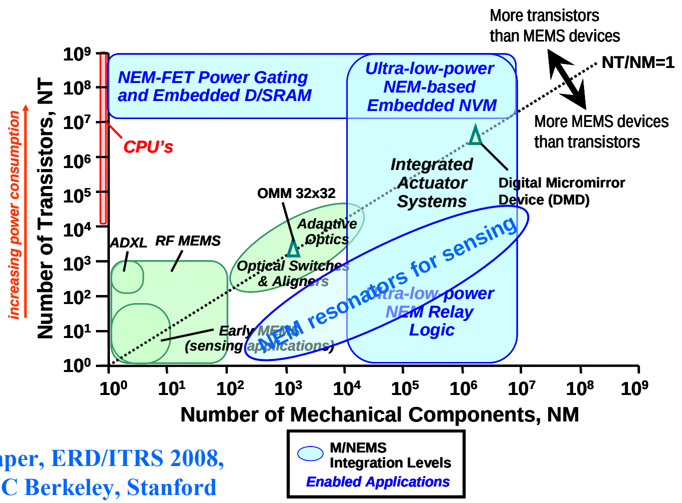
- f_{res}= 394.57 MHZ
- enables sensitivity less than 10-100 zg/Hz





F. A. Hassani et al., SSDM 2009.

Future NEM applications



White paper, ERD/ITRS 2008,
EPFL, UC Berkeley, Stanford

MEM/NEM challenges

- Surfaces and interfaces
- Reliability and packaging
- Scaling
- New material
- Fabrication (control, robustness)
- Modeling (multi-physics)
- Integrate micro/nano power sources

Opportunities for NEMS

- Large opportunities for (N/MEMS) in **enabling new systems** (co-integration with silicon ICs)
- Look to M/NEM technology to **enable performance**; not drive down cost.
- Nanotechnology applications are driven from **top-down** not bottom-up.
- World competition is intense: **massive effort** and investment needed.

Summary (1)

- Key role of NEMS technology for power savings, new functionality and sensing
- NEM resonators: key components for future advanced signal electro-mechanical processing: role for **sub-attogram sensing by mass loading or damping in functionalized structures**
- Future role of **vibrant FET devices for integrated sensing**

Summary (2)

- **Vibrating Body FET as active resonator**, fres: 2MHz-71MHz
  - Signal gain: > +30dB
  - Reduction of the motional resistance: >100x
  - Flexible mechanical resonator design
- First active MEM resonator with built-in amplification: **resonator = oscillator**
- Low power consumption: <10µW
- Lowest power **self-resonant VB-FET**
- **Candidate for integrated resonant sensing**

Acknowledgements

- Daniel Grogg, Nanolab (VB-FET)
- Dimitrios Tsamados, Nanolab (SG-FET)
- Staff of CMI-EPFL (Process assistance)
- European Commission for FP7 project funding
- LETI-CEA for collaboration on RSG FET

Thank you

Questions?