Applications and Trends in RF MEMS

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Outline

I. MEMS Origins

II. MEMS Fabrication Technology

III. RF/Microwave MEMS Devices & Circuits Applications

- **A. Capacitors, Inductors, Transmission Lines**
- **B. Switches**
- **C. Resonators**
- **D. Tuned Amplifiers**
- **E. Adaptive Matching Networks**
- **F. Filters**

IV. MEMS in RF/Microwave Systems

V. Nano-MEMS Trends

VI. Conclusions

Micro Electro Mechanical Systems: ORIGINS

Richard P. Feynman (*APS Meeting* 1959): *"There is plenty of room at the bottom"*

Special type of research: Search for *boundless* field

Examples:

(1) Attaining Low Temperatures

(2) Attaining High Pressures

(3) ???

Miniaturization: Engage in program to make everything *small* !

Micro Electro Mechanical Systems: ORIGINS

What limits miniaturization?

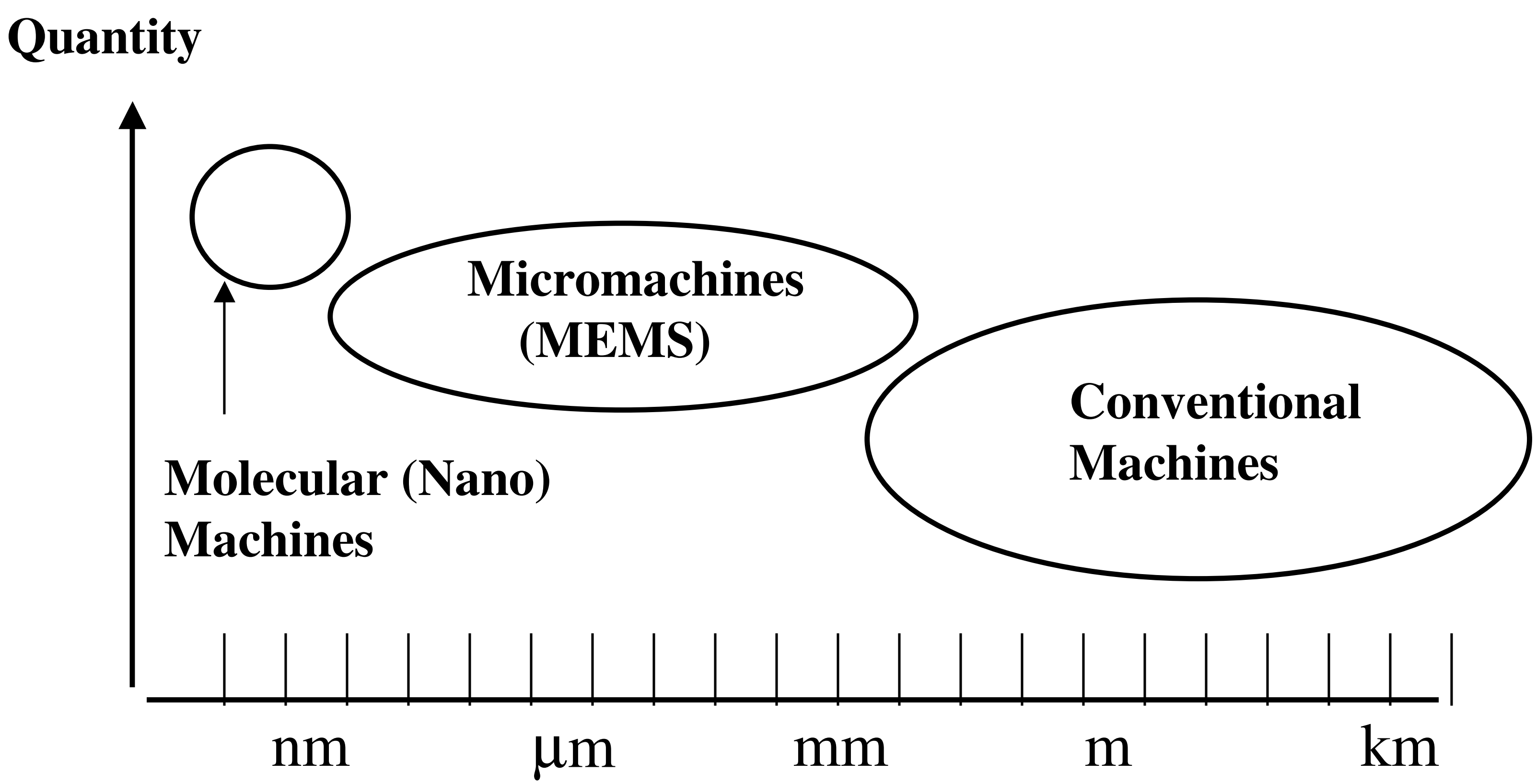
- **The laws of physics *don't* preclude (limit) miniaturization**
- **Limitations are imposed by technology (<u>ability to make small things</u>), not physics**
- **How would miniaturization impact:**

1) Information Storage

2) Computers

3) *Machinery-New design paradigms: machines would not simply scale down!*
different domain of material behavior!

What Do We Mean By Small?



Micro Electro Mechanical Systems: IMPETUS, MOTIVATION

- **Advent of Integrated Circuit technology in the 60's**

Circuits/Wafer → Profits

<u>Integration Level</u>

60's	90's
<10 devices per circuit	**>10^7 devices per circuit**

Micro Electro Mechanical Systems: IMPETUS, MOTIVATION

QUESTION : Would the application of IC fabrication concepts to:

MECHANICS, OPTICS, and FLUIDICS

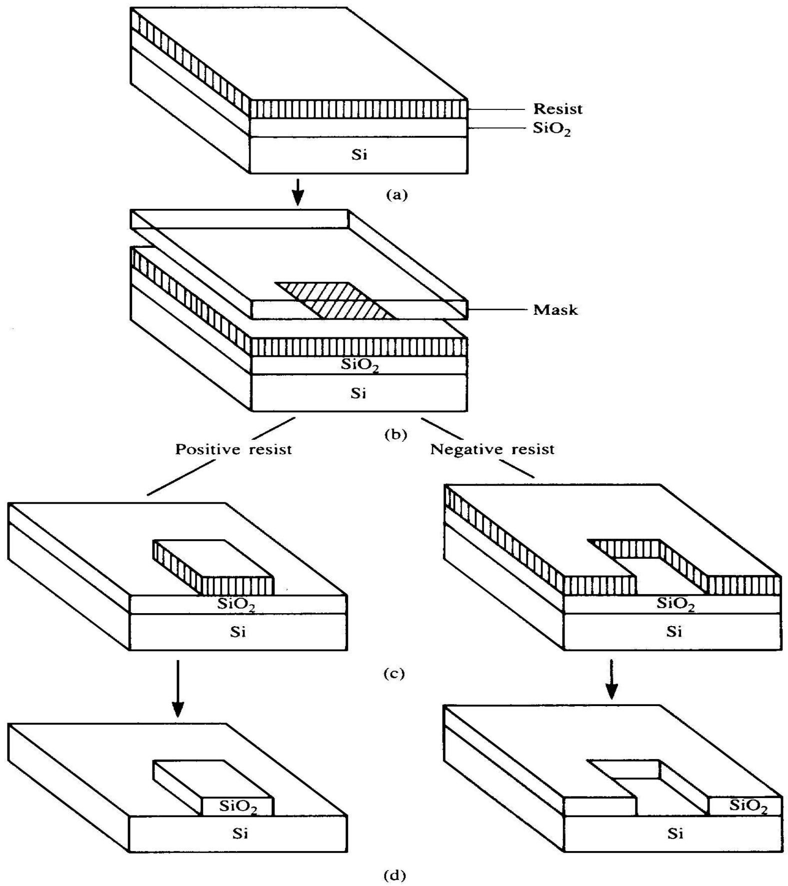
result in enhanced performance @ lower cost???

ANSWER : Maybe !

- **An IC extends in 2-D ! !**
- **A mechanical microstructure is 3-D ! ! !**

MEMS Fabrication Technology
(How to make small 3-D structures?)

Conventional IC Fabrication Process



Source: *Introduction to Microelectronics Fabrication*, Volume V, Modular Series on Solid State Devices, by R.C Jaeger, edited by G.W. Neudeck and R.F. Pierret. © 1988 by Addison-Wesley Publishing Company. Reprinted by permission.

MEMS Fabrication Technology Elements

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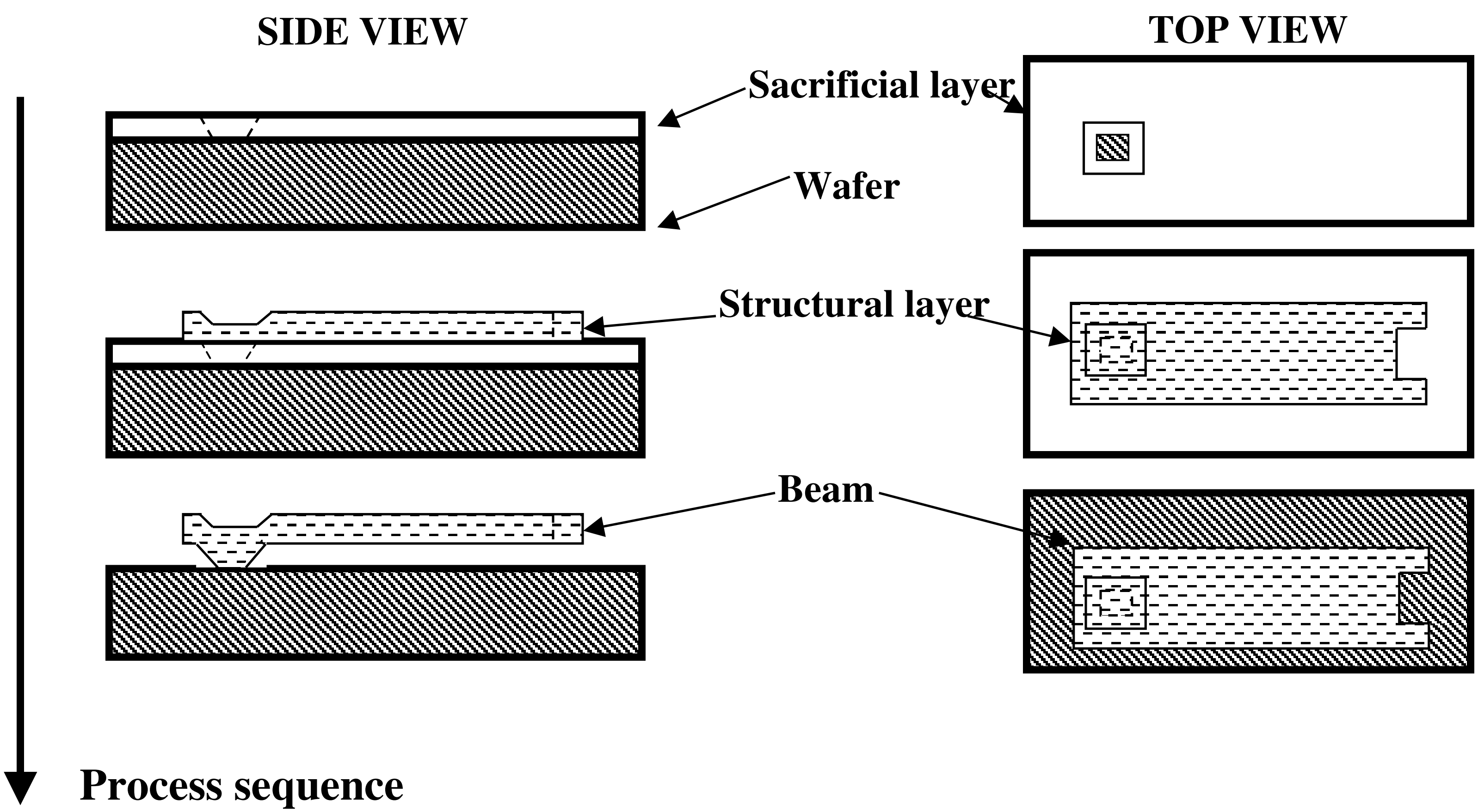
Surface Micromachining

Add thin film layers to wafer, then *remove* some layers



MEMS Fabrication Technology Elements

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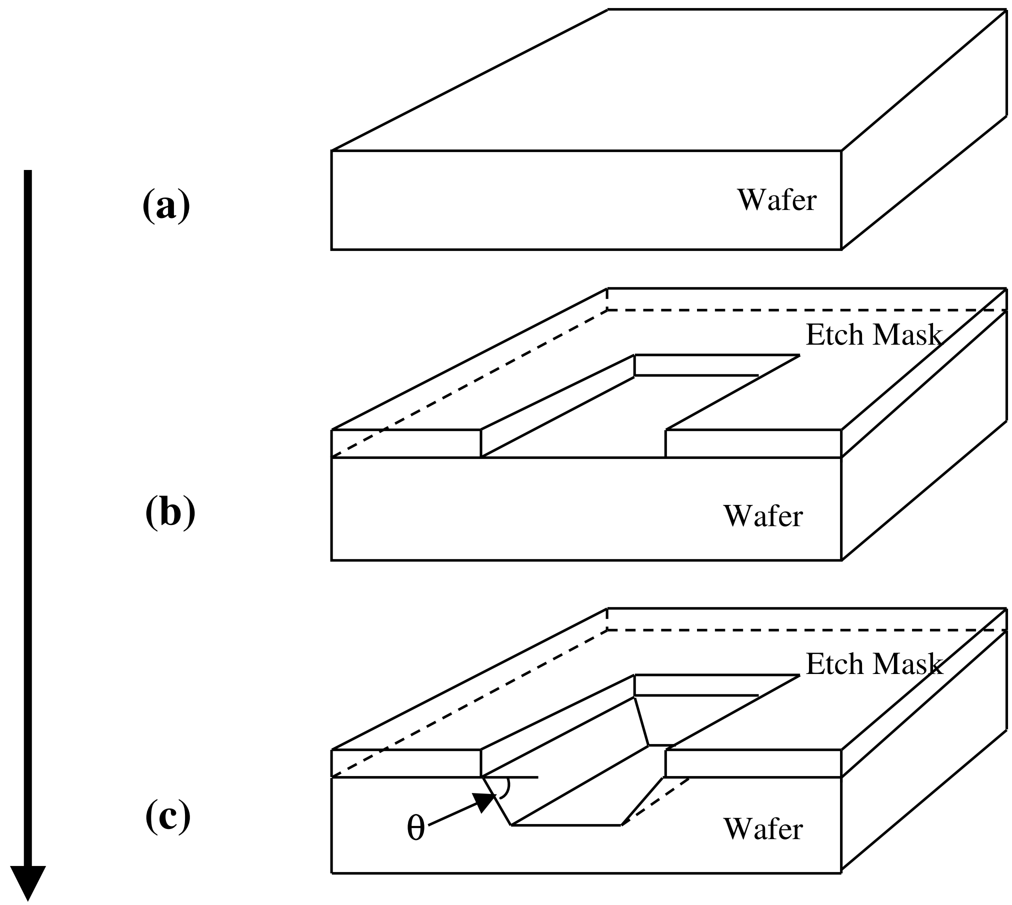
Bulk Micromachining

Sculpt wafer by anisotropic etching



Foundries

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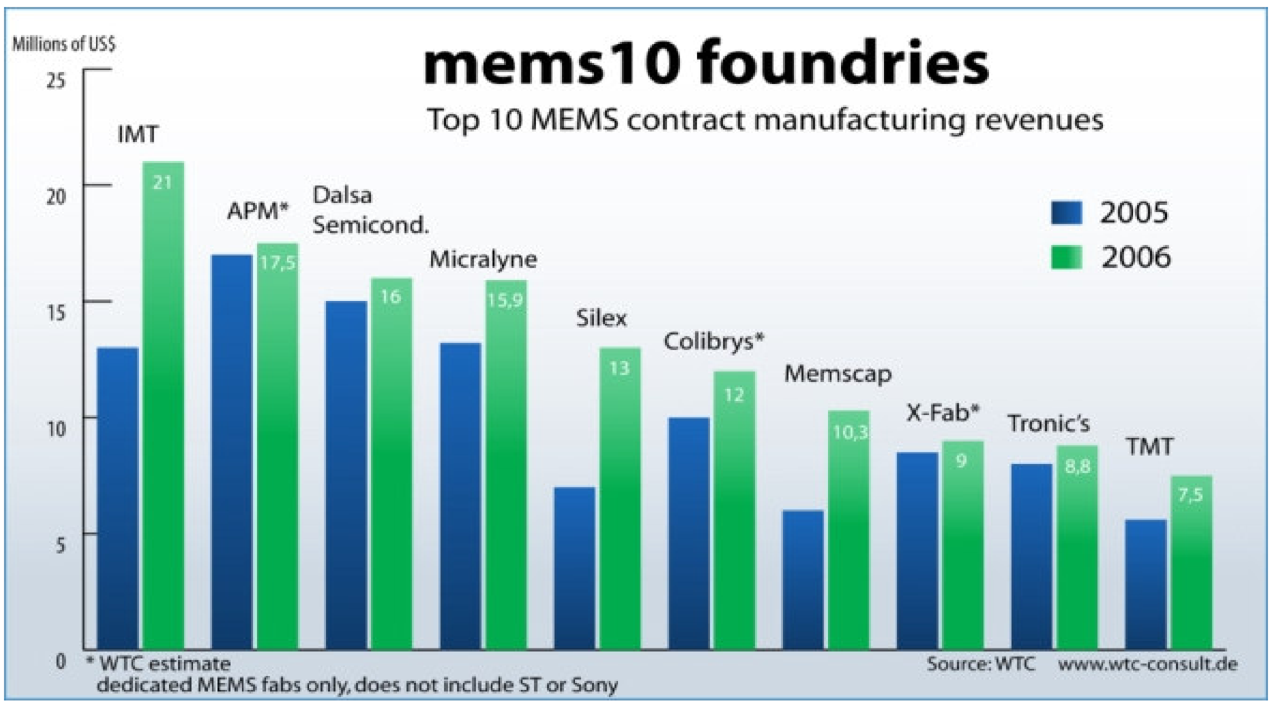
- Many established MEMS companies own fab, most startups fabless
- Over 80 foundries worldwide, front end (process) vs back end (packaging, test), development vs product capable, CMOS capability, wafer size 4-6-8in
- Many newly established IC foundries looking to exercise their capabilities, more are willing to develop MEMS now
- Use existing process, improve existing process, or develop a new process



Micro Electro Mechanical Systems: EXAMPLES

MATURE

- **Accelerometers (used in automobile air bags)**
- **Pressure Sensors**

EMERGING

- **Gyroscopes**
- **Flow Sensors**
- **Micromotors**
- **Switches**
- **Resonators**

Why is it expected that MEMS will revolutionize RF applications?

1) Availability of both electronic (2-D) and mechanical (3-D) fabrication techniques enables novel highly functional systems (SoC)

2) Potential for new levels of performance not achievable otherwise

- -Inherently smaller size and weight systems
- -Lower power consumption
- -Economies of scale (lower cost)

RF/Microwave MEMS-Enhanced Passive Components

(Capacitors, Inductors, Transmission Lines)

MEMS-Based Devices

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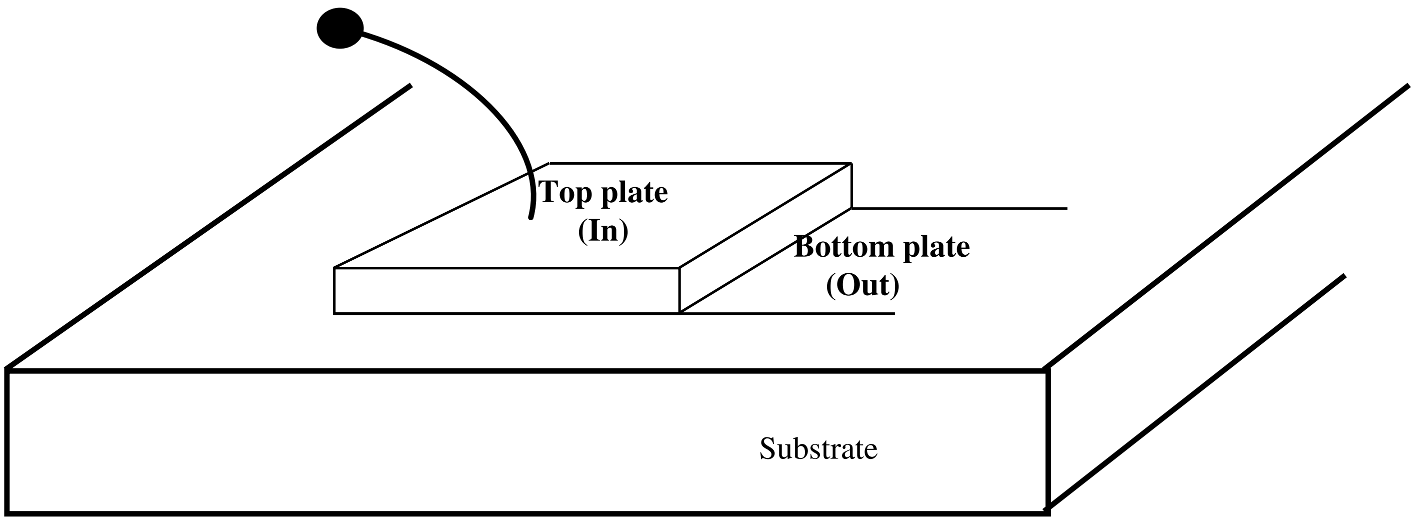
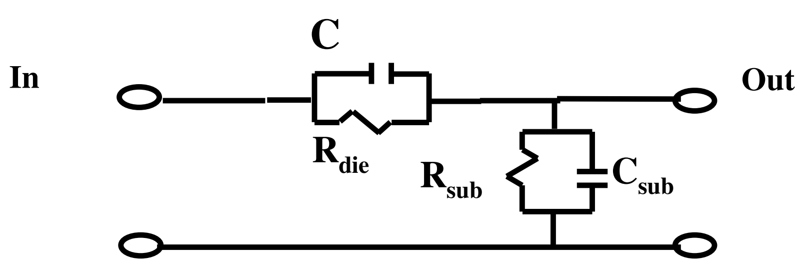
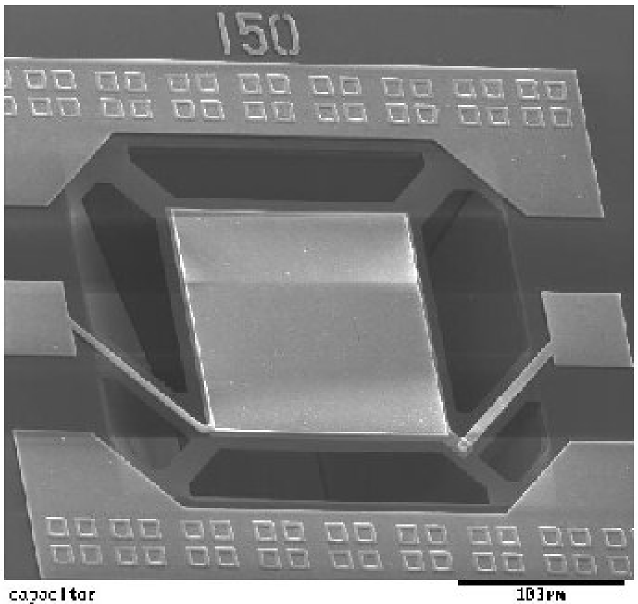
Parallel-Plate Capacitor



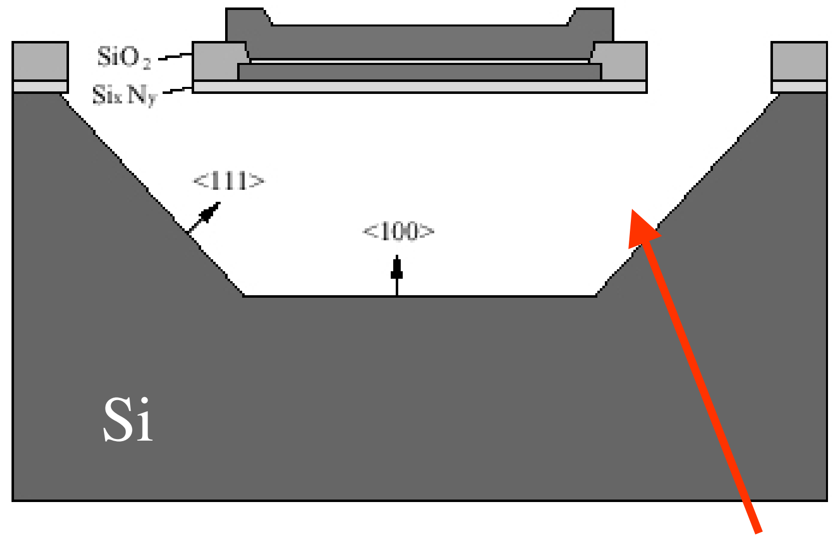


Bulk-Micromachined *MIM* Capacitor

Top View



Cross Section



Top-side KOH etching

Q=100@2GHz (Q<10 when directly fabricated on Si)
C=2.6pF
$f_{self\text{-}resonance}$ =15.8 GHz

Y. Sun, H. van Zeijl, J.L. Tauritz and R.G.F. Baets, "Suspended Membrane Inductors and Capacitors for Application in Silicon MMIC's," Microwave and Millimeter-wave Monolithic Circuits Symposium Digest of Papers, IEEE, 1996, pp. 99-102.

MEMS-Based Devices

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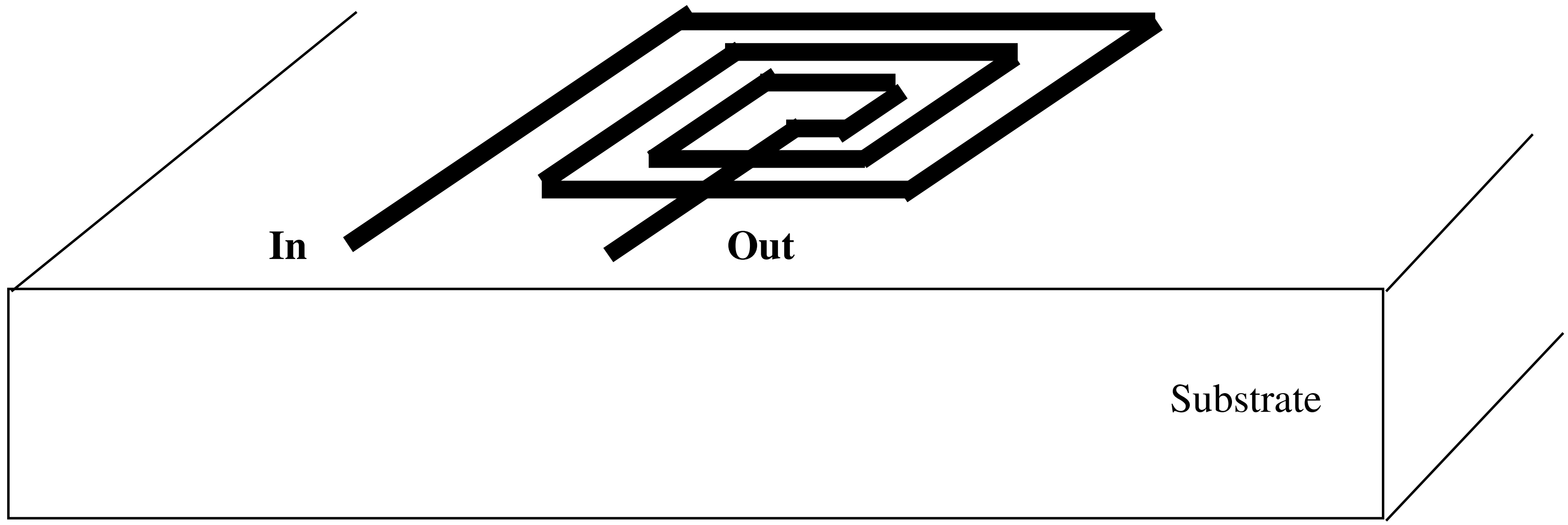
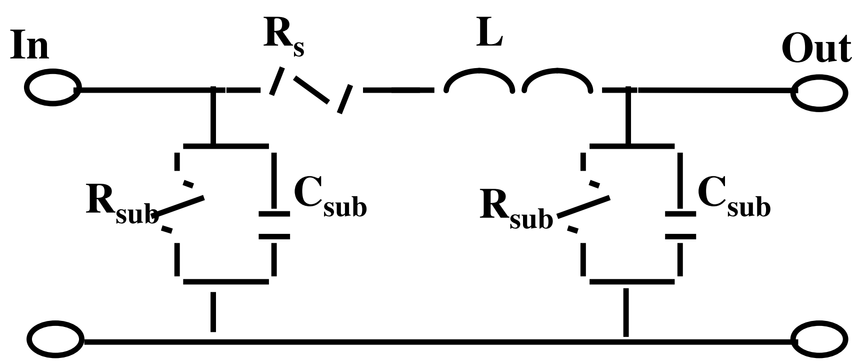
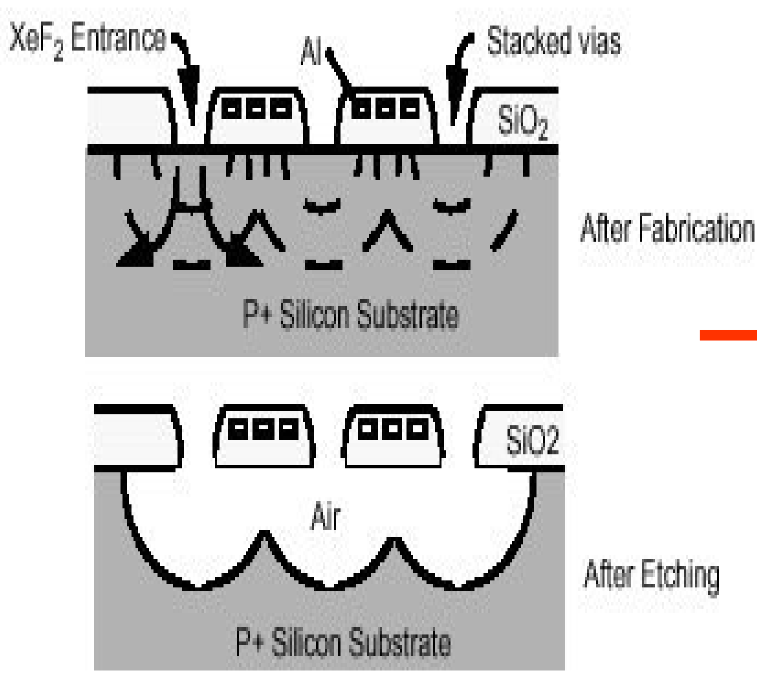
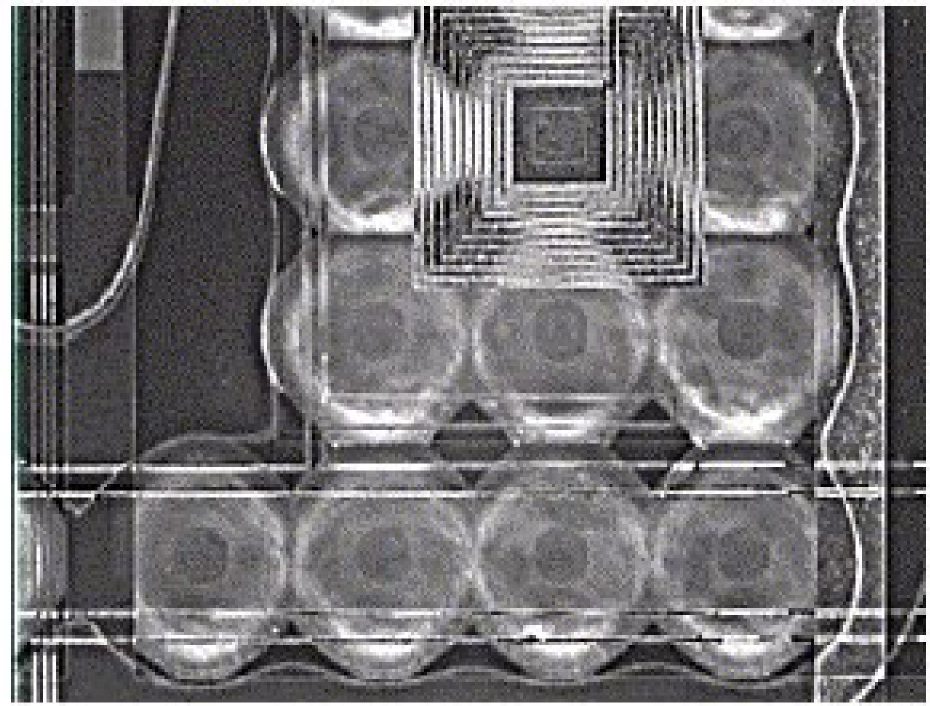
Monolithic Inductor





Bulk-Micromachined RF Inductors



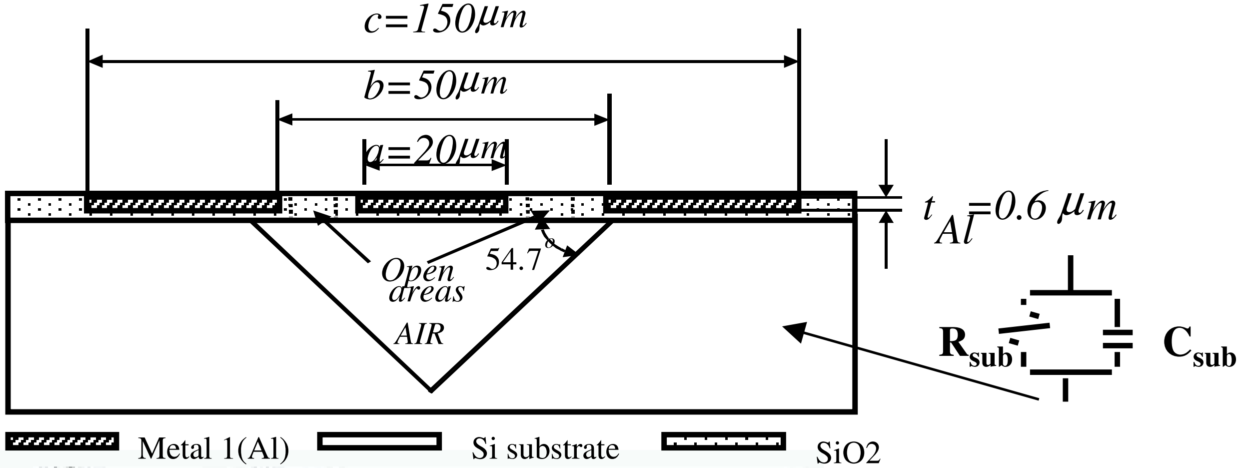


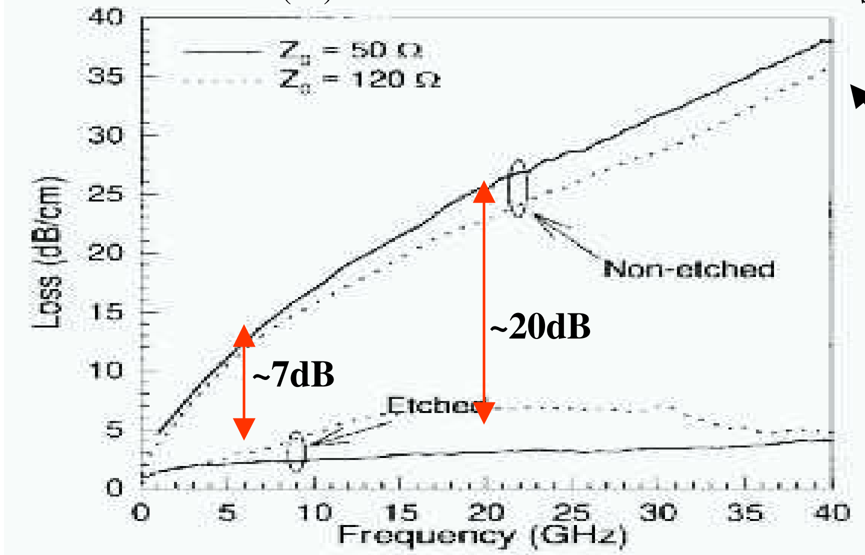
Q=22@ 270 MHz
L=115nH

J. Rael, et al, "Design methodology used in a single-chip CMOS 900 MHz spread-spectrum wireless transceiver," *Proc. Design Automation Conference*, pp. 44 -49, 1998.

MEMS-Based Devices

Bulk-Micromachined RF Transmission Lines





Bulk micromachining Reduces Substrate Loss Drastically!

Source: Figs. 5.23 & 5.25 *Introduction to Microelectromechanical (MEM) Microwave Systems*, Norwood, MA: Artech House (1999)

MEMS-Based Circuits

CMOS RF Amplifier with Air-Suspended Inductor

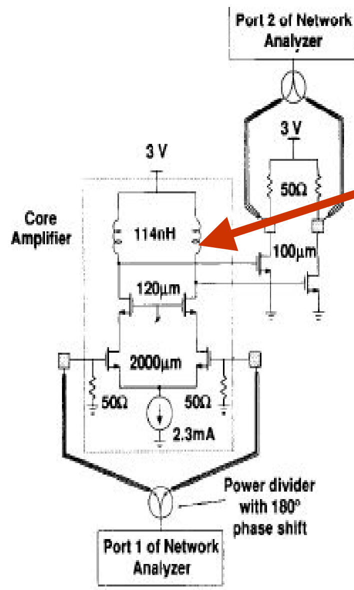


Fig. 3. Schematic of CMOS RF amplifier, including test arrangement. All FET's are 2-µm channel length. Bond pads define the chip periphery.

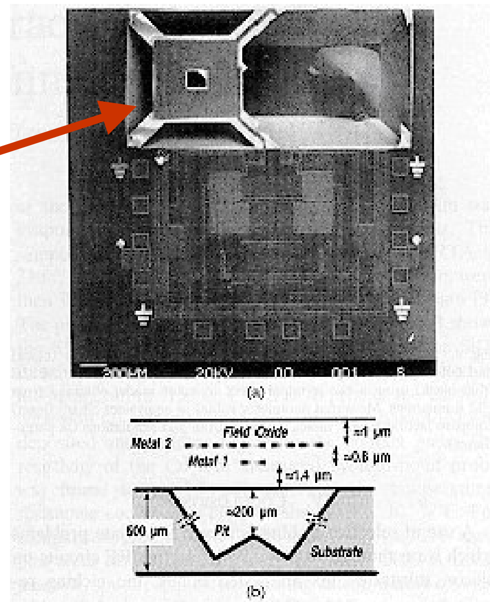


Fig. 2. (a) SEM of RF amplifier after selective substrate etch. Inductor shown is suspended on oxide layer attached to substrate at four corners. Spiral fabricated as second-level aluminum, while contact from center brought out on first level. Second inductor has been manually removed to show pit. (b) Cross section of suspended inductor and substrate after etching.

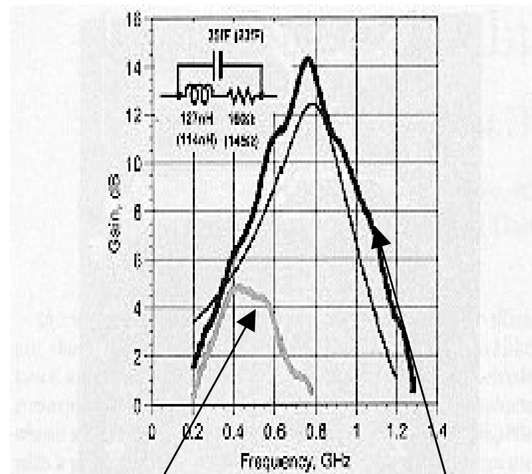


Fig. 4. Measured frequency response of core amplifier, after (black) and before (gray) substrate removal. Simulated response from SPICE (thin black) using a two-terminal *LCR* inductor model obtained from EM simulations. Measured parameter values in equivalent circuit (inset) compare favorably with values obtained from 3-D simulations (in parentheses).

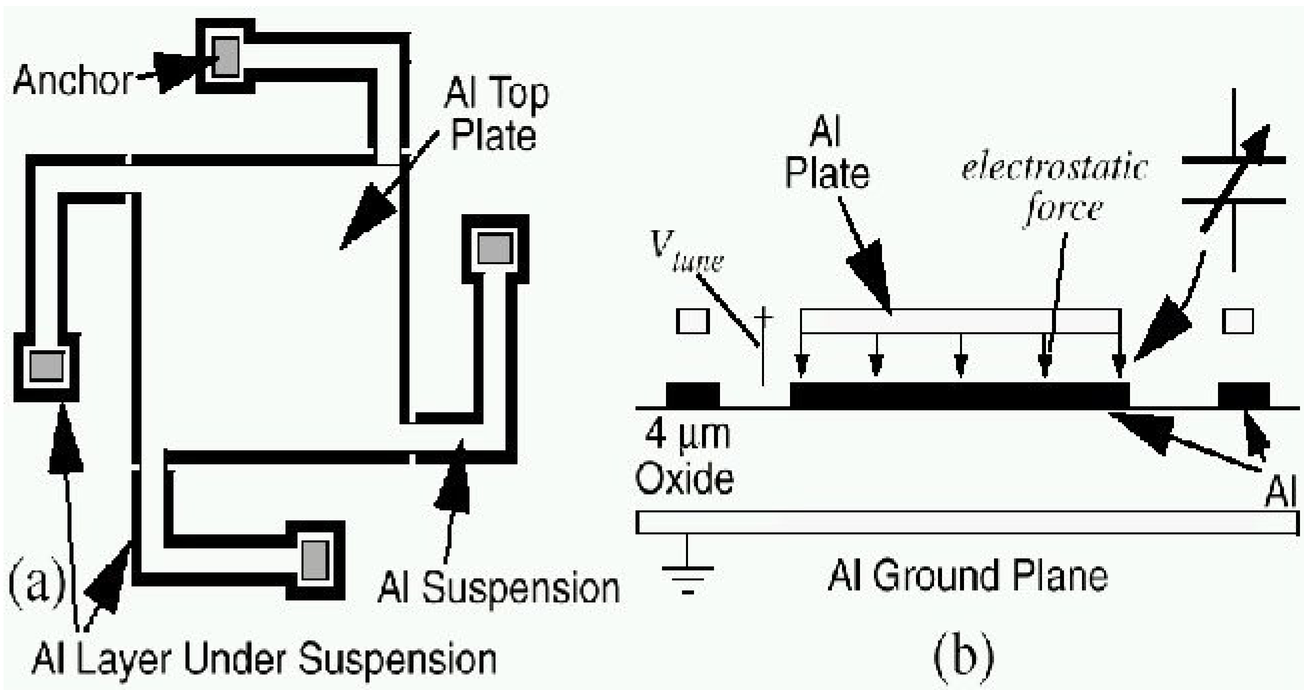
Before substrate removal

After substrate removal

J.Y.-C. Chang, A.A. Abidi, and M. Gaitan, "Large Suspended Inductors on Silicon and Their Use in a 2um CMOS RF Amplifier," *IEEE Electron Device Letters*, Vol. 14, 1993, pp.246-248.

MEMS-Based Devices

MEM Variable Capacitor (Varactor)

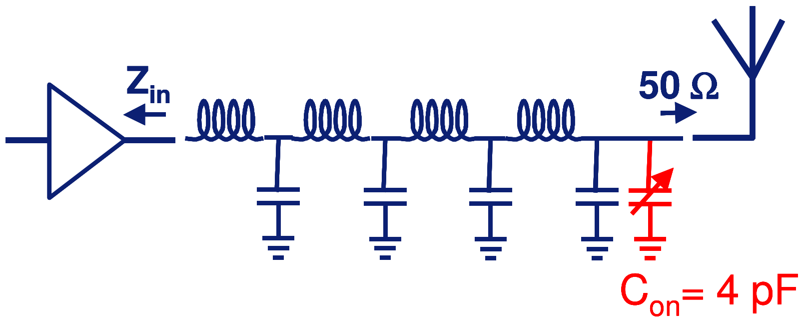


(a) Overhead and (b) cross-sectional schematics of a voltage-tunable µmechanical capacitor

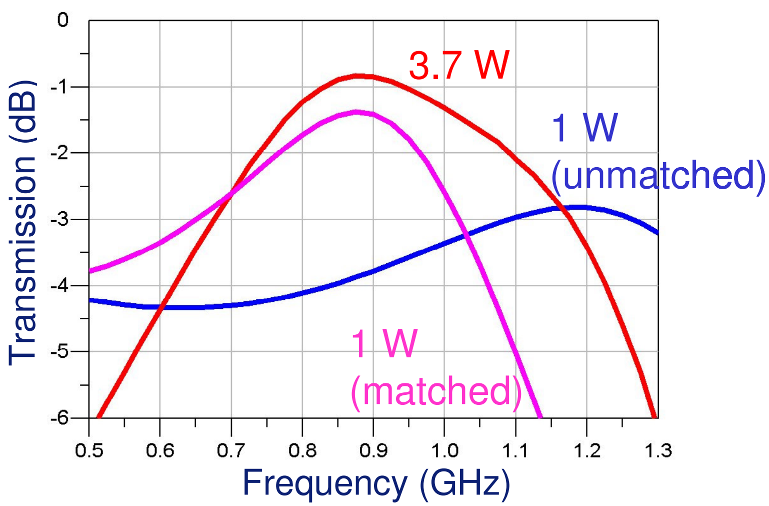
D.J. Young and B.E. Boser, "A micromachined variable capacitor for monolithic low-noise VCOs, Hilton Head '96, pp. 86-89.

RF MEMS-Based adaptive 900MHz PA

Output impedance matching network accommodates for variations in the optimal transistor load impedance, which is a function of transmitted PA power



Z_{in}= 4+3j Ω @ P=1.0W
Z_{in}= 2 Ω @ P=3.7W



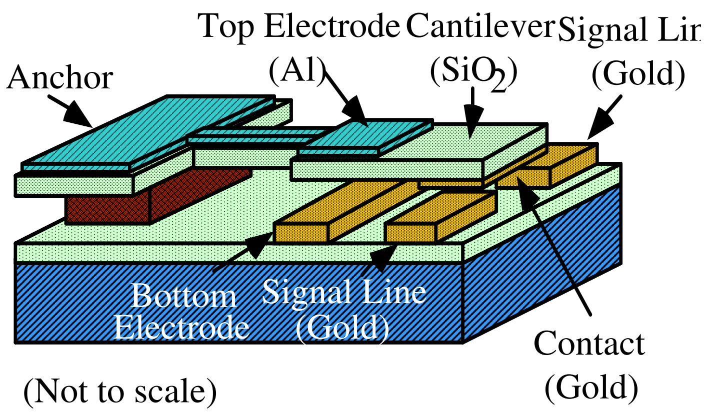
Th.G.S.M. Rijks, J.T.M. van Beek, M.J.E. Ulenaers, J. De Coster, R. Puers, A. den Dekker, and L. Van Teeffelen, "Passive Integration and RF MEMS: a toolkit for adaptive LC circuits", *Digest ESSCIRC* 2003, Estoril, Portugal, Sept. 16-18 2003, 269.

RF/Microwave MEM Switches & Applications

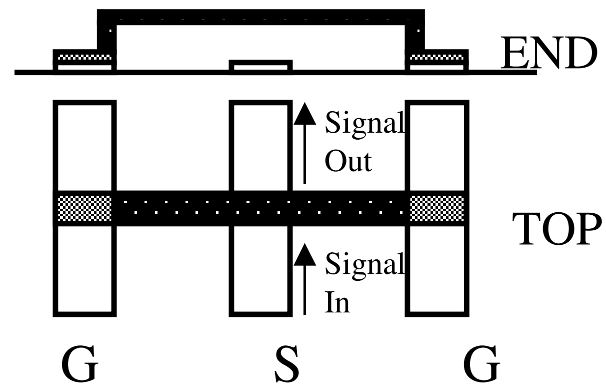
MEMS-Based Devices

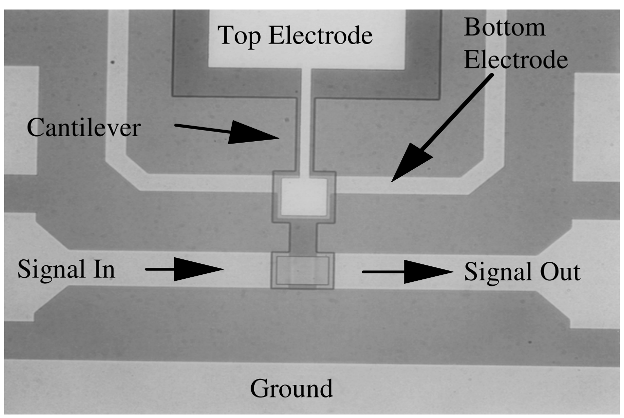
Fundamentals of RF/Microwave MEM Switches

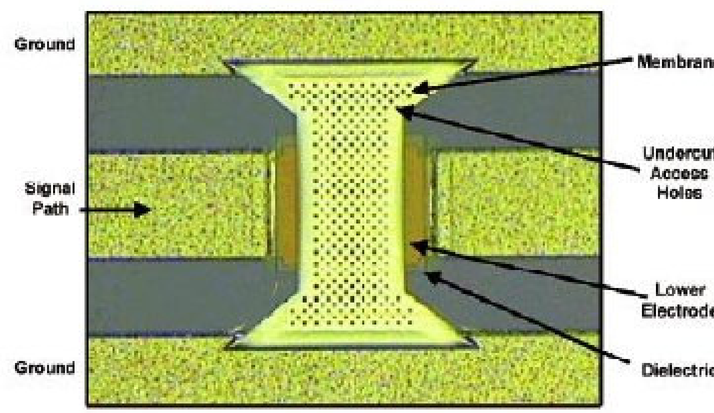
Series



Shunt







Sources: Figure 5.7 *Introduction to Microelectromechanical (MEM) Microwave Systems*, Norwood, MA: Artech House (1999)

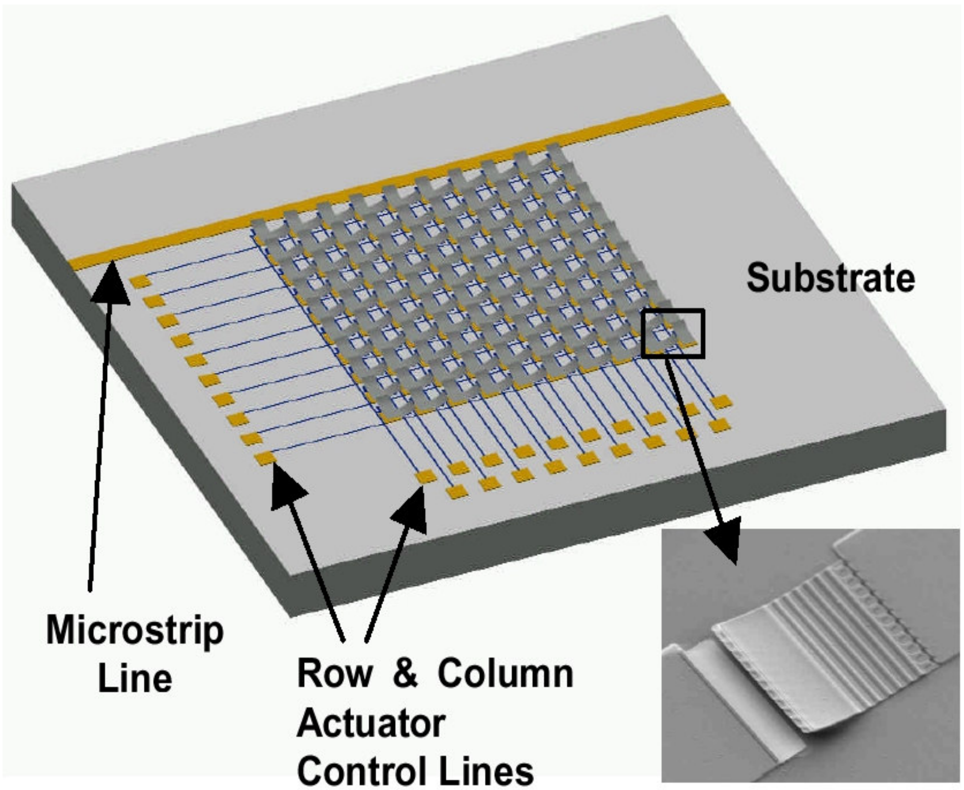
J. Jason Yao, TOPICAL REVIEW: "RF MEMS from a device perspective," *J. Micromech. Microeng*. 10 (2000) R9–R38.

Typical Published MEM Switch Performance

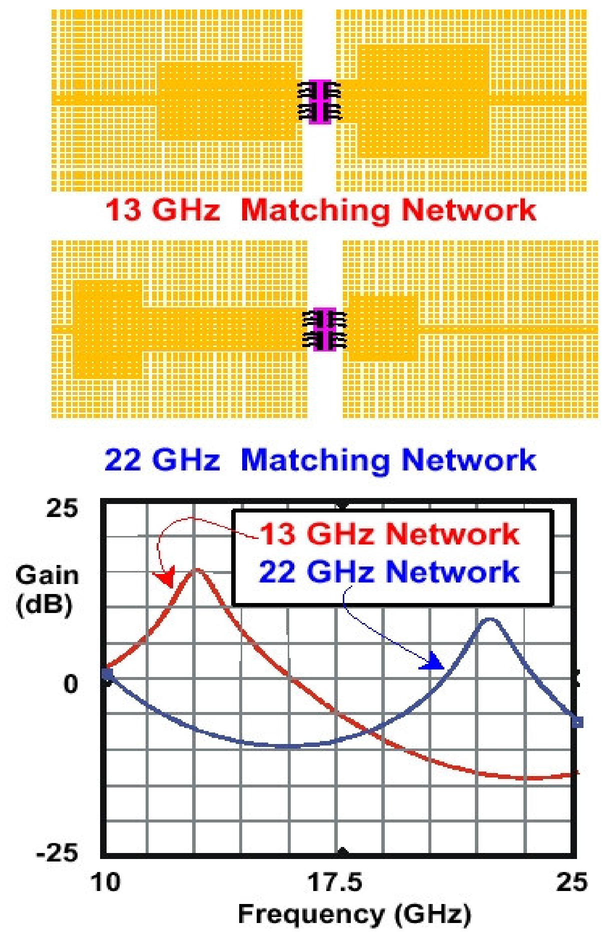
- Frequency: DC - 60 GHz
- Transmission:
    - Shunt Switch: I.L.: 0.1 dB @10 GHz, ISOL: -25 dB@ 20 GHz
    - Series Switch: I.L: 0.1 dB @4 GHz, ISOL:-50 dB @ 4 GHz
- Actuation Voltage: 20 - 60 V
- IP3: +66 dBm@ 2 GHz
- Switching Time: 4 - 20 μs

H.J. De Los Santos, *et al,* "MEMS-Based RF Switches for Nanosatellite Communications Systems," *2nd Int. Conf. MNT99,* April 11-15, Pasadena, CA, 1999, pp. 86-91.

Reconfigurable Distributed RF/Microwave Components



Frequency reconfigurable power amp



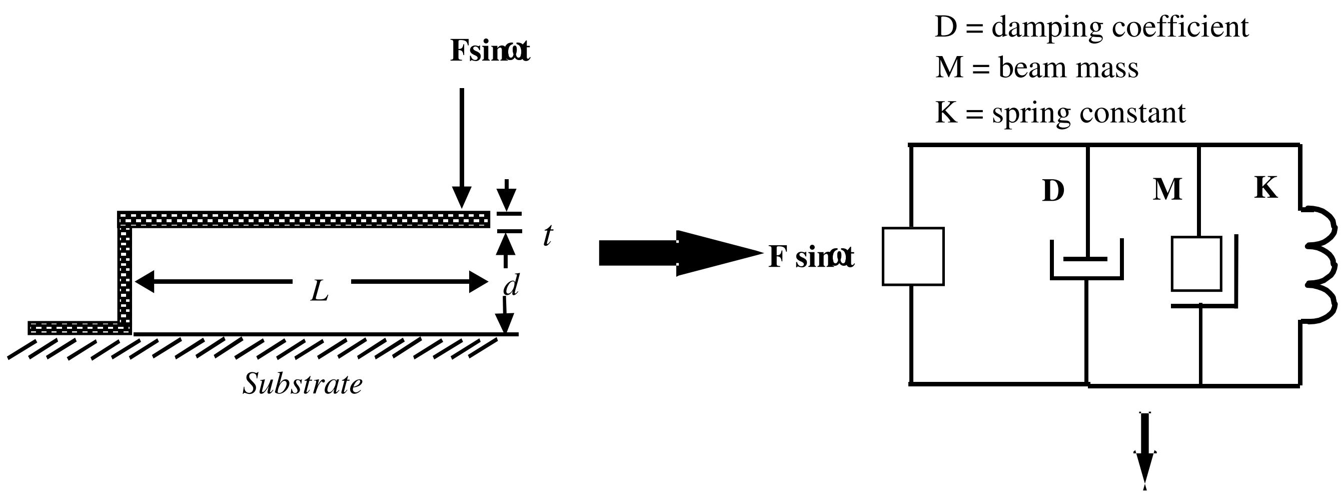
Key Features

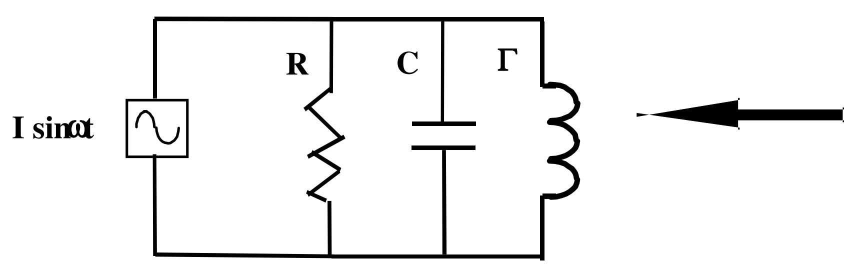
- **Microswitch arrayed in 2D**
- **Switches individually addressable**

C. Bozler, et al., "MEMS Microswitch Arrays for Reconfigurable Distributed Microwave Components," 2000 *IEEE IMS*, Baltimore, MD.

RF/Microwave MEM Resonators & Applications

Vibrating Cantilever Beam



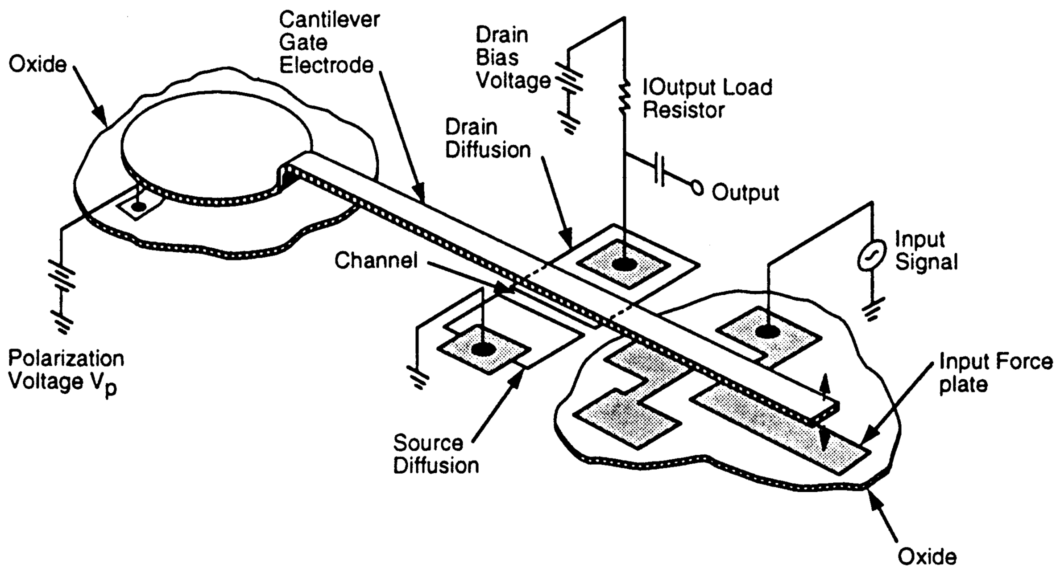


$$f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

Source: Figure 2.7 *Introduction to Microelectromechanical (MEM) Microwave Systems*, Norwood, MA: Artech House (1999)

MEMS-Based Devices

The Cantilever Beam MEM Resonator: Resonant Gate Transistor



Abandoned due to:
- Low Qs
- High TC at f_R, aging of metal films
- $F \sim 1/x^2$ --> nonlinear drive severely constraints input signal dynamic range

Source: Nathanson, *et al.,* "The Resonant Gate Transistor," *IEEE Trans. Electron Devices Vol. 14, No. 3, 1967*

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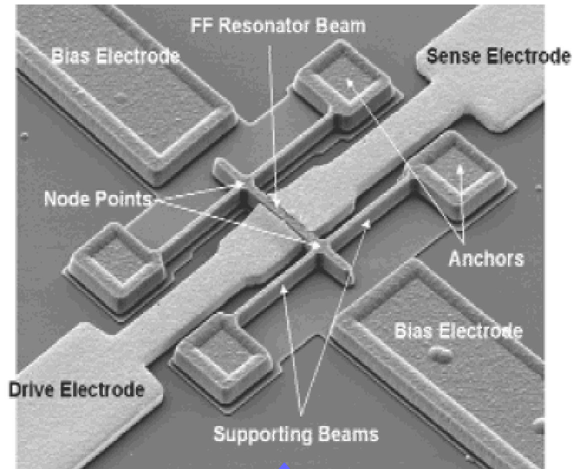
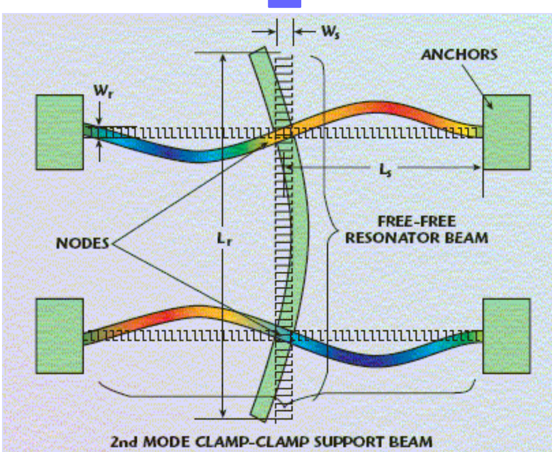
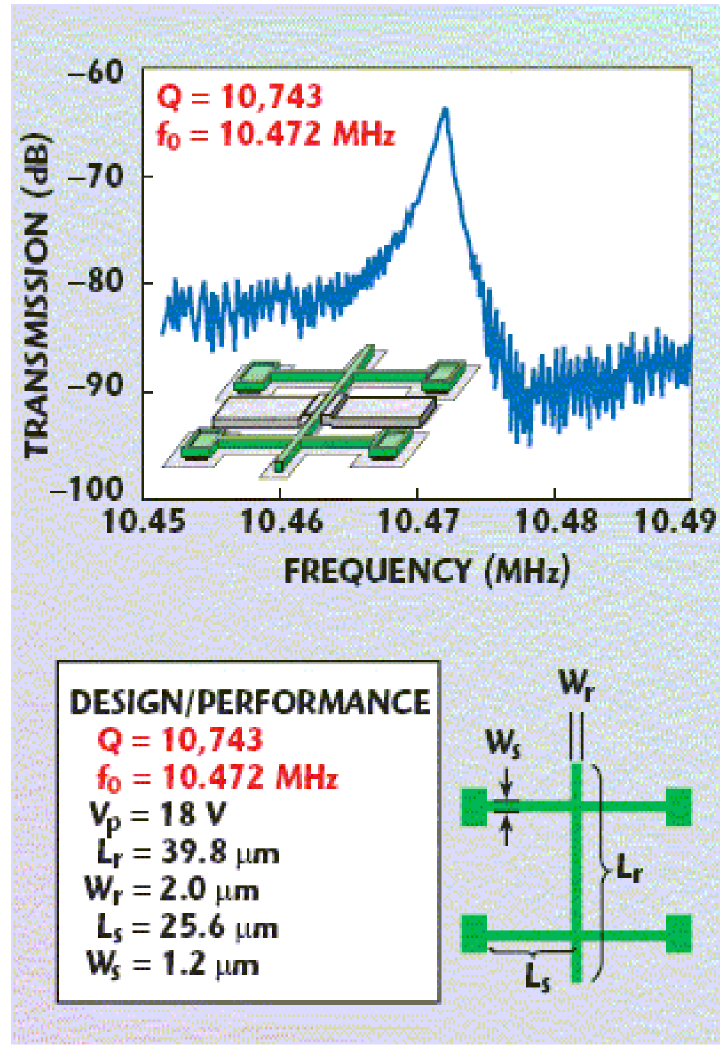
Free-free MEM resonator



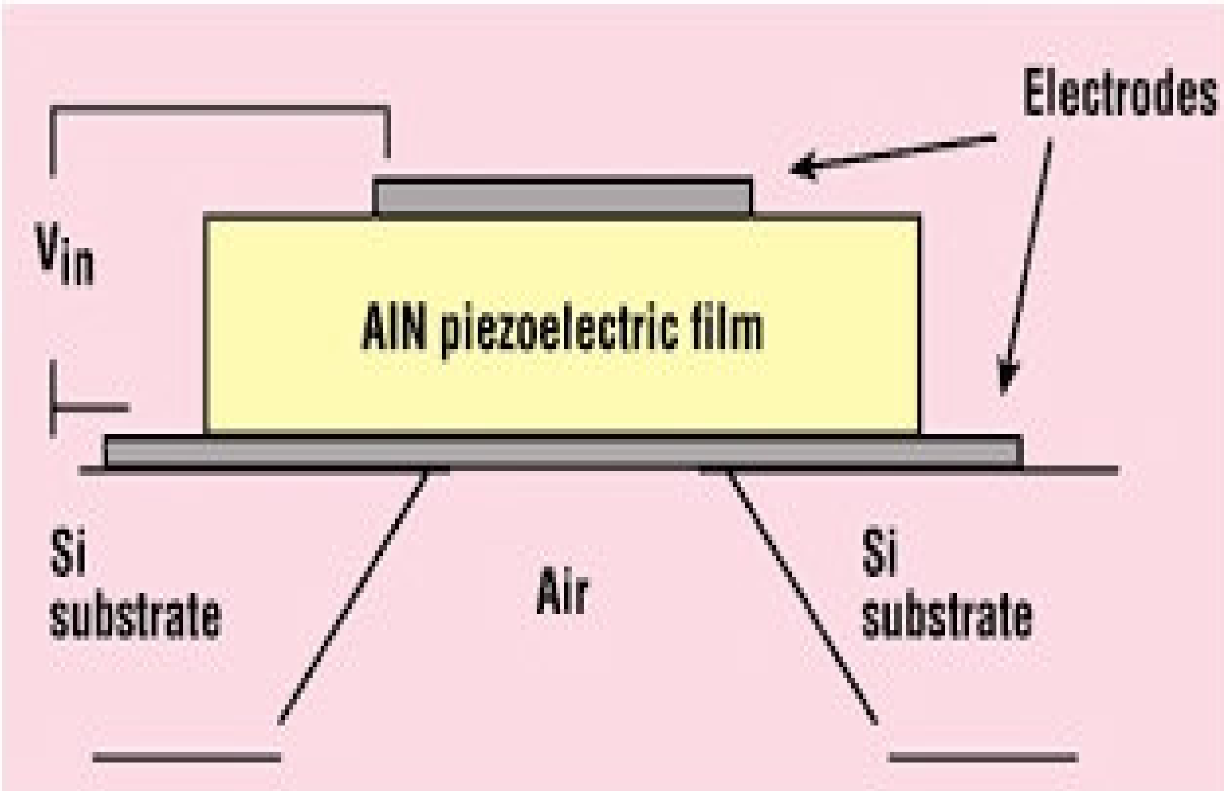




Hsu, W.-T., W.S. Best, H. J. De Los Santos, "Design and Fabrication Procedure for High Q RF MEMS Resonators," *Microwave J.*, February, 2004.

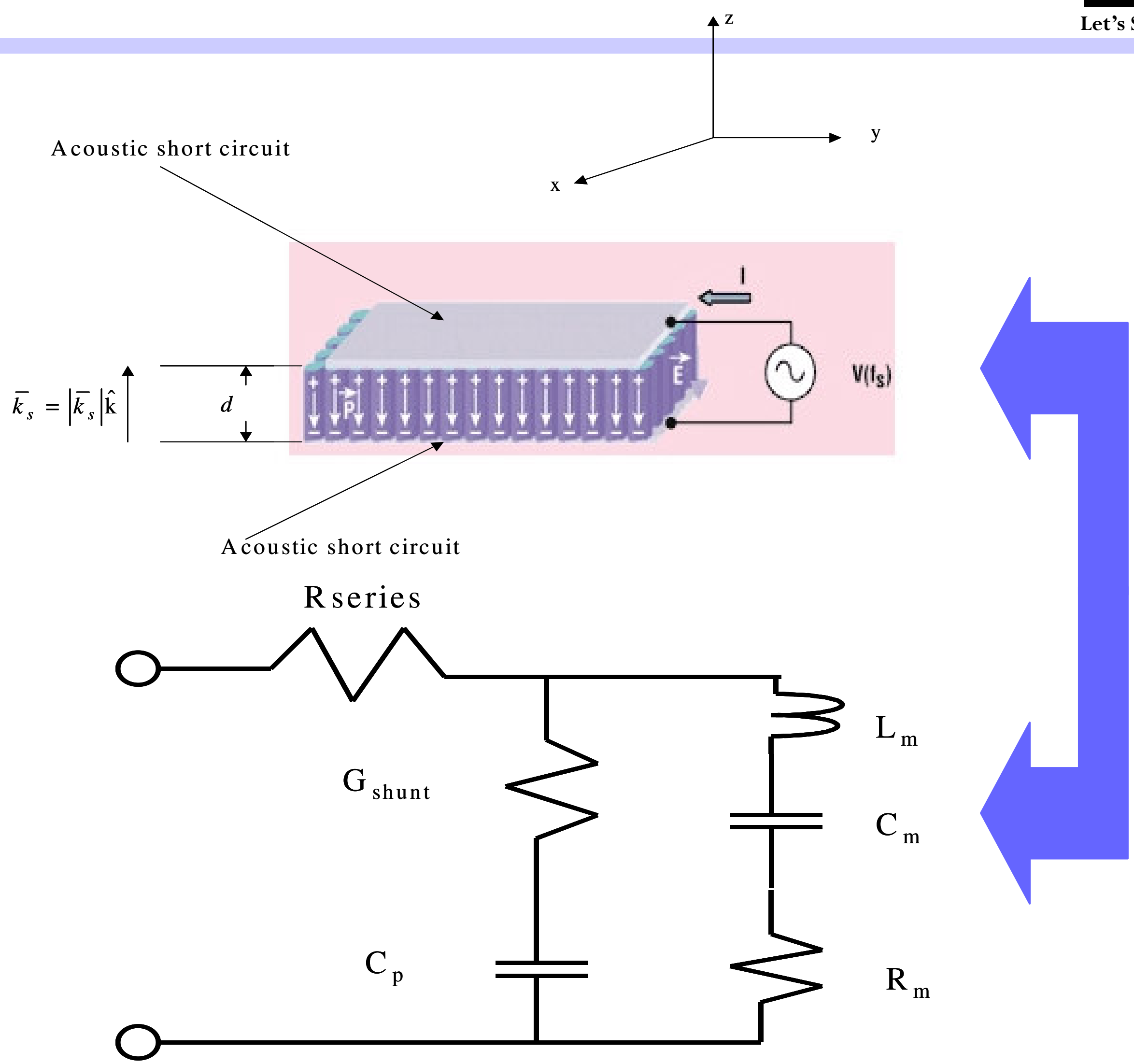
Film Bulk Acoustic Wave Resonator (FBAR)

Agilent's FBAR Structure



McNamara, "FBAR Technology Shrinks CDMA Handset Duplexers," *Microwaves & RF, September 2000*, pp. 135-138

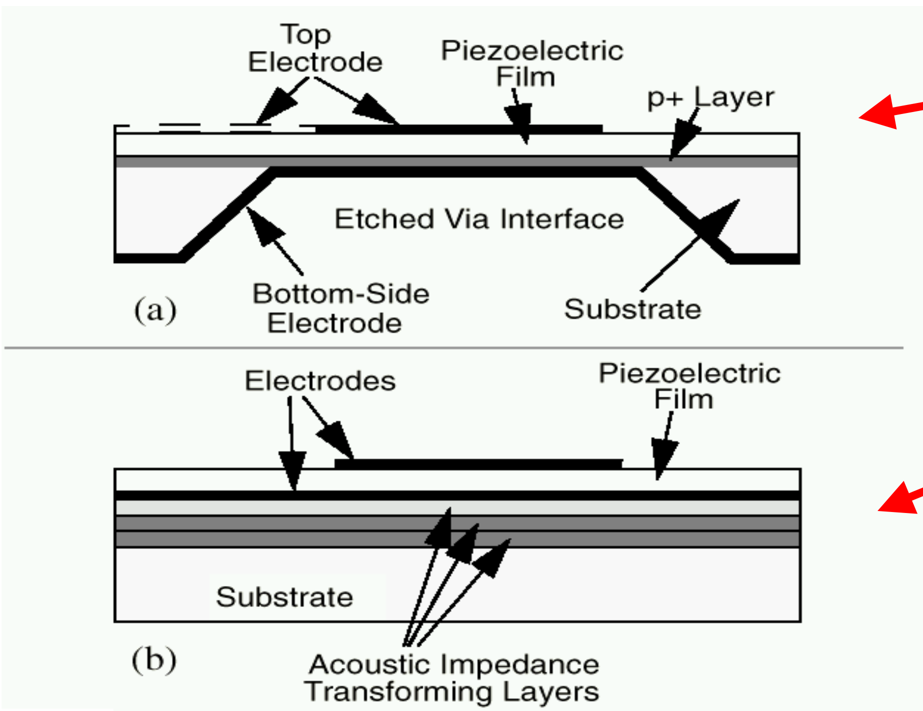
Physical Acoustic Resonant Cavity-Description & Its Circuit Model



McNamara, "FBAR Technology Shrinks CDMA Handset Duplexers," *Microwaves & RF, September 2000*, pp. 135-138

MEMS-Based Devices

High-Frequency SAW Resonators



Cross-sections of two thin-film bulk-acoustic resonators. (a) A membrane supported FBAR resonator (b) A solidly mounted resonator (SMR)

$Q's \geq 1000$

$1.5 \quad GHz < f_0 < 7.5 \quad GHz$

$0.5 \quad GHz < f_0 < 2.5 \quad GHz$

[1] S.V. Krishnaswamy, et al., "Compact FBAR filters offer low-loss performance," *Microwaves & RF*, Sept. 1991, pp. 127-136.
[2] K.M. Lakin, et al., "Development of miniature filters for wireless applications," *IEEE MTT-43*, No. 12, Dec. 1995, pp. 2933-2939.

FBAR Filters

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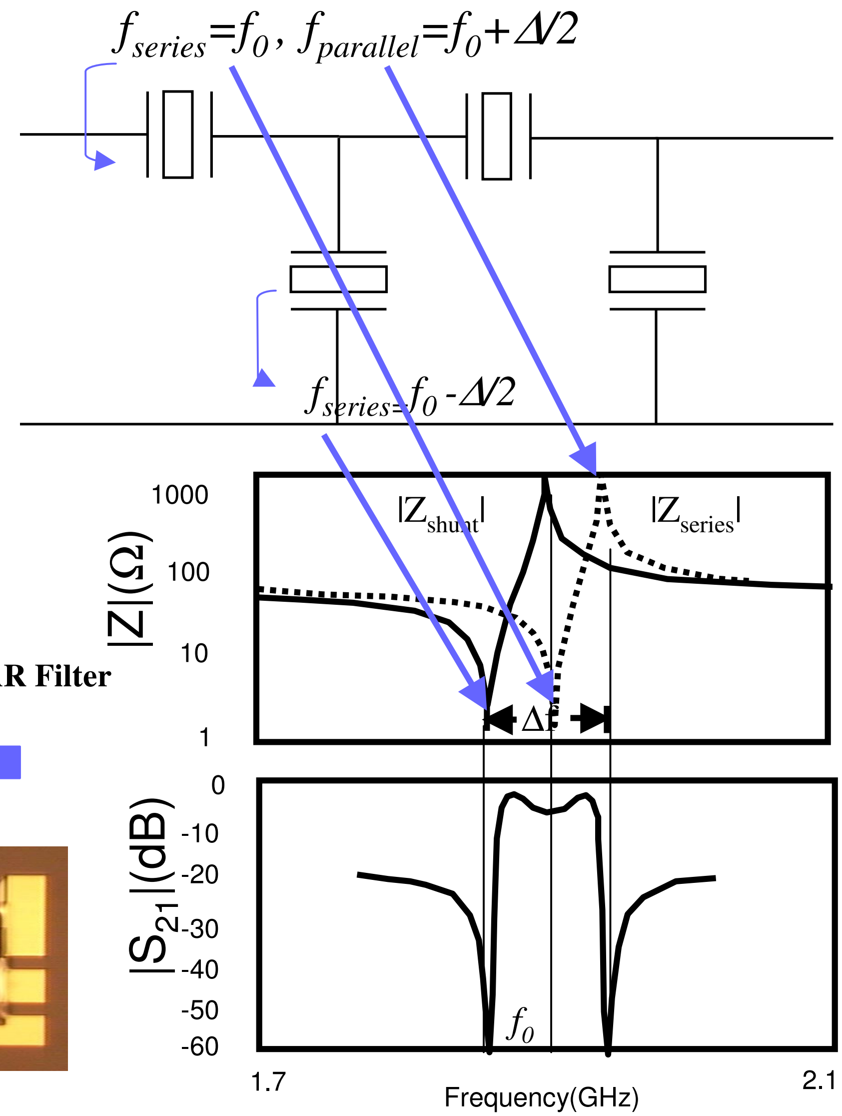
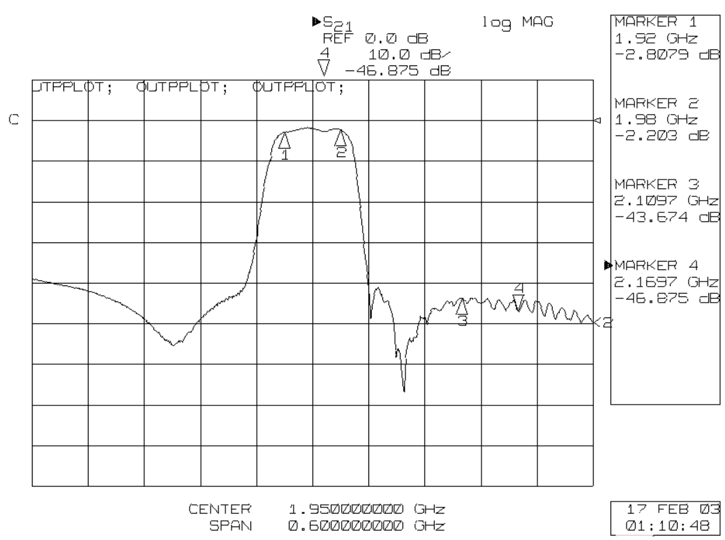
J.Y. Park, et al., Silicon Bulk Micromachined FBAR Filters for W-CDMA Applications, *33rd European Microwave Conference* - Munich 2003, pp. 907-910.

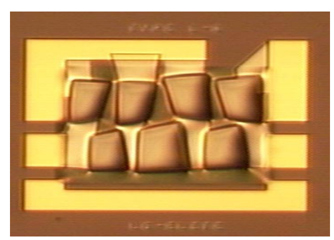
Motivation:
- **On-chip integration (RFIC)**
- **Power Handling**
- **Insertion Loss**
- **Small Size & Weight**

	FBAR	SAW
Passband:	**1.92-1.98 GHz**	
Insertion Loss:	**2.8dB**	**3.2dB**
Passband Ripple:	**0.5dB**	**1.2dB**





Seven-Resonator FBAR Filter
Size: 3 x 3mm



MEMS in RF/Microwave Systems

Potential MEMS Systems Applications of Greatest Impact

- Wireless Transceivers
- Routing/Switching Matrices
- Smart/Adaptive Antennas

RF Front-End for Cellular 3G Handset

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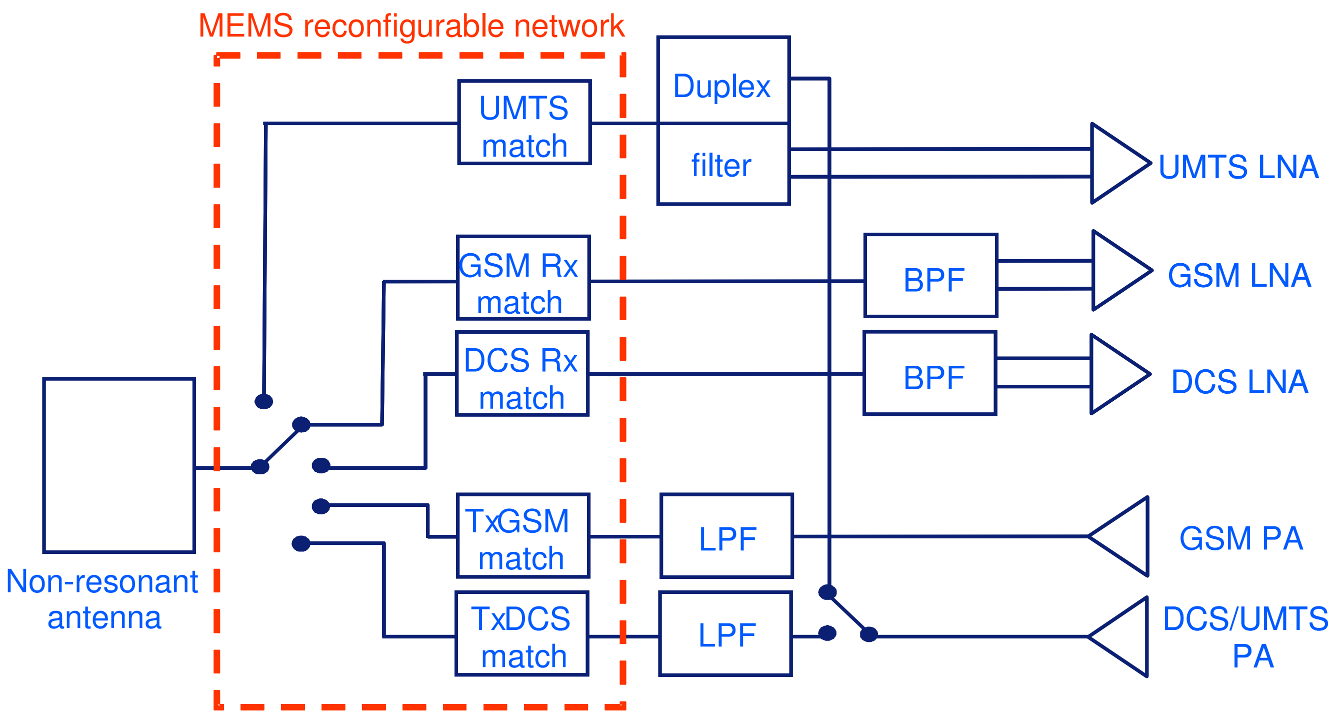

Th.G.S.M. Rijks, J.T.M. van Beek, M.J.E. Ulenaers, J. De Coster, R. Puers, A. den Dekker, and L. Van Teeffelen, "Passive Integration and RF MEMS: a toolkit for adaptive LC circuits", *Digest ESSCIRC* 2003, Estoril, Portugal, Sept. 16-18 2003, 269.

Adaptive Impedance Matching

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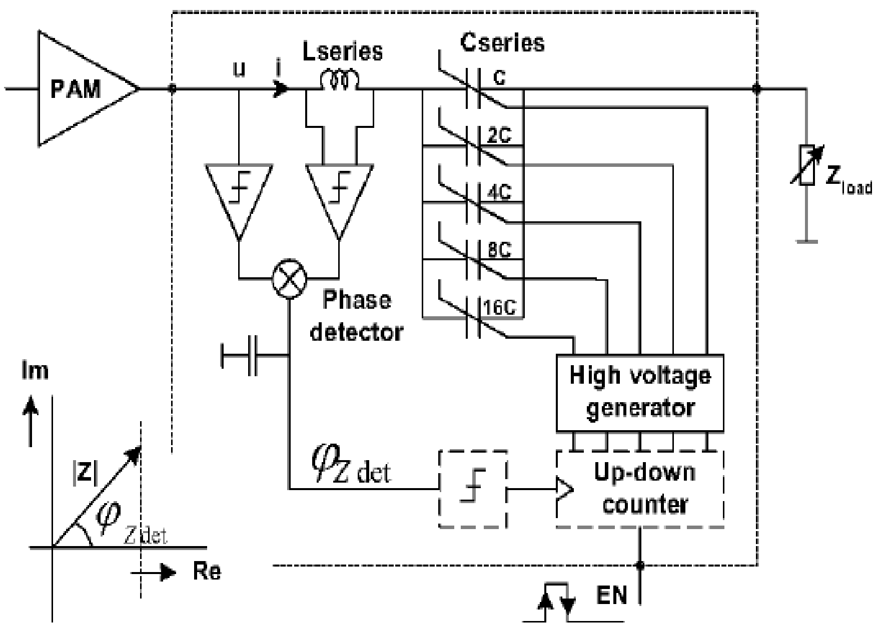
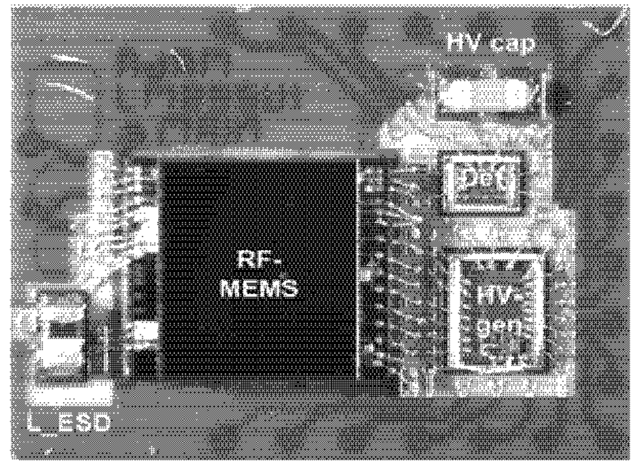
Compensating Antenna Detuning Due To Body-Proximity

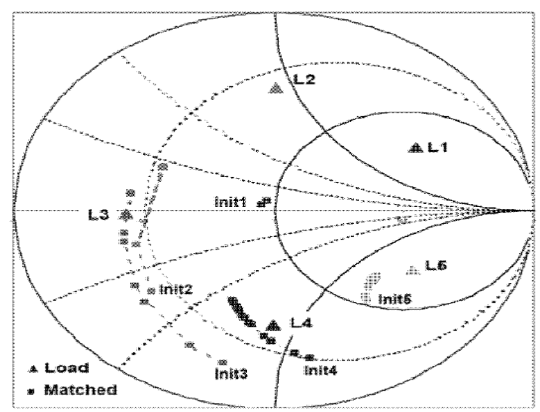
Block diagram of the adaptive series-LC matching module—It compensates the reactive part of the load impedance by controlling the detected phase (ϕ_{Z_DET}) of the matched impedance to zero.



Block diagram of the high-voltage generator providing a 60 V actuation and 30 V hold voltage. The bridge circuit allows for bipolar actuation of the RF-MEMS devices.



Impedance adaptation trajectories measured For loads with VSWR of 4. f = 900 MHz



Nano-MEMS Trends

Nano Micro Electro Mechanical Systems: ORIGINS

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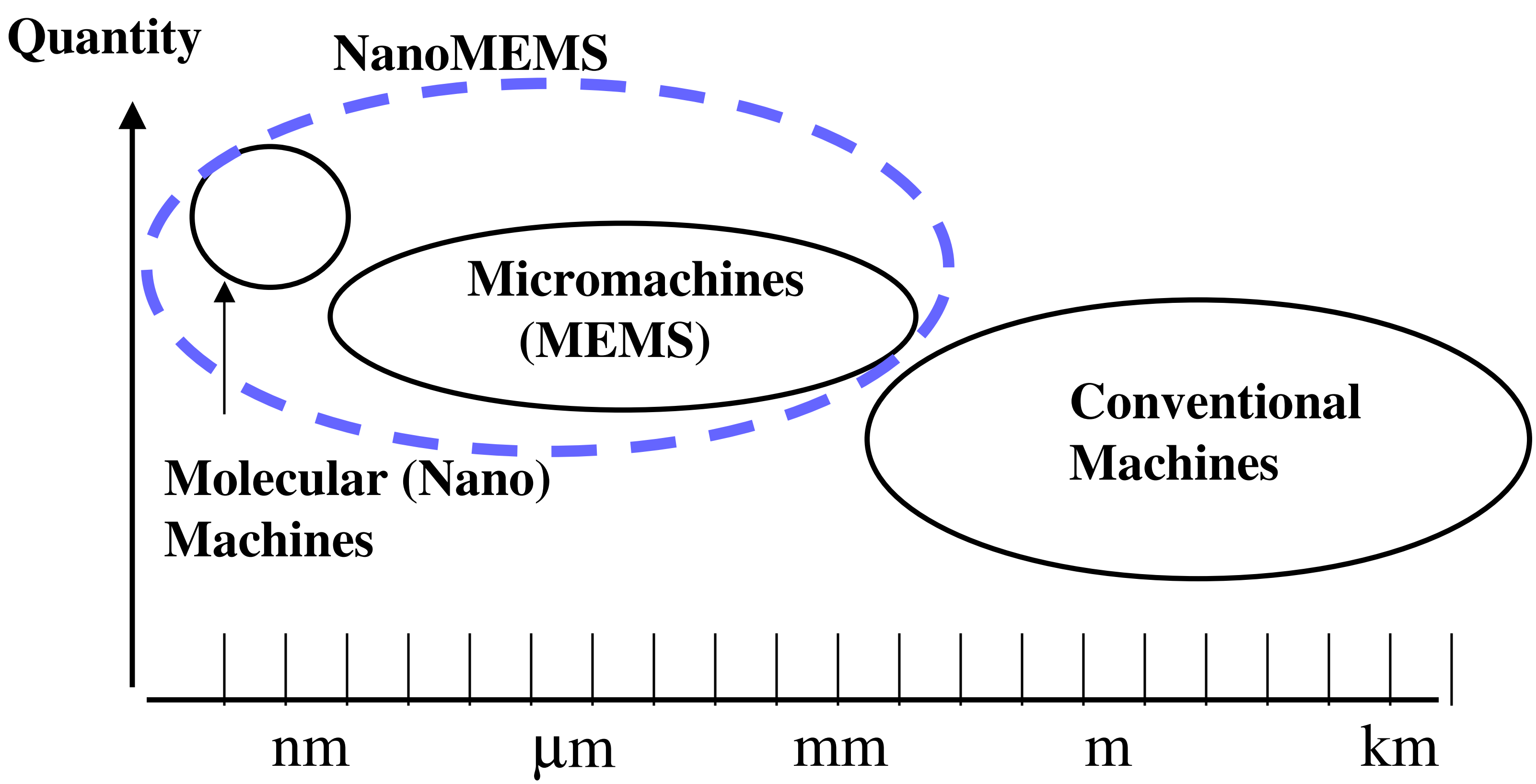
What Do We Mean By Small?



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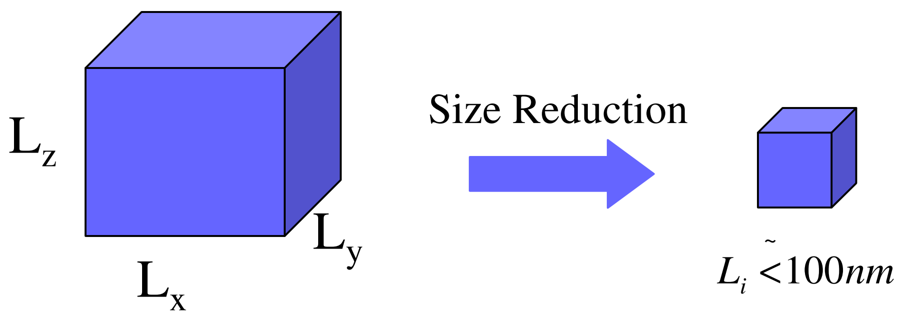
NanoMEMS Physics

Countinuous Energy

$$p = mv \qquad E \sim \frac{p^2}{2m}$$

Quantized **Energy**

$$p = \frac{\hbar}{\lambda} \qquad E = \hbar\omega \qquad \Delta x \cdot \Delta p_x \tilde{>} \hbar$$

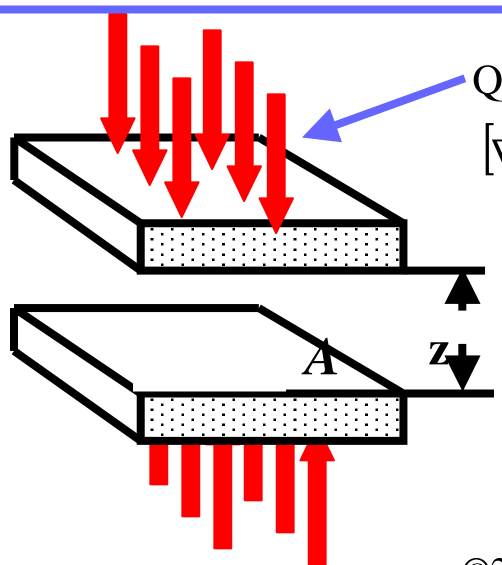


$$E(n_x, n_y, n_z) = \frac{\hbar}{2m}\left[\left(\frac{n_x \pi}{L_x}\right)^2 + \left(\frac{n_y \pi}{L_y}\right)^2 + \left(\frac{n_z \pi}{L_z}\right)^2\right]$$

Wave, Particle Behavior Devices

- **Interference, Diffraction, Tunneling, etc.**
- **Coulomb Interaction** $E_{Coulomb} = \frac{Q^2}{L}$

Casimir Forces



QED "Vacuum" Pressure

$$\left[\nabla^2 - c^{-2}\partial^2/\partial t^2\right]\vec{E} = 0 \rightarrow \bar{\vec{E}} = 0$$

$$\overline{\left|\vec{E}^2\right|} \neq 0$$

$$\frac{F_{Casimir}}{A} = -\frac{\pi^2 \hbar c}{240}\frac{1}{z^4}$$

$z = 0.5\mu m \qquad A = 1cm^2$

$F_{Casimir} = 2\mu N$

Impact of the Casimir Force on Movable-Dielectric RF MEMS Varactors

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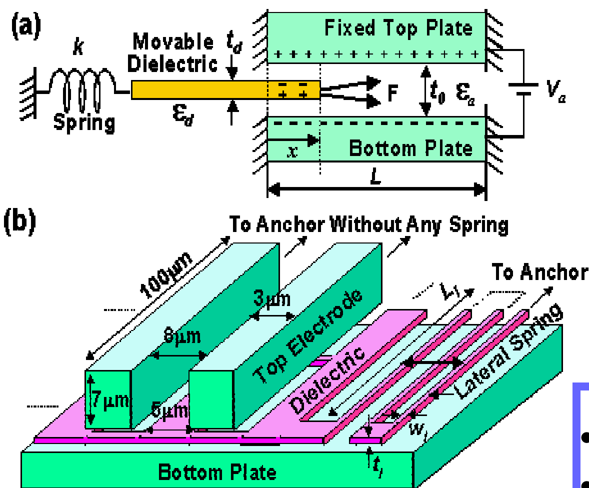
RF MEMS Varactor

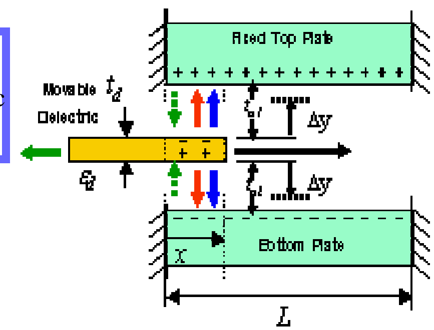


Yoon and Nguyen, '98

Reduced Tuning Range

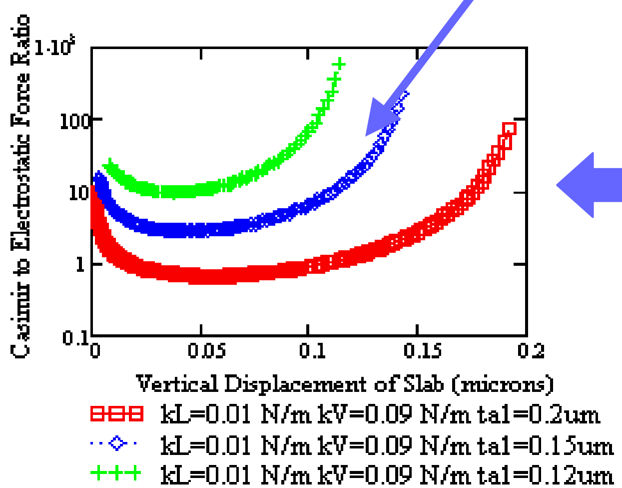
ΔC_{Ideal}: 47%
$\Delta C_{Measured}$: 15%

Forces on Varactor



- Greater asymmetry → $F_{Casimir} >> F_{Electrostatic}$
- ΔC Reduction due to Casimir Force!

Quantum Mechanical Pull-in!



$F_{Spring\_1} = -k_L x$	$F_{Spring\_2} = -k_V \Delta y$	$F_{Electrostatic\_1} = \frac{\varepsilon_a L_1 x V^2}{2(t_a - \Delta y)^2}$; $F_{Electrostatic\_2} = \frac{\varepsilon_a L_1 x V^2}{2(t_a + \Delta y)^2}$
$F_{Casimir\_1} = \frac{2.992\times10^{-25} L_1 x}{(t_a - \Delta y)^4}$; $F_{Casimir\_2} = \frac{2.992\times10^{-25} L_1 x}{(t_a + \Delta y)^4}$	$F_{Lateral} = \frac{L_1 t_d \varepsilon_a (\varepsilon_d - \varepsilon_a)}{2 t_0 [(t_0 - t_d)\varepsilon_d + \varepsilon_a t_d]} \cdot V^2$	

H. J. De Los Santos, *IEEE NANO'03*, San Francisco, CA, August 12-14, 2003

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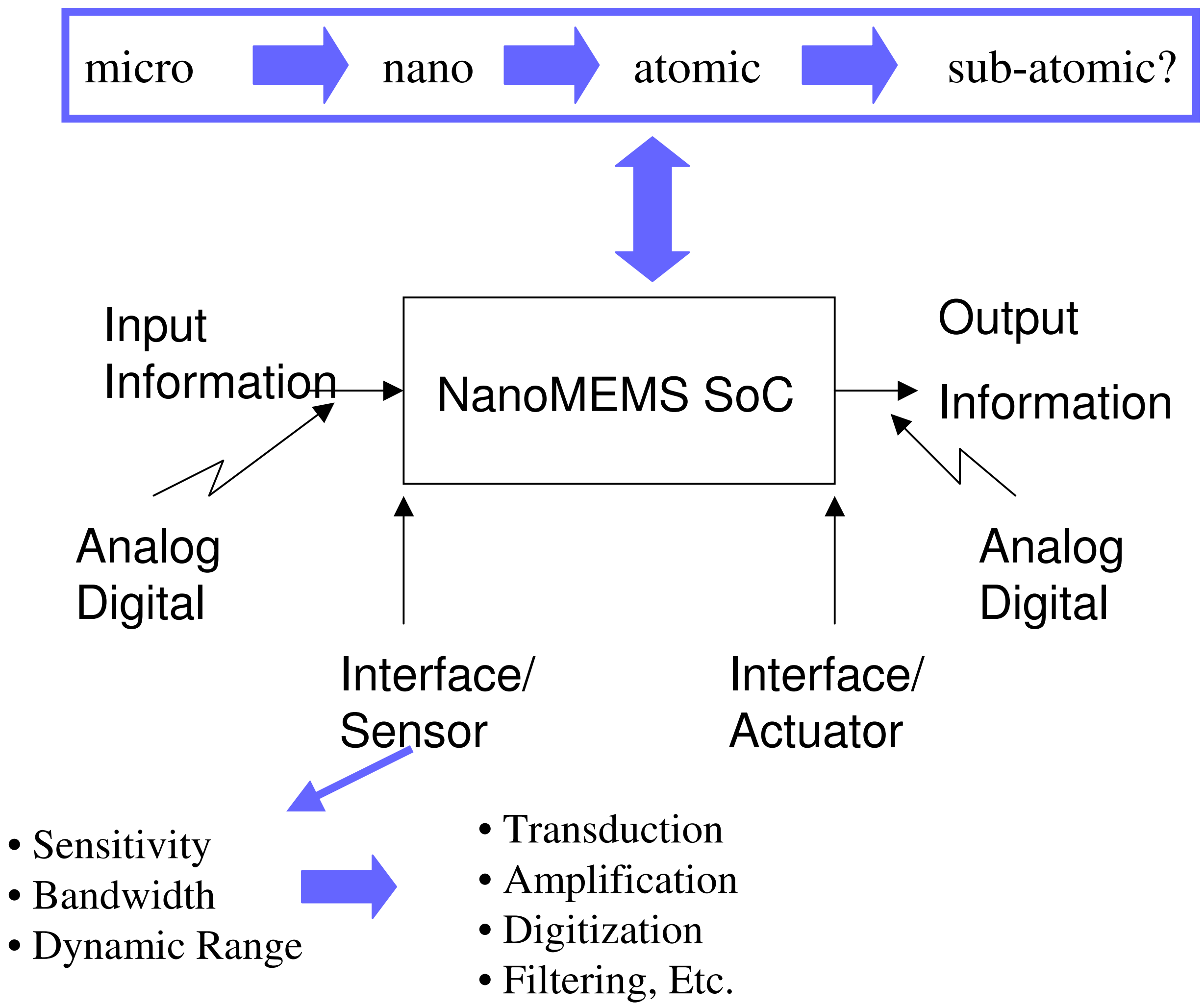
NanoMEMS SoC—Building Blocks

Signal Processing Realm



NanoMEMS SoC—Signal Processing

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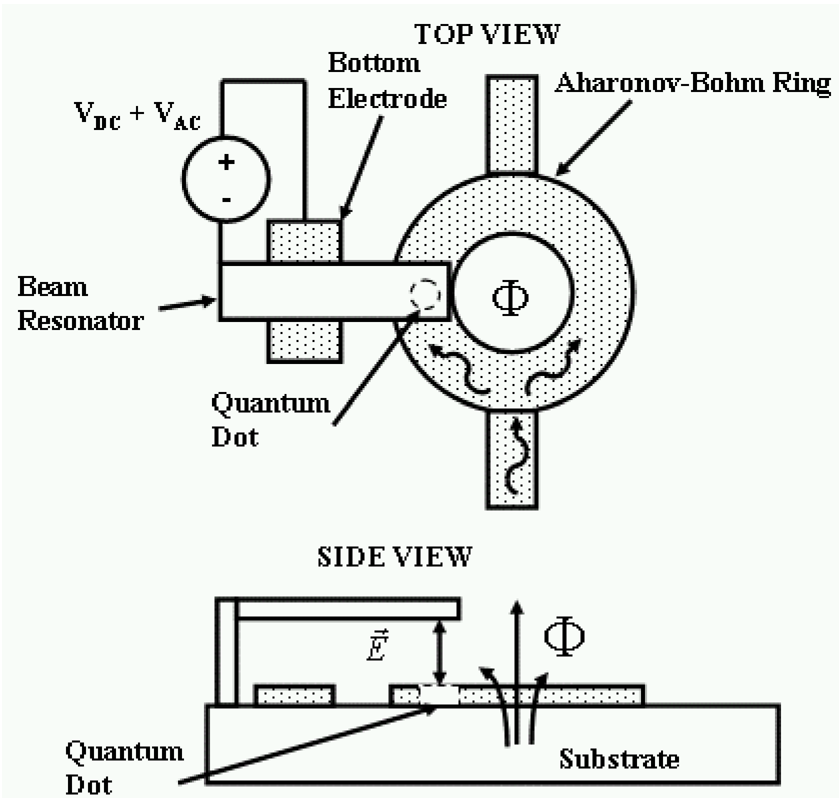
Mechanical Which-Path Electron Interferometer



Coupling between vibrating beam and QD Modulates electron dwell time in QD and induces interference in Aharonov-Bohm ring.

A.D. Armour and M.P. Blencowe, "Possibility of an electromechanical which-path interferometer," *Phys. Rev*. **B 64**, p.035311 (2001).

NanoMEMS Applications: Nanomedicine

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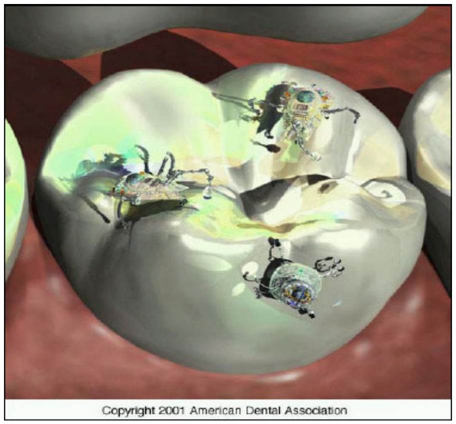
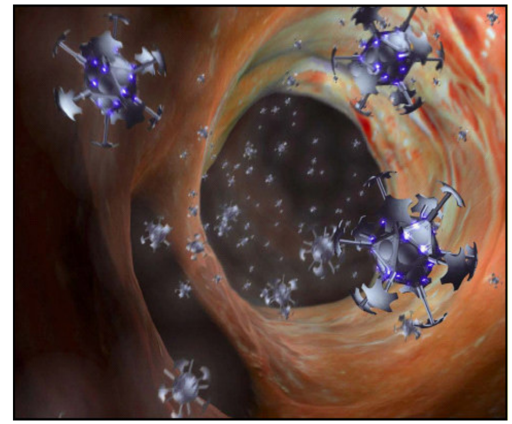
Futuristic

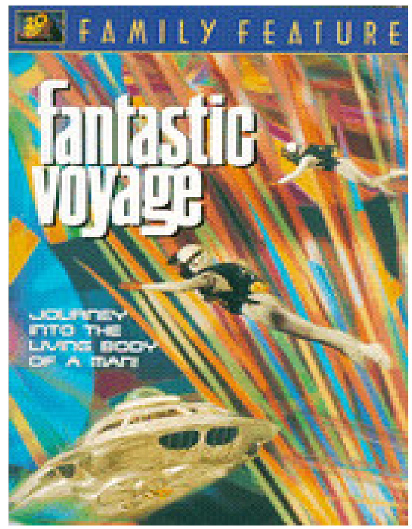
Tooth Cleaning Robots



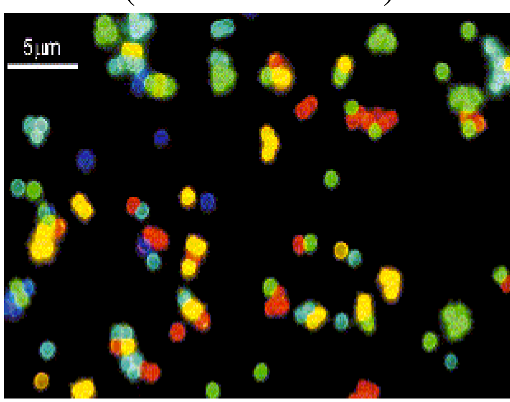
Lung Cleaning Robots



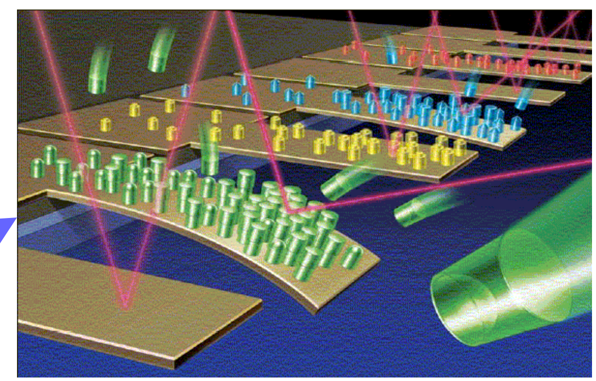
Science Fiction



Improved Imaging and Diagnostics (Nano Bar Codes)



Detection Using Cantilever (Nanomechanics for Biomolecular Recognition)



Realistic

www.chem.ch.huji.ac.il~porathNST2Lecture%2013Lecture%2013.pdf
Scientific America, September 2001

J. Fritz et al, *Science*, 288, 14 APRIL 2000, pp. 316-318

Applications: Medicine

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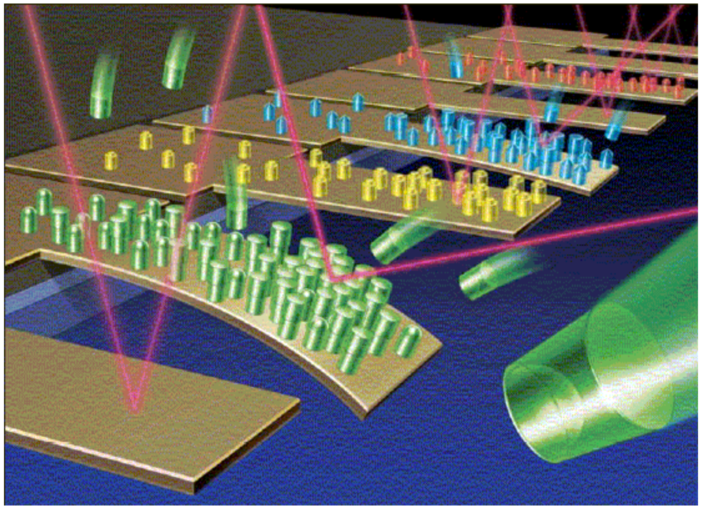
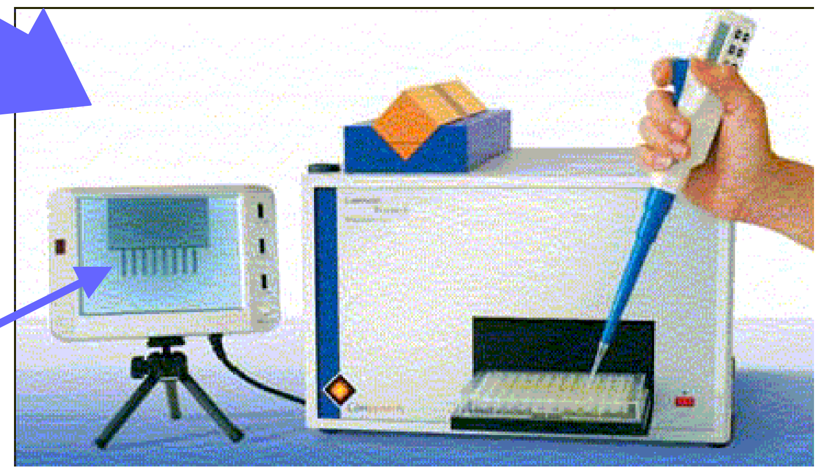
Nanomechanics for Biomolecular Recognition



Nanomechanics+Biochemical Surface Functionalization (Coating)

Selective Species (Mass) Sticking $\rightarrow \Delta f_0$

Instrument Prototype Available



Scanning electron micrograph of a microfabricated cantilever array. Eight cantilevers with dimension of 500 um x 80 um x 7 um.

Concentris, GmbH

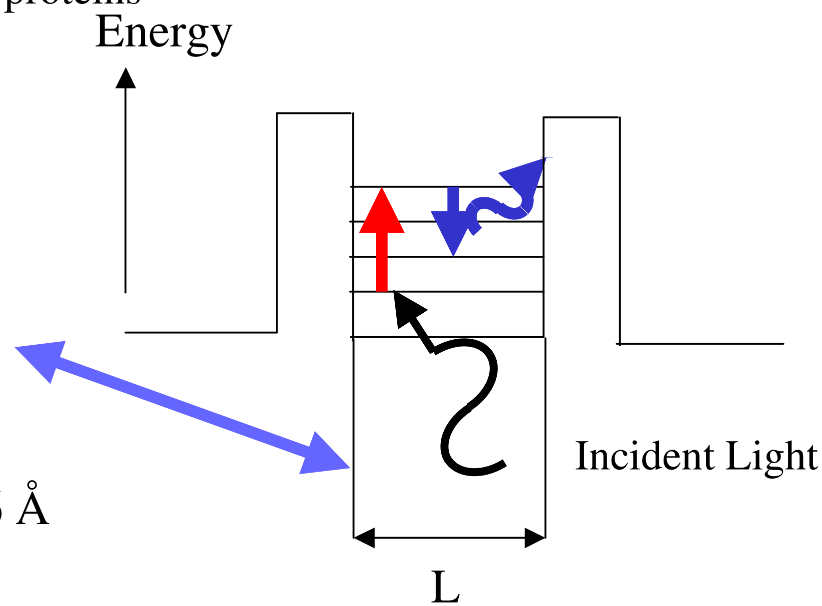
Applications: Medicine

Quantum Dots

- Metal and semiconductor nanoparticles in the 2–6 nm size
- Unique size-dependent properties
- Size similar to biological macromolecules: nucleic acids, proteins

Quantum Confinement

Particle dimension~Bohr exciton: $$a_{ex} = \frac{\varepsilon \cdot \hbar^2}{m_{ex} e^2}$$



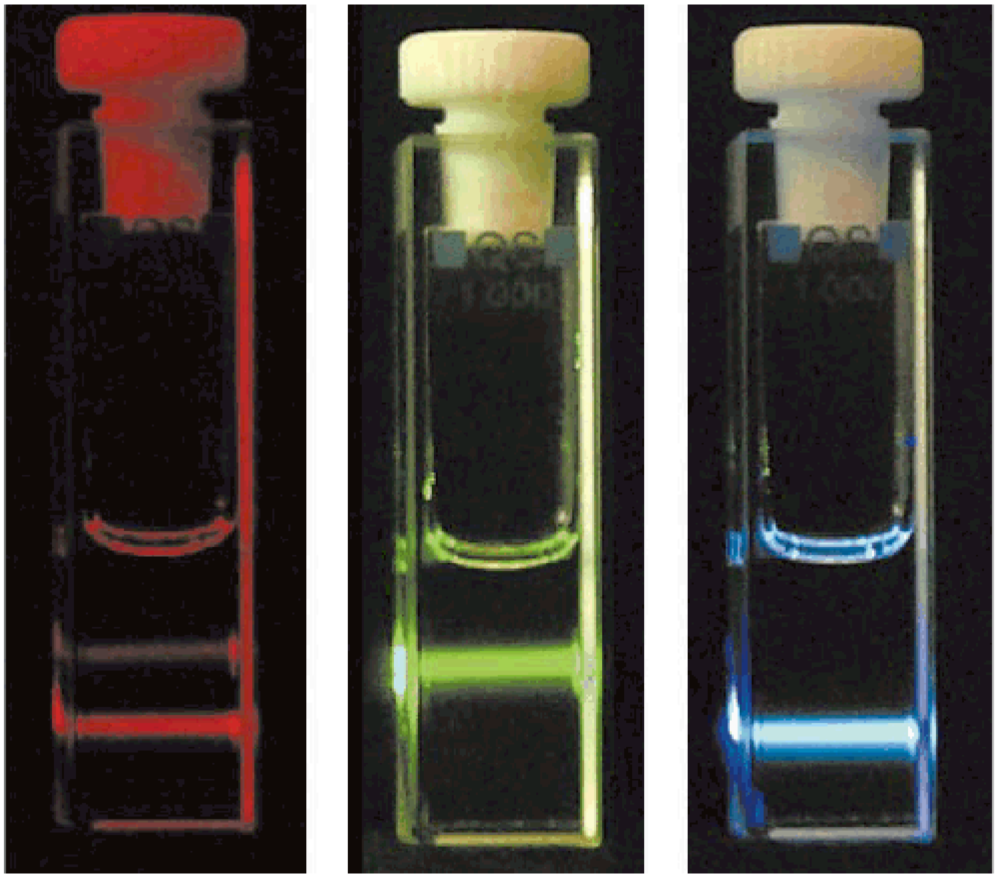
Examples: $a_{CuCl} = 7$ Å, $a_{GaAs} = 100$ Å and $a_{CdSe} = 56$ Å

Discretization of Energy Levels

X. Michalet, F. Pinaud, T. D. Lacoste, M. Dahan, M. P. Bruchez , A. Paul Alivisatos and S. Weiss, "Properties of Fluorescent Semiconductor Nanocrystals and their Application to Biological Labeling," Single Mol. 2 (2001) 4, 261-276

Applications: Medicine

Size-Controlled Emission of Quantum Dots



Howard Lee and his colleagues at LLNL have synthesized silicon and germanium quantum dots ranging in size from 1 to 6 nanometers. The larger dots emit in the red end of the spectrum; the smallest dots emit blue or ultraviolet.

"Mighty Small Dots," *S&TR*, Lawrence Livermore National Laboratory, July/August 2000, pp. 20-21.

Conclusions

NanoMEMS is Growing Field

Nanotechnology R&D Funding by Agency

<u>Many Directions $$$</u>

- Fundamental Phenomena & Processes
- Nanomaterials
- Nanoscale Devices & Systems
- Instr. Research, Metrology & Standards
- Nanomanufacturing
- Major Research Facility & Instr. Acquisition
- Social Dimensions

Table 2
NNI Budget, 2005-2007 (dollars in millions)*

	2005 Actual	2006 Estimate	2007 Request
NSF	335	344	373
DOD	352	436	345
DOE	208	207	258
DHHS (NIH)	165	172	170
DOC (NIST)	79	78	86
NASA	45	50	25
EPA	7	5	9
USDA (CSREES)	3	3	3
DHHS (NIOSH)	3	3	3
USDA/FS	0	2	2
DHS	1	2	2
DOJ	2	1	1
DOT (FHWA)	0	0.1	0.1
TOTAL**	1,200	1,303	1,278

http://www.nano.gov/NNI_07Budget.pdf

MEMS R&D and Commercial Growth

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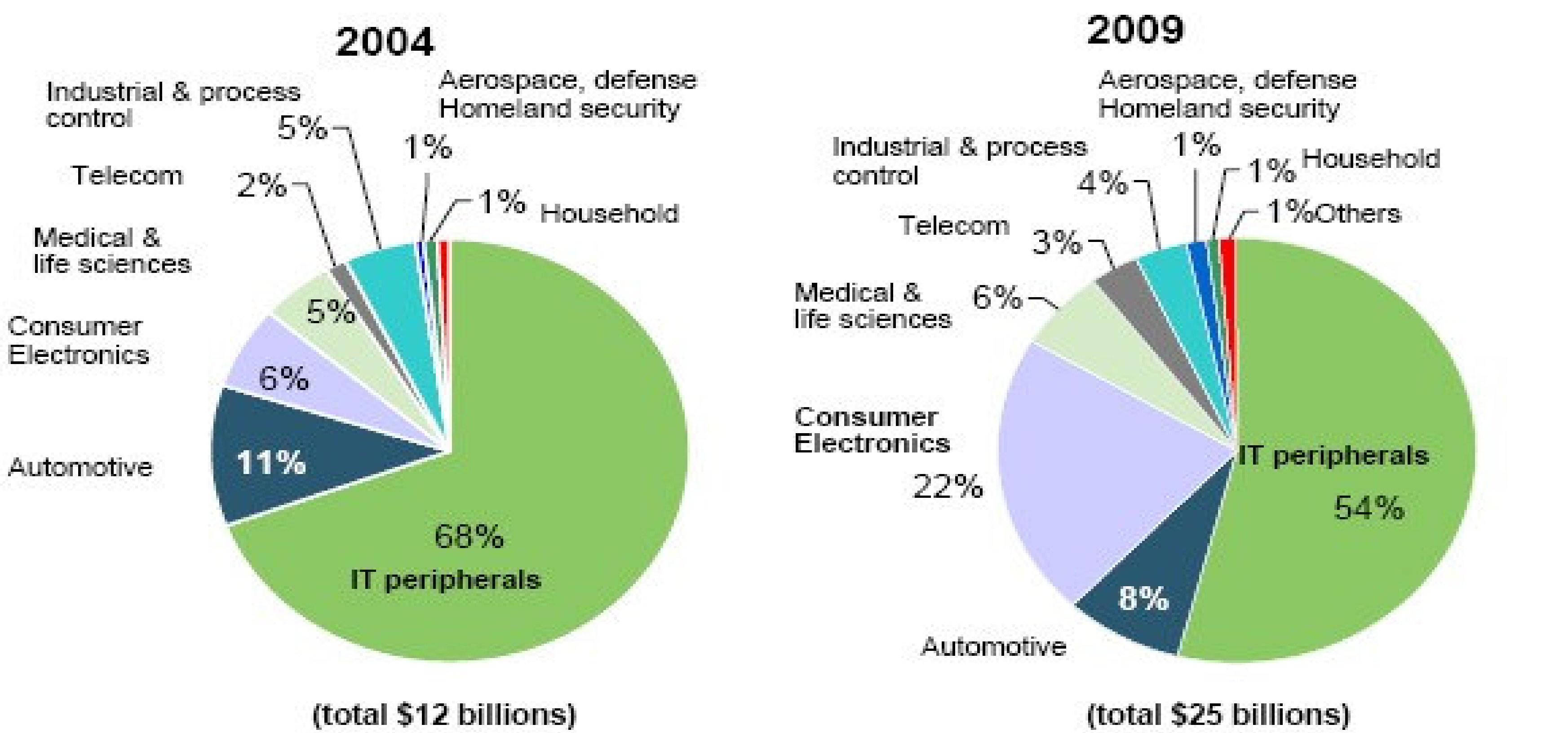
Application fields in 2004 and 2009



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RF MEMS R&D and Commercial Growth

Many Directions $$$

- Military Phased Arrays
- Military Tactical Radio
- Satellites
- RF Test and ATE
- Automotive
- Microwave Communications
- Base stations
- Consumer electronics and IT
- WLAN and WPAN
- Mobile Telephony