MEMS RF : a review

Master SESI,

UE MEMS,

Cours 3

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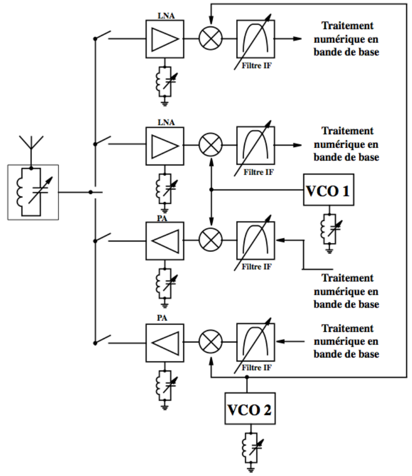
Outline

- Introduction
- MEMS RF switches
- Liquid Metal RF switches
- MEMS Resonators

Application domain: the SoftWare Defined Radio



RF application trend : multistndard transievers

Frequency definig components: filters, oscillators

Way to achieve reconfigurability:
- frequency tunning
- switching

MEMS technology is promising for the both.

Application domain: the SoftWare Defined Radio

Hisory

MEMS metal-to-metal DC-60 GHz switch: Rockwell Science Center, 1995

MEMS Capacitive 10-120 GHz switch : Texas Instruments, 1995

1998 : research in MEMS RF area is very active in american academic laboratories (Berkeley, UCLA, Michigan, MIT…)

2001 : more that 30 companies working in the area, including Motorola, AD, Samsung, STM, …

Application domain: the SoftWare Defined Radio

Four distinct areas :

RF MEMS switches, vacastors and inductors : DC-120 GHz

Micromachined hyperfrequency components: transmission lines, high-Q resonators, filter, antenna (12-200 GHz). No mobile parts, no operation in mechanical domain. Not a truly MEMS devices, but using technologies similar with MEMS devices.

FBAR (thin Film Bulk Acoustic Resonators), filters : integrable very high Q filters/resonators for <3 GHz applications, essentially in wireless communications

Mechanical resonators based RF resonators and filters : promising but still marginal in RF applications

RF switches : MEMS vs Solid-state

TABLE 1.2. Performance Comparison of FETs, PIN Diode, and RF MEMS Electrostatic Switches

Parameter	RF MEMS	PIN	FET
Voltage (V)	20–80	±3–5	3–5
Current (mA)	0	3–20	0
Power consumption[a] (mW)	0.05–0.1	5–100	0.05–0.1
Switching time	1–300 μs	1–100 ns	1–100 ns
C_{up} (series) (fF)	1–6	40–80	70–140
R_s (series) (Ω)	0.5–2	2–4	4–6
Capacitance ratio[b]	40–500[b]	10	n/a
Cutoff frequency (THz)	20–80	1–4	0.5–2
Isolation (1–10 GHz)	Very high	High	Medium
Isolation (10–40 GHz)	Very high	Medium	Low
Isolation (60–100 GHz)	High	Medium	None
Loss (1–100 GHz) (dB)	0.05–0.2	0.3–1.2	0.4–2.5
Power handling (W)	<1	<10	<10
Third-order intercept point (dBm)	+66–80	+27–45	+27–45

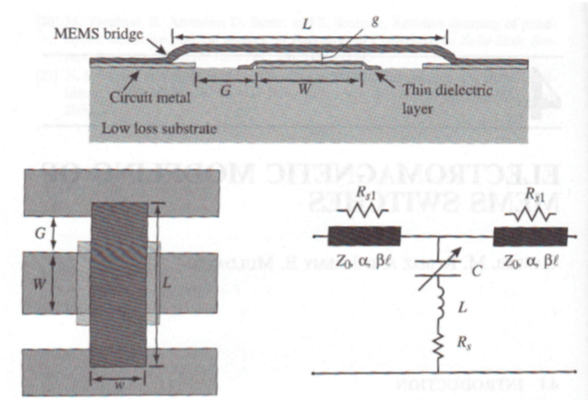
[a] Includes voltage upconverter or drive circuitry.

[b] Capacitive switch only. A ratio of 500 is achieved with high-ϵ_r dielectrics.

Capacitive switches

The most efficient and promising, since no mechanical contact : a large lifetime

Drawbacks : efficient only at high frequencies, limited insulation



Capacitive switches

Typical parameters :

- dielectric thickness 1000-1500 Å
- Dielectric constant : 5.0-7.6
- Bridge height (g) : 1.5-5 μm,
- length L : 250-400 μm,
- width W : 25-180 mm

mm-wave switches :

- capacitance : 35fF/3 pF
- parasitic inductance 6-12 pH
- series resistance : 0.2-0.3 Ohms

X-band switches :

- Capacitance : 70 fF/5.6 pF,
- inductance 4-5 pH,
- resistance 0.1-0.2 Ohms

Performances :

- The resonance frequency

$$f_0 = \frac{1}{2\pi}\frac{1}{\sqrt{LC}}$$

Cutoff frequency : the frequency where the capacitance ratio of the off (up-state) and on (down-state) degrades to unity :

$$f_c = \frac{1}{2\pi C_u R_s}$$

Capacitive switches

•Up-capacitance : the dielectric layer can be neglected

•Tens of fF

•Holes in the upper membrane : needed for the releasing
of the mobile part

•Holes : 4-6 mm diameter, spaced by 5-6 mm period.

•Typical gap : 3-4 mm

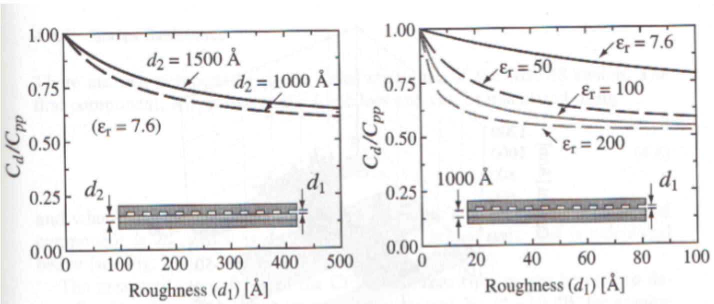
•The holes don't affect the up-state capacitance: fringe field
•(D_h<3g : the up capacitance is not affected)

Capacitive switches

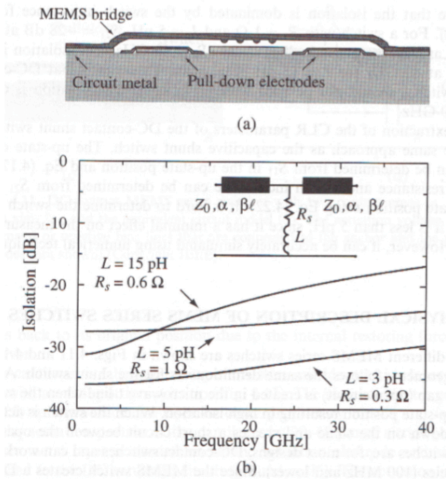
• Down capacitance : defined by the dielectric (thickness, dielectric constant).

• Should be as high as possible, however, limited by the Minimal thickness of dielectric (~1000-1500 Å) which should support the actuation voltage (20-50 V)

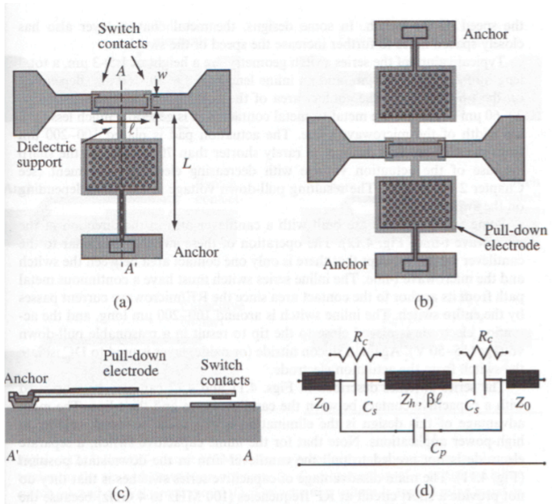
Roughness of the surface : a degradation of the down-capactiance



DC-contact shunt switches



DC-contact series switches



DC-contact series switches

Relevant parameters:

- Up-state capacitance
- Contact series resistance
- Inductance

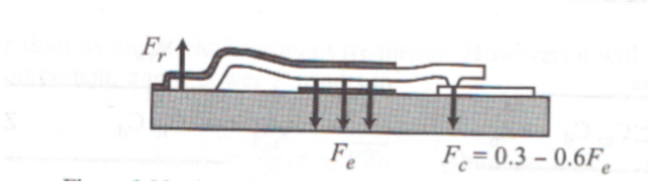
Gold-to-gold contact : 0.1 Ohms for applied force of 100-500 μN, contact area of 20 μm^2,

MEMS switches and pull-in phenomenon

- Two parameters: pull-in voltage and hold-down voltage
- Hysteretis characteristic x(V)
- Exercice: calculate the pull-in voltage and the pull-down voltage if W=100μm, w=80 μm, k=30 N/m, t_d=0.1 μm, eps=7. k is supposed to be constant
- Calculate the contact force in down position

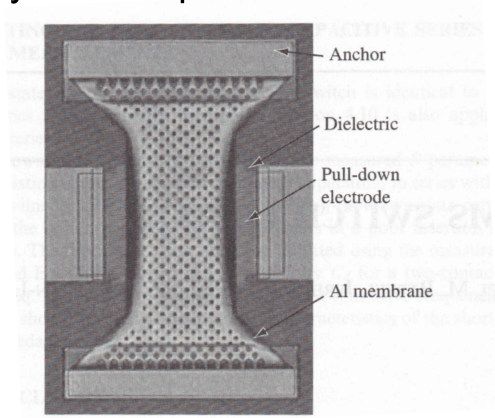
MEMS switches contact forces

- The contact force: may be different from the pull-in force



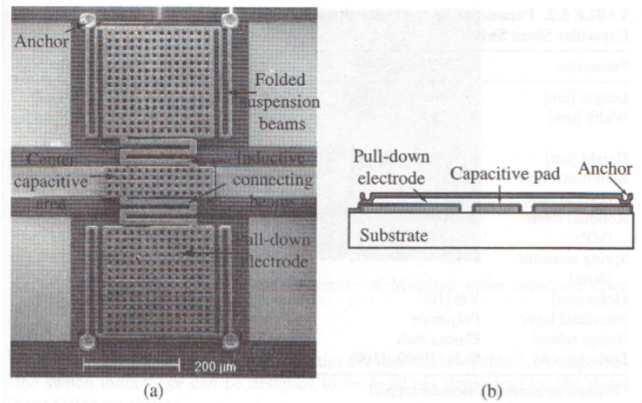
Examples of RF switches

- Raytheon capacitive shunt switch



Examples of RF switches

Univ. Michigan MEMS capacitive shunt switch



Liquid Metal MEMS switch

- Drawback of the ohmic switches :
  - Lifetime : up to 100 billions of cycles, however, doubts exist about their long-term reliability
  - Two common failure mecanism :
    - Dielectric charging
    - Contact degradation
    - Causes: arcing, welding at the solld-solid contact
  - One of the solutions : contact based on liquid metal

Examples of RF switches

Univ. Michigan MEMS capacitive shunt switch

TABLE 5.2. Parameters for the University of Michigan Low-Voltage MEMS Capacitive Shunt Switch

Parameter	Value	Parameter	Value
Length [μm]	500–700	Actuation area [μm^2]	200 × 200 (×2)
Width [μm]	200–250	Actuation voltage^a [V]	6–20
Height [μm]	4–5	Switch time^a [μs]	20–40 (D)
Membrane type	Nickel	C_d [pF]	1–3
Thickness [μm]	2–2.5	Capacitive ratio	30–50
Residual stress [MPa]	20–100	Inductance [pH]	1–2
Spring constant [N/m]	1–10	Resistance [Ω]	0.2–0.3
Holes [μm]	Yes (10)	Isolation [dB]	−25 (30 GHz)
Sacrificial layer	Polyimide	Intermodulation	N/A
Bridge release	Plasma etch	Loss [dB]	−0.1 (1–40 GHz)
Dielectric (Å)	Si_3N_4 (1000–1500)		

^{a}Depends on number of meander support.

Liquid Metal MEMS switch

- Idea of LM swich : the contact electrodes are coated with a liquid metal layer (mercury, gallium, galinstan…), or the contact is achieved with a droplet of liquid metal
- The contact quality is better (no bouncing), the solid contact supports are less damaged
- The switch lifetime is much greater

Liquid Metal MEMS switch

Liquid metals :

- There is only 5 chemical elements liquid at the ambiant temperature : Mercury, Gallium, Cesium, Francium and Bromine
- Three materials used in switches: mercury, gallium and gallistan (a gallium-based alloy)

Liquid Metal MEMS switch

Mercury:

- Hg, discovered around 500 B.C.
- Melting point :-38,84°C, a fair (not excellent) thermal and electrical conductor
- Boils at 357°
- The surface tension : 485 mN/M at room temperature
- Very toxic, use highly restricted over past decades

Liquid Metal MEMS switch

Gallium:

- Ga, Discovered in 1875 by Lecoq de Boisbaudran (Gallium <=Gallus=Lecoq).
- Melting point :29,77 °C
- Boils at 2205°C
- The highes surface tension : 680 mN/M at melting point
- Very agressive (attack nearly every metals)

Liquid Metal MEMS switch

Galinstan:

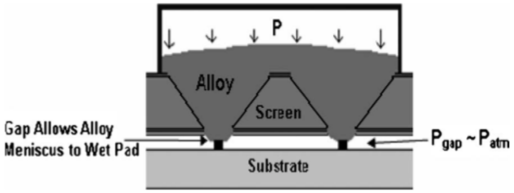
- 68.5% gallium, 21.5% indium, 10% tin,
- The name: Gal + In + Stan (stannum = lat. of tin)
- Widely used for mercuryless thermometers
- Nontoxic
- Very promising material for swithes
- Good conductor (better thant mercury)
- Melting point : -19°C
- Boiling point: >1300°C
- Easily wet and adheres to most surfaces
- Gallium oxide coat : prevents from the wetting

Liquid Metal MEMS switch

LM deposition : a challenging task

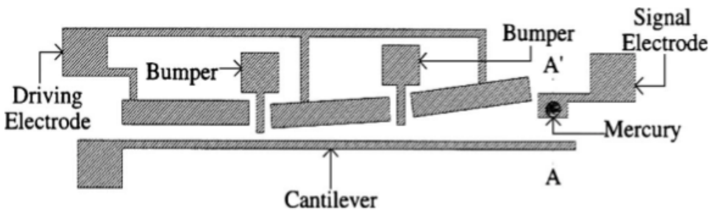
- The goal : to deposit a micrometer-size droplet
- Complicated because of high surface tension
- Mercury : slective condensation of mercury vapor on a gold plate
- Gallium and Gallium Alloys : the lowest vapor pressure among metals
  - Very difficult to evaporate
  - Must be heated to 750°C
  - Screen printing technology

(Truong, 2000)



Electrostatically driven microcantilever-based mercury contact (1996)

- **Shaped electrodes**
- **Bumpers prevent the contact with electrodes**
- **Mercury droplet captured at the contact point**



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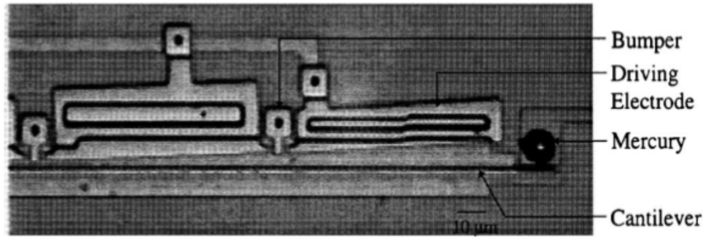
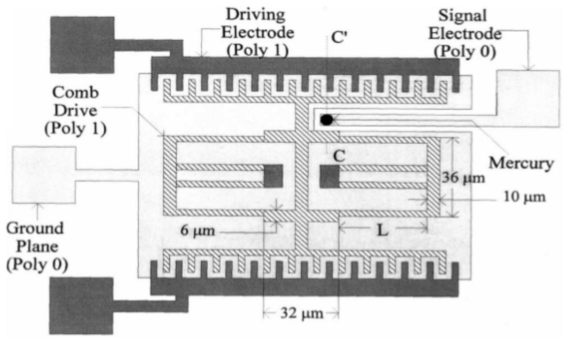


Electrostatically driven comb-drive-based mercury contact switch (1998)

- **Comb-driven electrode,**
- **Back (bottom) transducer increases the restoring force**



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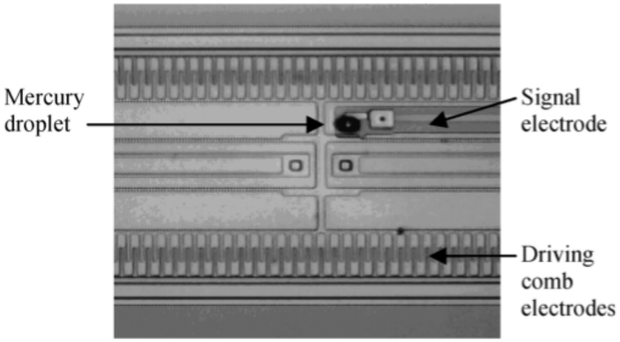
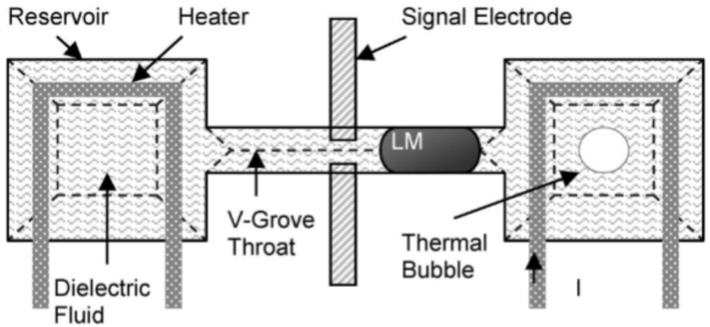


Electrostatically driven comb-drive-based mercury contact switch (1998)

- Actuation voltage : 35 V DC
- 4 μm mobile contact travel
- 4 Hz actuation frequency (?)
- 11 mA max. switching current

LM-actuaded switches

- The earliest LM-actuated switch (Simon et al., 1996) : thermal vapor buble actuated LM microrelay



LM-actuaded switches

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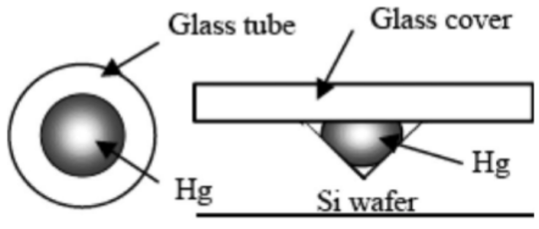
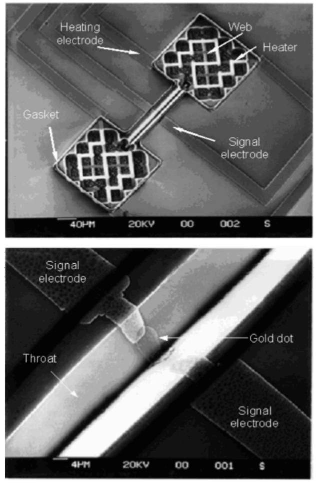
- Possible canal profiles



(a) (b)

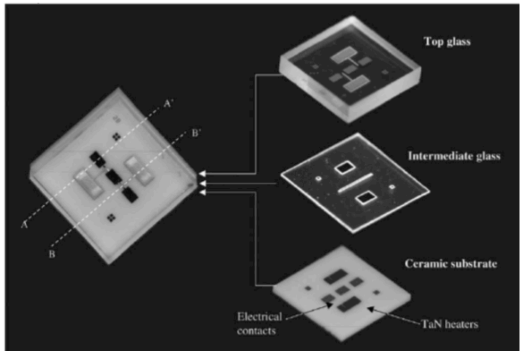
LM-actuaded switches

- The earliest LM-actuated switch (Simon et al., 1996) : thermal vapor buble actuated LM microrelay
- Photo of the fabricated device



LM-actuaded switches

- Thermally actuated LM (2000, Kondoh et al.)



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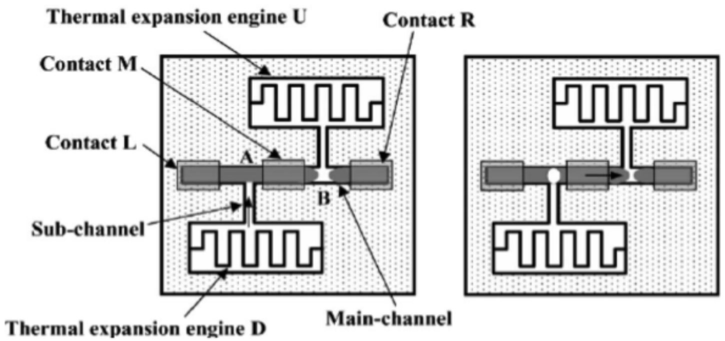


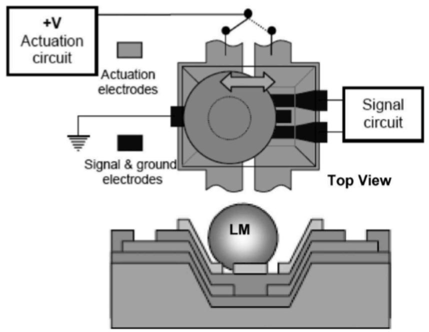
LM-actuaded switches

- Electrostatically actuated LM droplet : 2002, Kim et al.

Actuating force : 6.7 μN for a 300 μm diameter droplet

Actuation voltage: 100-150 V DC

Frequency : 1 Hz



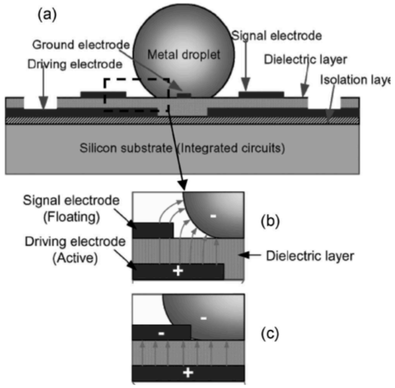
LM-actuated switches

- Electrostatically actuated LM droplet : planar design bv Shen et al., 2006

Actuation voltage : 15V

Stability issue : only 3g stability

With 80 V DC actuation voltage, 300g stability



RF MEMS resonators

Main applications : **oscillators** and filters

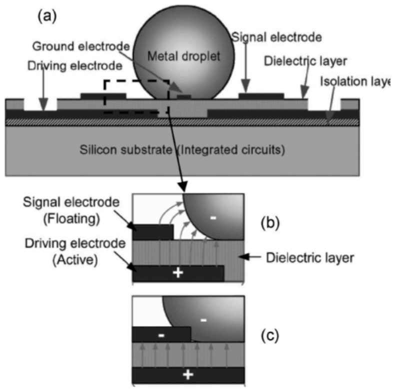
Filters: BAW resonators/filters (Bulk Acoustic Wave)
Oscillators: integrated frequency reference generator

Electrical vs mechanical oscillators (2012)

Resonator technology	Accuracy df/f_0 (ppm)	Noise FoM_2	Size L x W x H (mm)	System integration
mechanical	<10	~130	>1.6x1.2x0.35	•Bulky hermetic package •Non-CMOS compatible
electrical	>100	~90	<0.5x0.5X0	•Standard plastic package •CMOS design

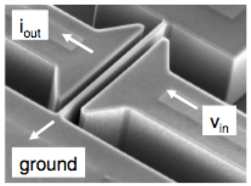
LM based MEMS switches

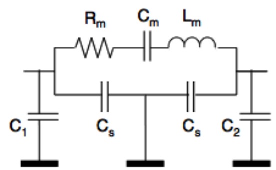
- Promising field, but many material issues,
- The state of developme embrionic
- Further R&D are requir
- A key technology : a lov temperature hermetic p in indert environment



RF MEMS resonators

A typical HF clamped-clamped beam resonator geometry





RF MEMS resonators

Travaux de Clark T.-C. Nguyen (Berkley)
http://www.eecs.berkeley.edu/~ctnguyen

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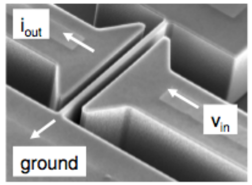
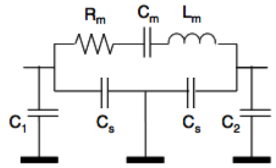
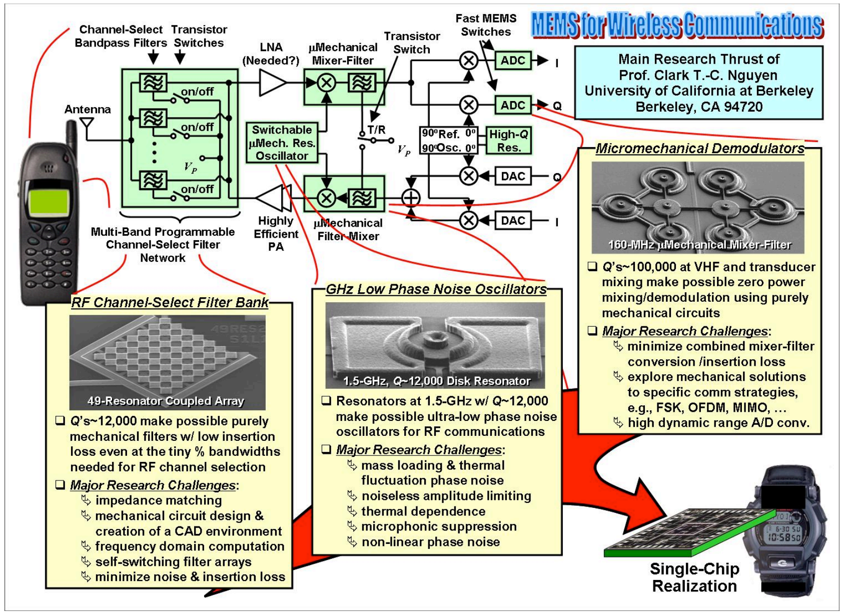
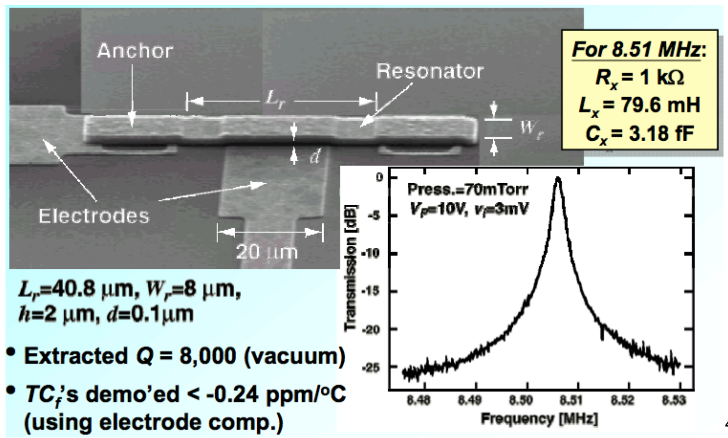






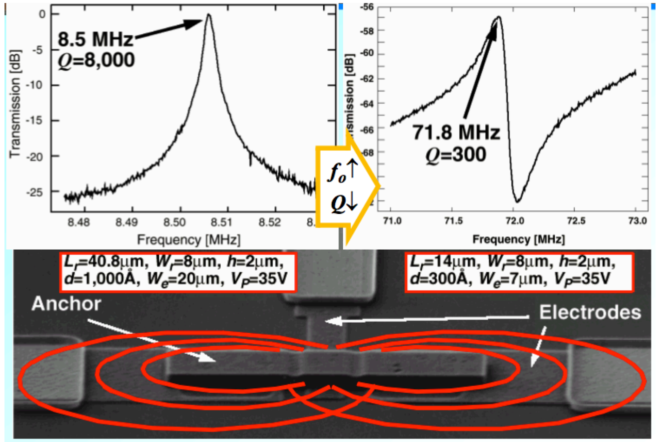
RF MEMS resonators

A typical HF clamped-clamped beam resonator geometry (2)



RF MEMS resonators

Main dissipation mechanism : dissipation in anchors



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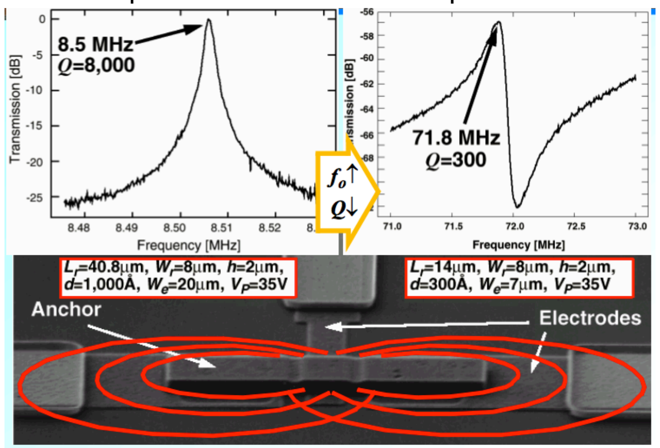

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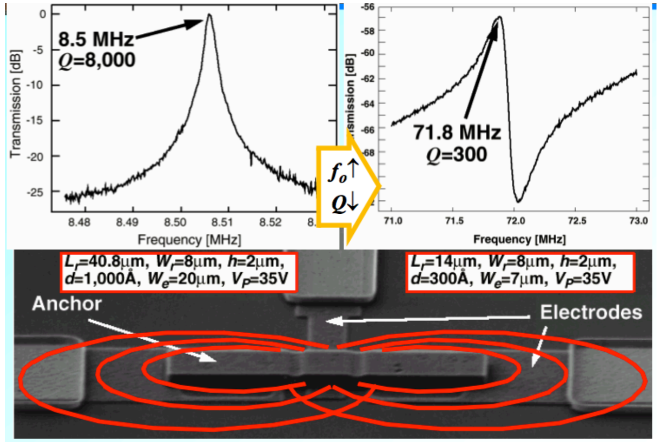
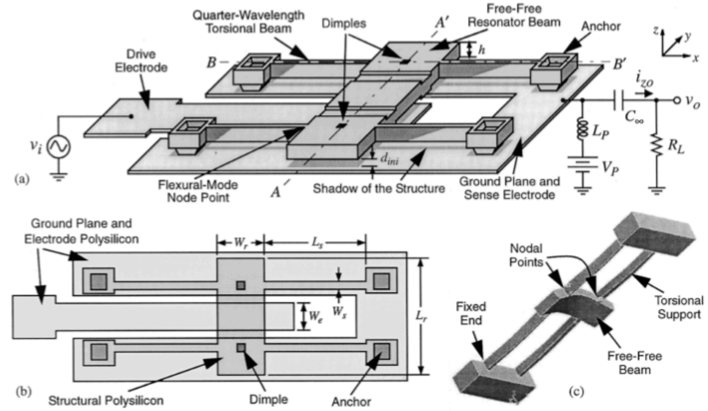


RF MEMS resonators

The solution : clamp the vibrating structure in the fixed vibration points. Example : a free-free vibrating beam



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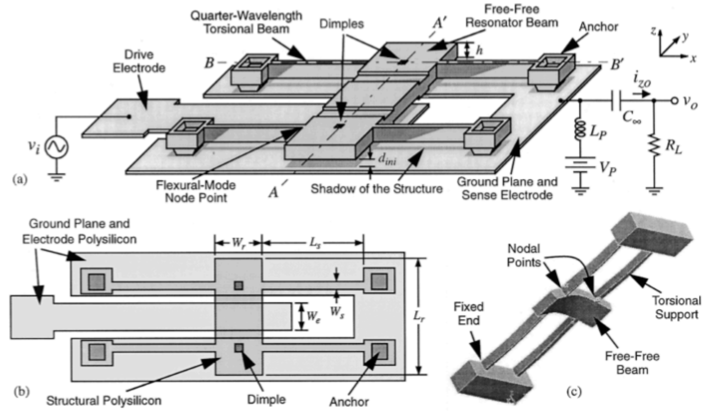
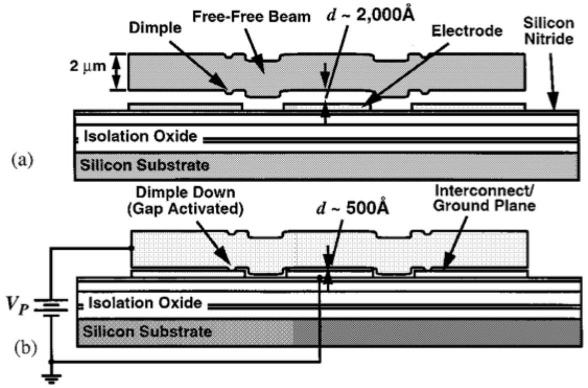


RF MEMS resonators

Post fabrication gap reduction (K. Wang et al., 2000)



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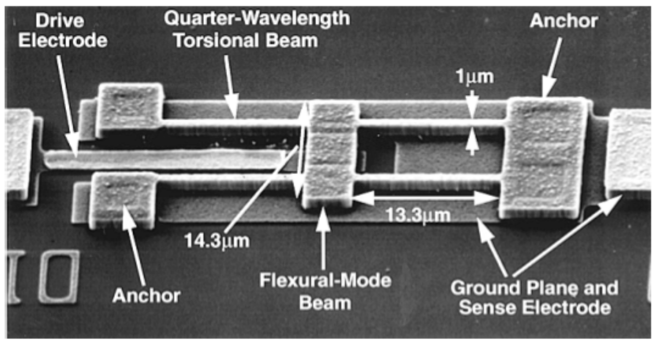


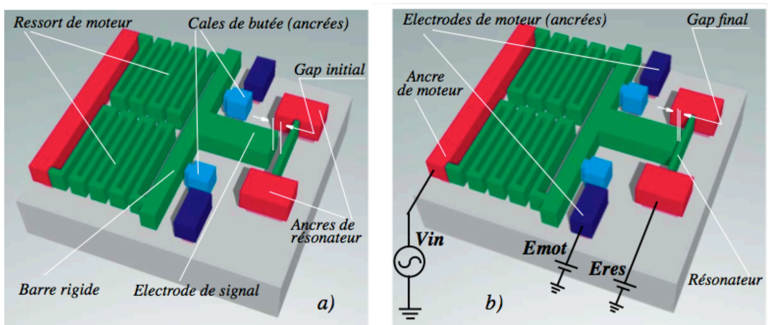
RF MEMS resonators

Parameters of the fabricated free-free beam resonators

	Row No.	Parameter	Source	Target Frequency				Unit
				30 MHz	50 MHz	70 MHz	90 MHz	
Designed/Fabricated/Given	1	Resonator Beam Length, L_r	layout	23.2	17.8	14.9	13.1	µm
	2	Resonator Beam Width, W_r	layout	10	10	6	6	µm
	3	Supporting Beam Length, L_s	layout	30.6	18.4	13.1	10.3	µm
	4	Supporting Beam Width, W_s	layout	1	1	1	1	µm
	5	Node Location 1, L_{n1}	layout	5.2	4	3.3	2.9	µm
	6	Node Location 2, L_{n2}	layout	18	13.8	11.6	10.2	µm
	7	Polysilicon Film Thickness, h	measured	2.05	2.05	2.05	2.05	µm
	8	Electrode Width, W_e	layout	7.4	4.5	4	2.8	µm
	9	Typical Initial Physical Gap, d_{ini}	measured	1,600	1,600	1,600	1,600	Å
	10	Typical Physical Dimple Height, d	measured	1,230	1,230	1,230	1,230	Å
	11	Torsion Constant, γ	Eq. (18)	0.469	0.469	0.469	0.469	μm^4
	12	Young's Modulus, E	measured	150	150	150	150	GPa
	13	Poisson Ratio, ν	[19]	0.226	0.226	0.226	0.226	—
	14	Freq. Modification Factor, ζ	chosen	1	1	1	1	—
Measured	15	Measured Frequency, f_o	measured	31.51	50.35	71.49	92.25	MHz
	16	Measured Quality Factor, Q	measured	8,140	8,430	8,250	7,450	—
	17	V_P Used in Measurement, V_{Pm}	measured	22	86	126	76	V
	18	Measured Series Resistance, R_z	meas./Eq. (24)	31.1	10.7	34.9	167.0	kΩ
Analytically Determined	19	Timoshenko Freq., $f_o(V_P=V_{Pm})$	Eq. (9), (5)	30.63	50.83	71.39	90.99	MHz
	20	Timoshenko Freq., $f_o(V_P=0V)$	Eq. (5)	30.70	51.16	71.64	91.07	MHz
	21	Euler-Bernoulli Freq., $f_o(V_P=V_{Pm})$	Eq. (9), (1)	31.62	53.51	76.57	99.29	MHz
	22	Euler-Bernoulli Freq., $f_o(V_P=0V)$	Eq. (1)	31.68	53.82	76.81	99.36	MHz
	23	Calculated Series Resistance, R_z	Eq. (19)	30.9	10.8	34.8	168.9	kΩ
	24	Adjusted/Extrapolated Gap, d	Eq. (19)	1,300	1,510	1,920	1,780	Å
	25	Resonator Stiffness, $k_r(y=L_r/2)$	Eq. (13)	27,423	57,926	57,390	81,965	N/m
	26	Resonator Mass, $m_r(y=L_r/2)$	Eq. (12)	7.40×10^{-13}	5.68×10^{-13}	2.85×10^{-13}	2.51×10^{-13}	kg
	27	Dimple-Down Voltage, V_d	Eq. (21)	9.2	25.3	57.4	98.2	V
	28	Catastrophic Pull-In Voltage, V_c	Eq. (11) = 1	232	521	1024	1262	V

RF MEMS resonators

10 MHz resonators with post-fabrication gap adjustment
(Galayko et al., 2002)



RF MEMS resonators

10 MHz resonators with post-fabrication gap adjustment
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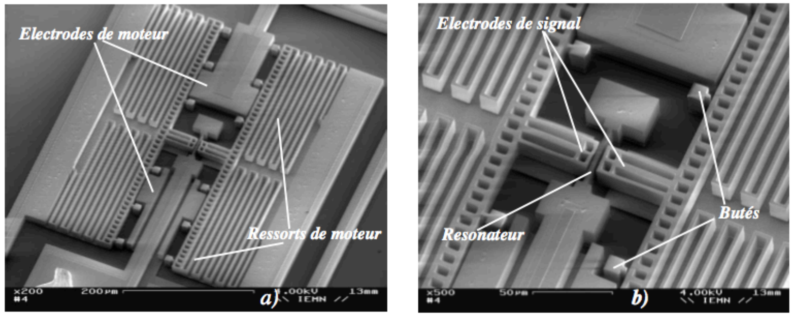

RF MEMS resonators

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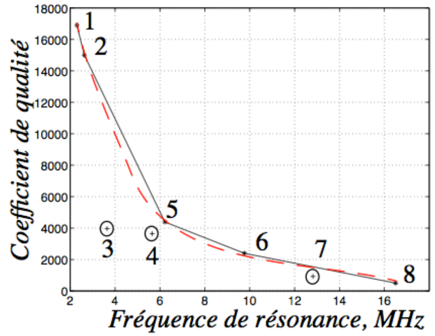


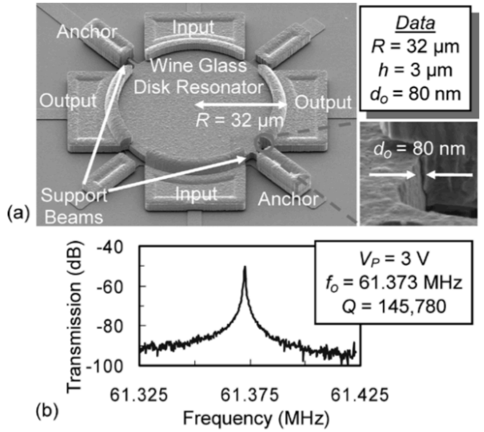
Dimensions :

W=1.8 µm,
L=25…100µm
h=15 µm

RF MEMS resonators

Very high frequency MEMS resonators: the volume / acoustic waves

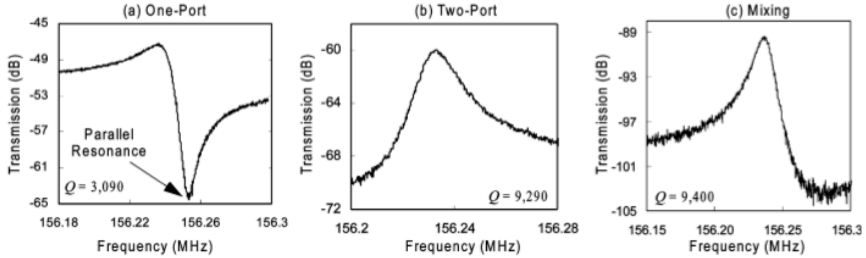
Y. W. Lin et al., 2004



RF MEMS resonators

Very high frequency MEMS resonators: the volume / acoustic waves

J. R. Clark et al., 2005 : performances

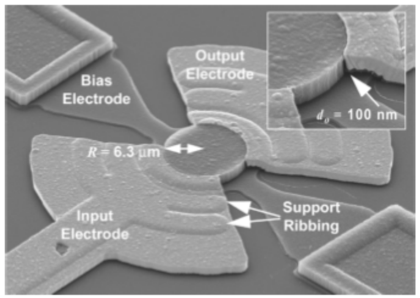


Design	One-Port Meas. [direct from (a) data]	Two-Port Meas. [direct from (b) data]	One-Port Extrapolated [ext. from 2-port data]
$R = 16.7\ \mu m$	$R_x = 22.287\ k\Omega$	$R_x = 99.9\ k\Omega$	$R_x = 24.975\ k\Omega$
$t = 2\ \mu m$	$L_x = 70.15\ mH$	$L_x = 945.4\ mH$	$L_x = 236.35\ mH$
$d_o = 100\ nm$	$C_x = 14.793\ aF$	$C_x = 1.098\ aF$	$C_x = 4.392\ aF$
$D_{stem} = 2\ \mu m$	$C_o = 57.78\ fF$		$C_o = 18.6\ fF$
$V_P = 35\ V$	$P = 50\ \mu T$	$P = 50\ \mu T$	$P = 50\ \mu T$
$f_o = 156.234\ MHz$			

RF MEMS resonators

Very high frequency MEMS resonators: the volume / acoustic waves

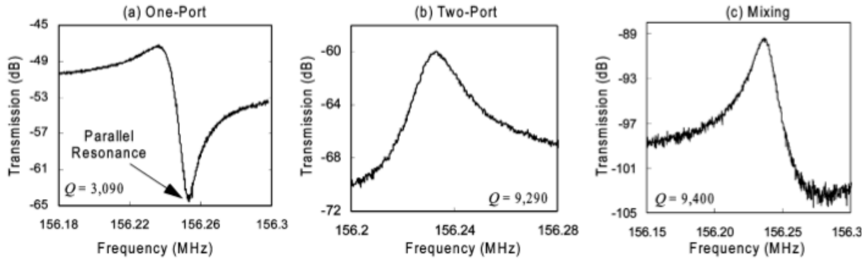
J. R. Clark et al., 2005



RF MEMS resonators

Very high frequency MEMS resonators: the volume / acoustic waves

J. R. Clark et al., 2005 : performances



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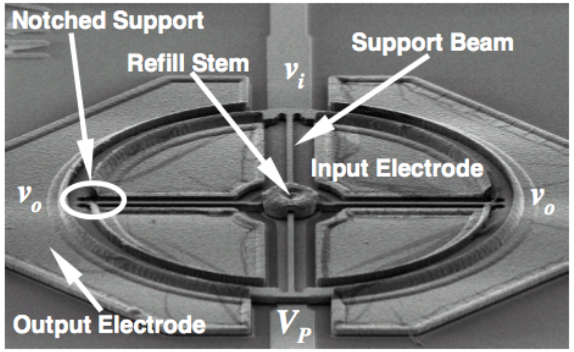
RF MEMS resonators

Very high frequency MEMS resonators: the volume / acoustic waves

S. S. Li et al., 2004 :



RF MEMS resonators

Very high frequency MEMS resonators: the volume / acoustic waves

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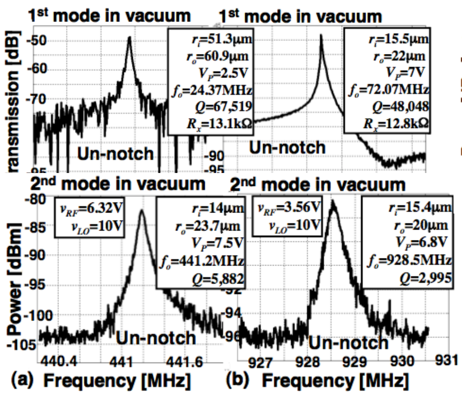
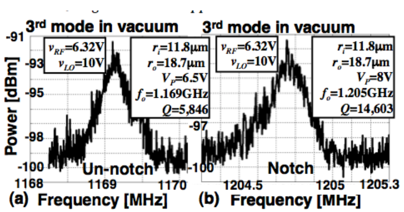
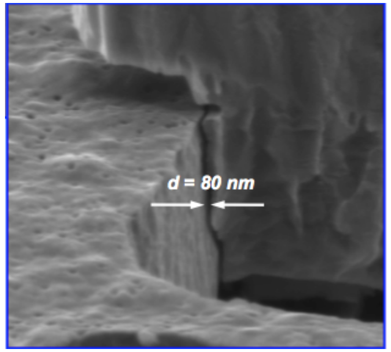




RF MEMS resonators

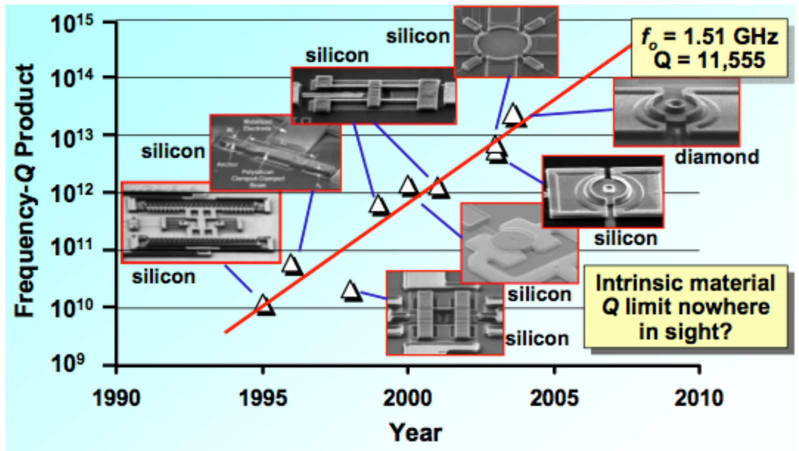
Importance of gap : the impedance at resonance is proportional to gap^4

Special gap reducing techniques are emploied



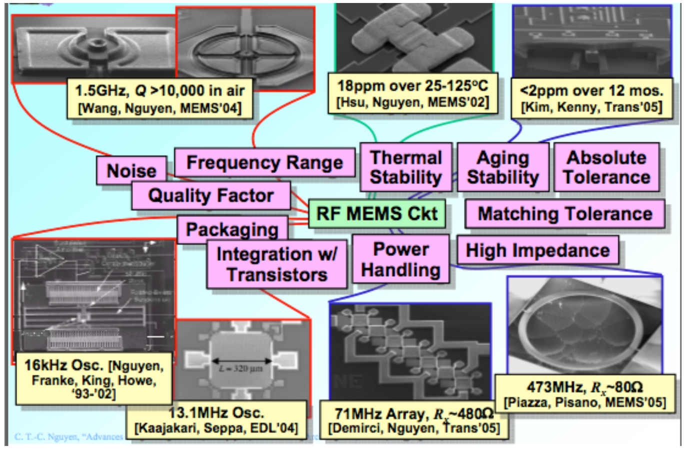
RF MEMS resonators

Summary of MEMS resonator evolution



RF MEMS resonators

Summary of MEMS resonator evolution



RF MEMS resonators

Association of MEMS resonators : high order analog MEMS filters

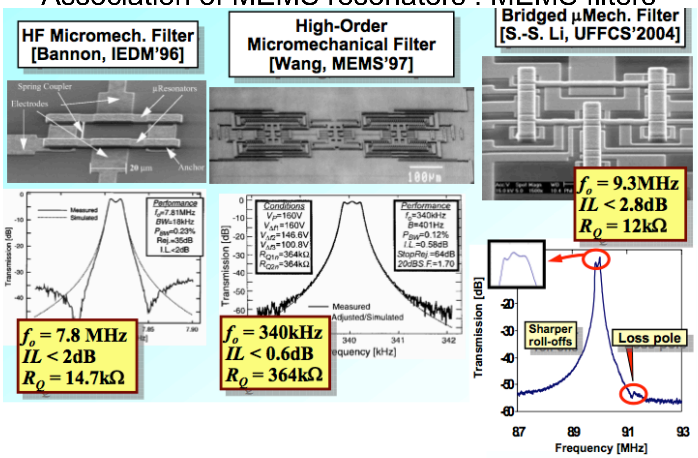
Poor drive power capability and high series resistance !

Low frequency

Can't compete with digital signal processing techniques (digital filters)

RF MEMS resonators

Association of MEMS resonators : MEMS filters



Another RF MEMS components

Micromachined passive elements : inductors, microstrips

Phase shifters

Variable capacitors

Litterature

- (RF Switches) Gabriel M. Rebeiz, RF MEMS: Theory Design and Technology, Wiley, 2003
- (MEMS resonators)J. T. M. van Beek et al., A review of MEMS oscillators for frequency reference and timing applications, Journal of Micromechanics and Microengineering, 2012, 22, 013001
- (Liquid RF switches) P. Sen et al., Mircoscale Liquid-Metal Switches - A Review, IEEE Transaction on Industrial Electronics, vol. 56, no. 4, april 2009
- (Mems resonators) Clark T.-C. Nguyen group publications : http://www.eecs.berkeley.edu/~ctnguyen
- (MEMS resonators) PhD dissertation of D. Galayko , 2002