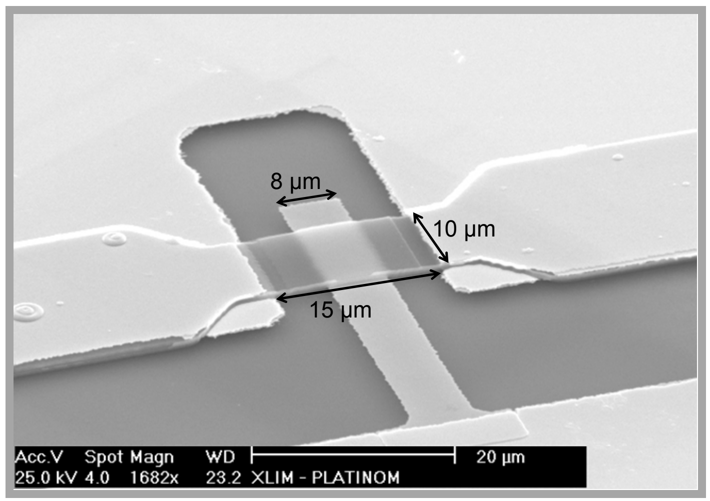
Miniature RF MEMS switched capacitors using nanogaps to achieve 50ns switching speed capabilities



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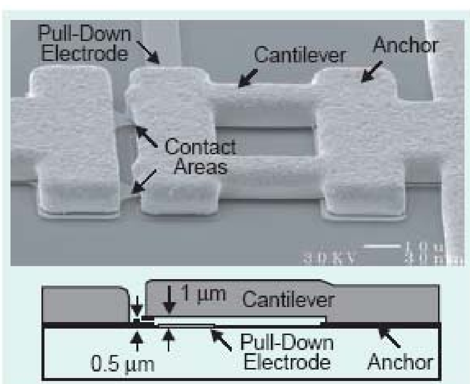
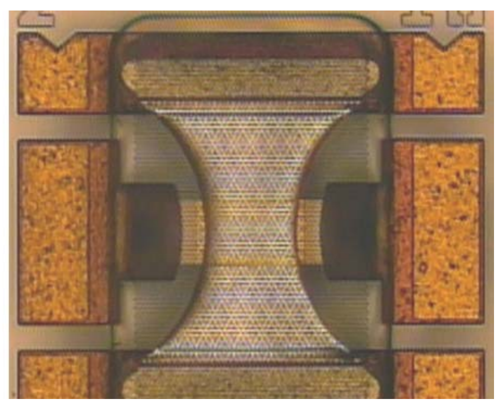
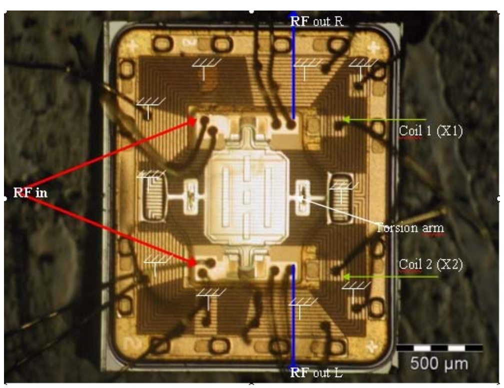
Motivation of this work

- RF MEMS capacitive switches are very promising for microwave communications
  - Low loss performance
  - Low power consumption
  - Superior linearity
- But switching speed are limited to few µs to few ms:
  - *Moving a mechanical element required some delay*
  - *Switching speed firstly relies on the actuator*
  - *Switching speed also relies on the design*

Radant MEMS	**Memtronic (Raytheon)**	**Magfusion**
		
Electrostatic Act: t_c= 3-5µs	**Electrostatic Act : t_c= 1-3µs**	**Magnetic Act: t_c= 0.2 -1ms**

- <u>Objective of this work</u>: Study new concepts to achieve switching time below 100 ns

Design rules

Type of Actuator

✓*Parallel plate vertical electrostatic actuator*

+
- Easy to implement : *Capacitive actuator can also be used as a RF tunable capacitor*
- Small power consumption (nW-µW): *Current flow only during moving period*
- **Relatively fast:** ***At least in the µs range***

-
- Quite high biasing voltage (tens of V): *Can be reduced using nanogaps actuators*
- **Actuator reliability issues :** ***Drift of actuation voltages as function of biasing & temperature***
- Sensitivity to RF signal power

Proposed mechanical design approach

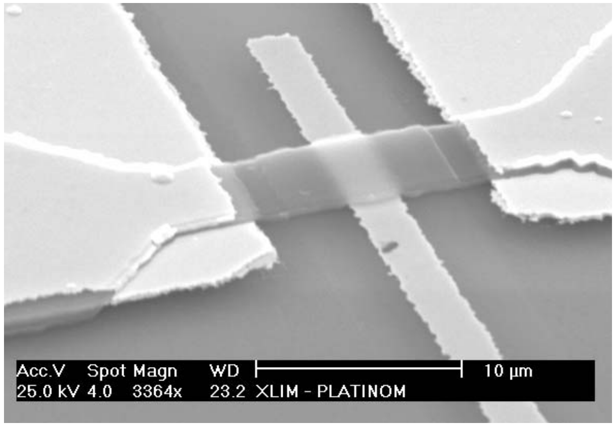
✓*Miniature beam:*

10 factor compared to conventional components

✓*Nanometrics air gaps:*

10 factor compared to conventional components

✓*Appropriated structural materials for beams*



How improve switching speed?

Switching speed for an electrostatic actuator

$$t_s \approx 3.67 \frac{V_{pull-in}}{2\pi V_{act} \; f_0}$$

Intrinsic Pull-in voltage

Mechanical resonance frequency (fundamental mode)

Applied biasing Voltage

Valid if Vact > 1.2Vp à 2Vp

Mechanical resonance frequency has to be high

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

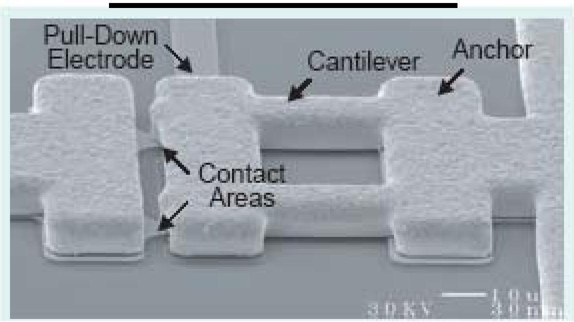
Beam spring constant

Moving structure mass

➡ ***Stiff and light movable beams***

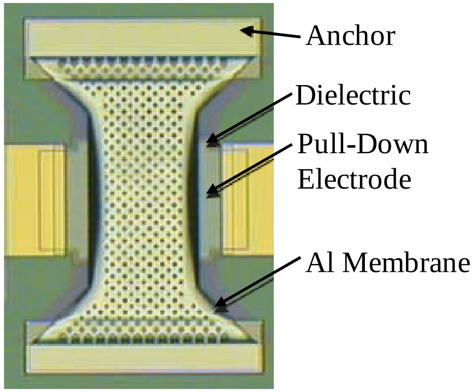
Some representative components

Radant MEMS



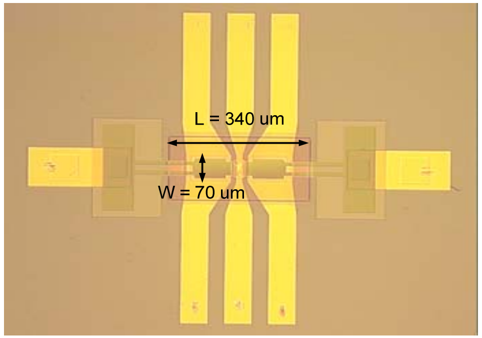
Thick gold alloy cantilever
- Spring constant: 100 N/m
- Mechanical resonant frequency :50-100 kHz
- Gap distance: 0.8-1.2µm
- Switching time : 3-5 µs

Raytheon



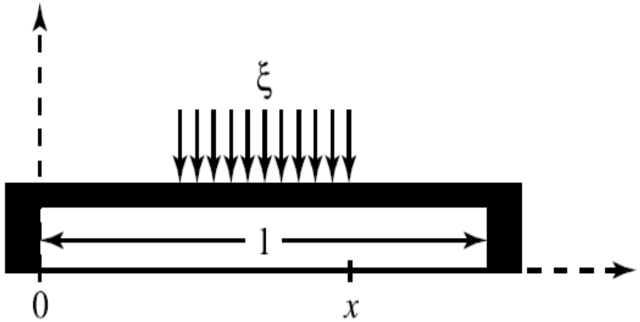
Tensile aluminum membrane
- Spring constant: 6 to 20 N/m
- Mechanical resonant frequency :70 –200kHz
- Gap distance: 2-5µm
- Switching time : 1-3 µs

CEA - LETI



Tensile silicon nitride membrane
- Mechanical resonant frequency :160 –400kHz
- Gap distance: 0.5-0.9µm
- Switching time : 0.5-1 µs

Mechanical design considerations



<u>Membrane design</u>: Fixed-fixed beam with a slight tensile stress

<u>Spring constant:</u>

$$\mathbf{k} = \underbrace{32Ew\left(\frac{t}{l}\right)^3 \frac{1}{8(x/l)^3 - 20(x/l)^2 + 14(x/l) - 1}}_{k_1} + \underbrace{8\sigma(1-\nu)w\left(\frac{t}{l}\right)\frac{1}{3 - 2(x/l)}}_{k_2}$$

Structural material properties (E, σ)

k_1 Geometry induced stiffness

k_2 Stress induced stiffness

As short the beam will be as high will be its stiffness

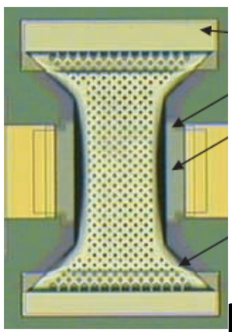
Why is it interesting to miniaturize?

Aluminum membrane (low density material) with σ = 10 Mpa stress

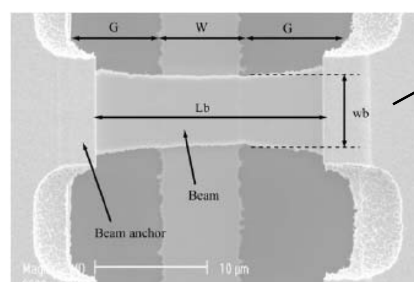
With w=10 µm, t=0,35µm except *

l (µm)	300*	100	80	60	2^3 40	2^3 20	2^3 10
k1 (N/m)	0,56	0,58	1,14	2,70	9,10	72,8	583
k2 (N/m)	5,24	1,22	1,53	2,04	2 3,06	2 6,1	2 12,2

***Raytheon (w=100µm, t=0,5µm)**



l (µm)	300*	100	80	60	40	20	10
t_s (ns)	3 800	1040	770	500	250	70	18



- **l = 20 µm**
- **w = 8 µm**

V_p = 25-35 V
T_s = 200 ns

D. Mercier, et al, "Miniature RF MEMS switched capacitors," IEEE MTT-S IMS , vol. 3, pp. 1931–1934, June 2005

Choice of appropriated structural material

The structural material can also be influent

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

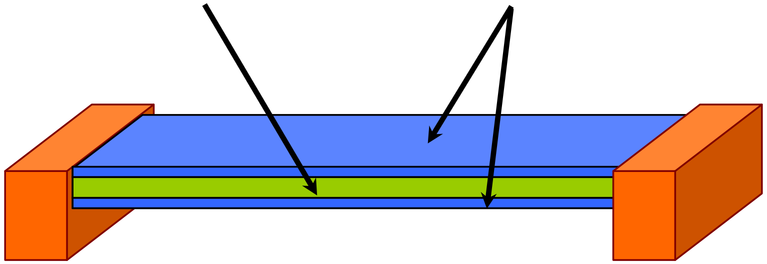
Beam spring constant(E, ν)

Beam Mass (ρ)

Materials properties:

$(2.6)^2$ $(\sim 2)^2$

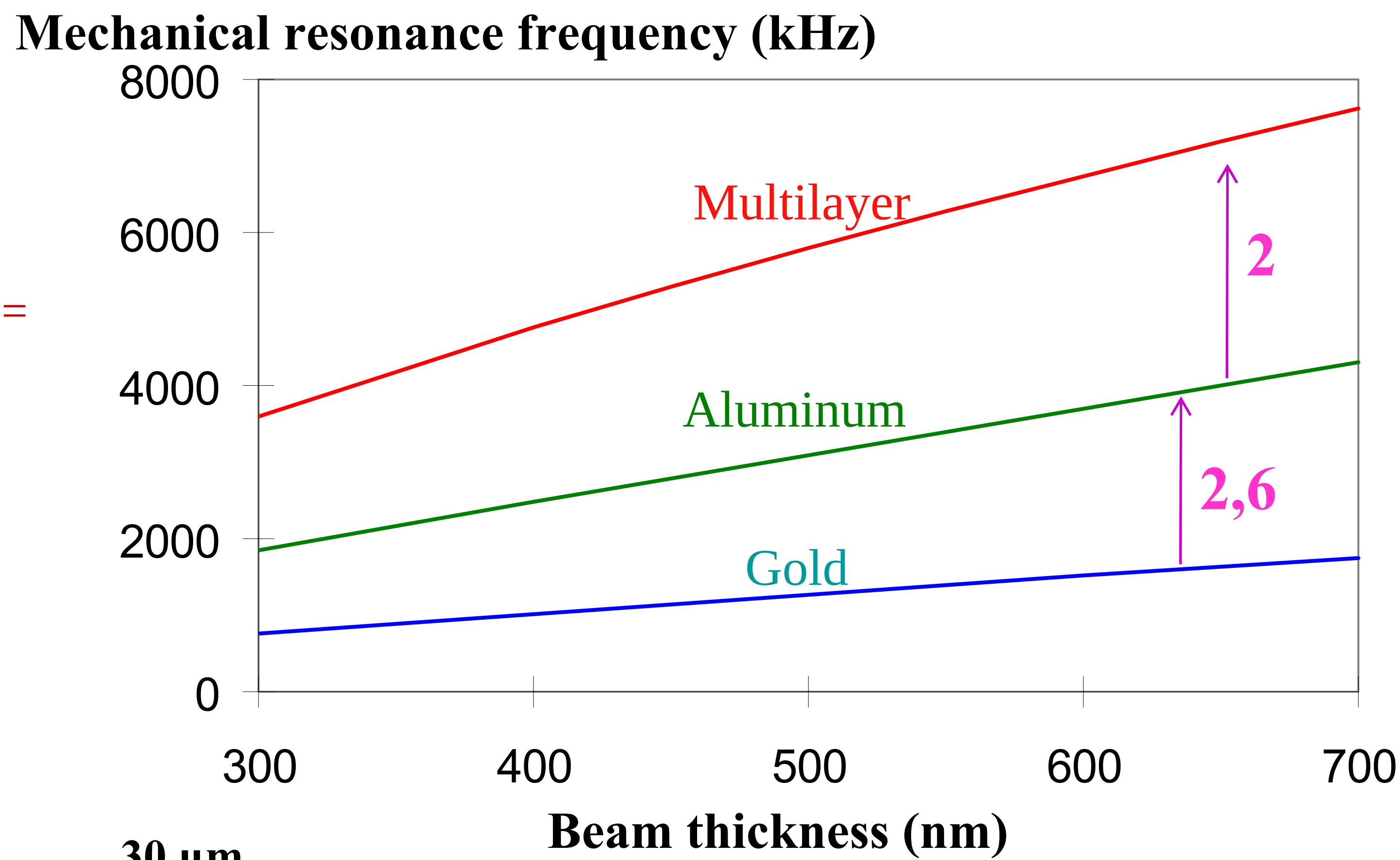
	Gold	Aluminum	Alumina
Young's modulus (GPa)	78	70	<u>380</u>
Poisson's ratio	0.42	0.345	0.25
Density (g/cm^3)	19.3	<u>2.7</u>	<u>3.9</u>

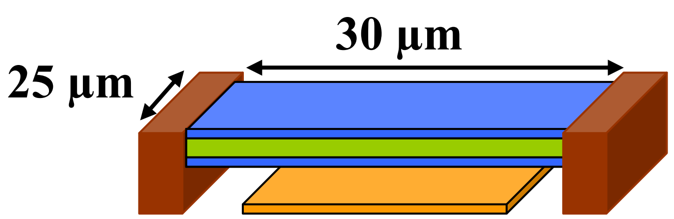


Slight and stiff materials can be combined to form the beam

Impact on the mechanical resonance frequency

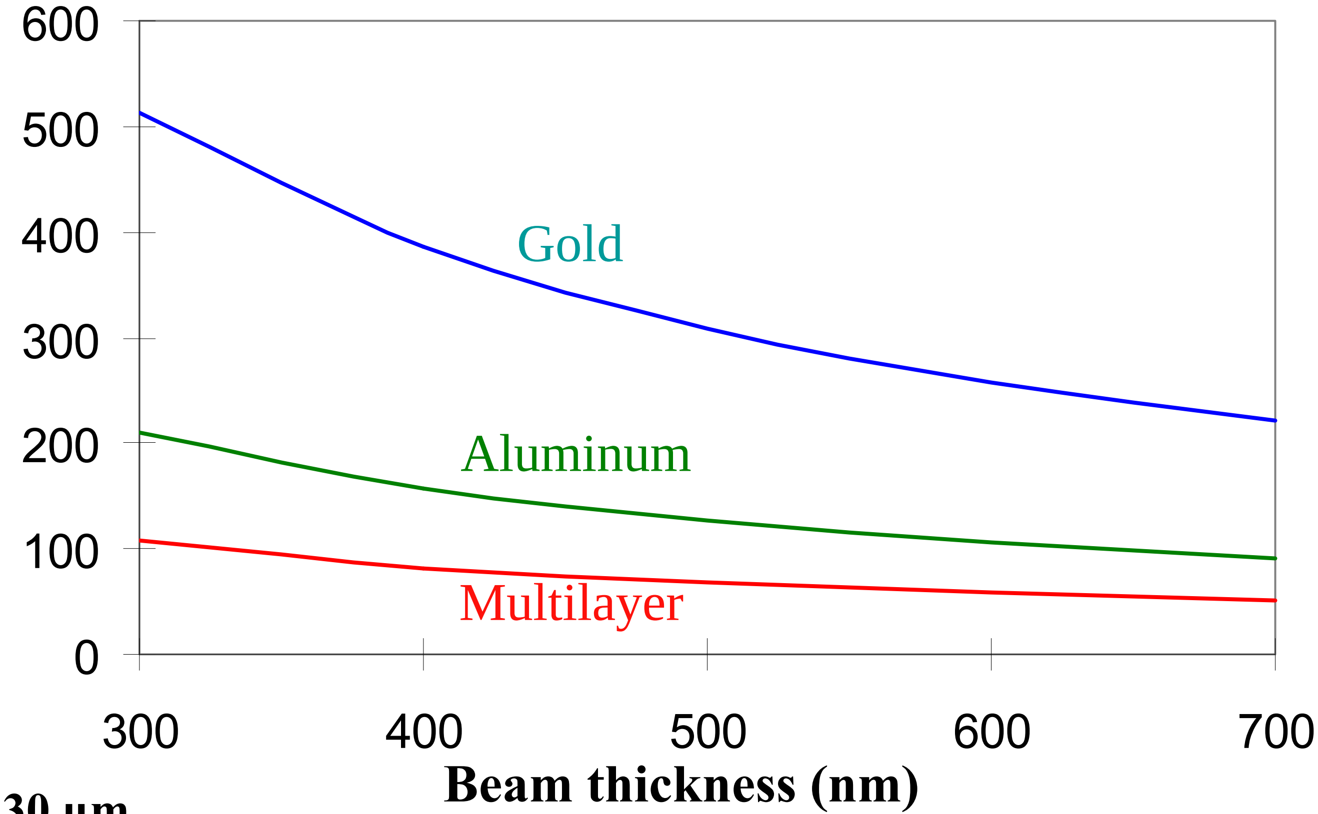
Multilayer beam =
Al_2O_3 (100 nm)
Al (x nm)
Al_2O_3 (100 nm)



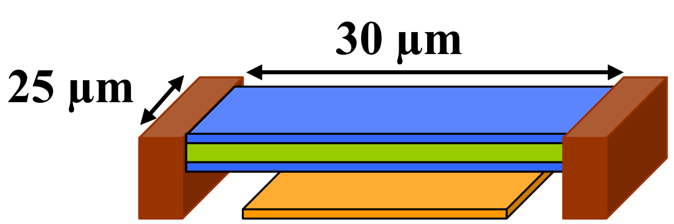


Impact on the switching time

Switching time (ns) @ 1.5 Vp



Multilayer beam =
Al_2O_3 (100 nm)
Al (x nm)
Al_2O_3 (100 nm)

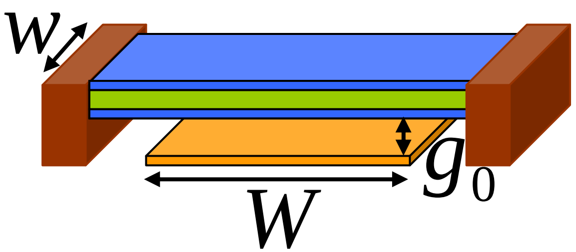


Master required actuation voltages

$$V_{pull-in} = \sqrt{\frac{8k}{27\varepsilon_0 W w} g_0^{\,3}}$$

Spring constant

Initial gap

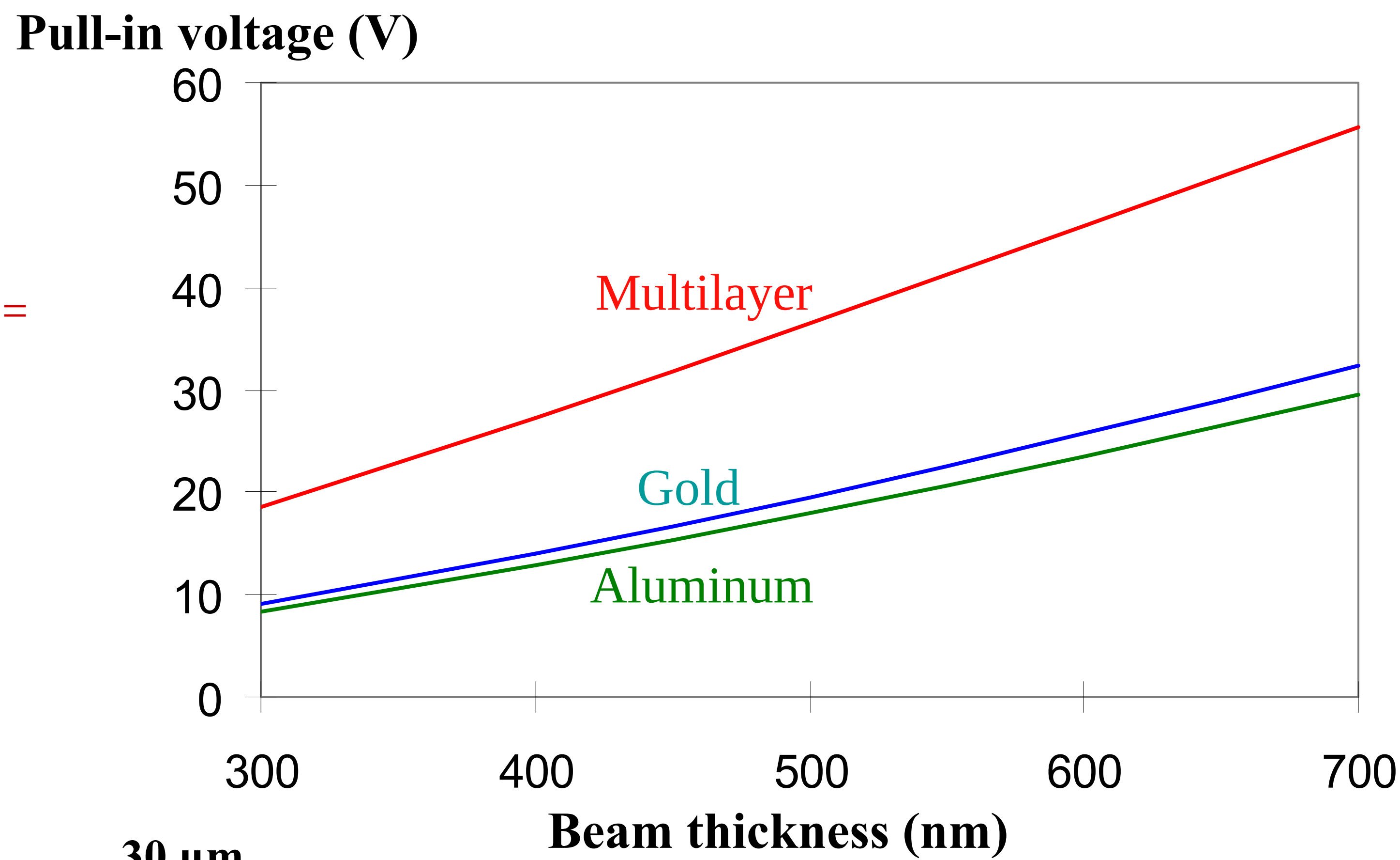


High stiffness ➔ pull-in voltage increases

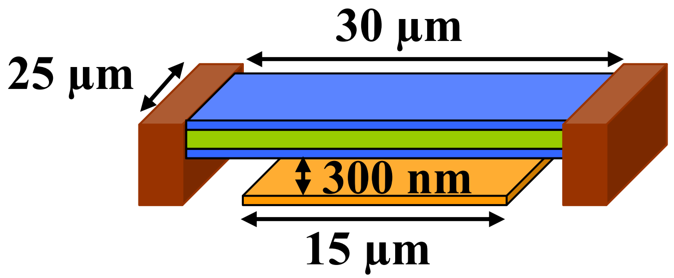
Compensated by ↘ the gap (≈ few 100 nm)

Due to membrane miniaturisation, air gaps must also to be reduced

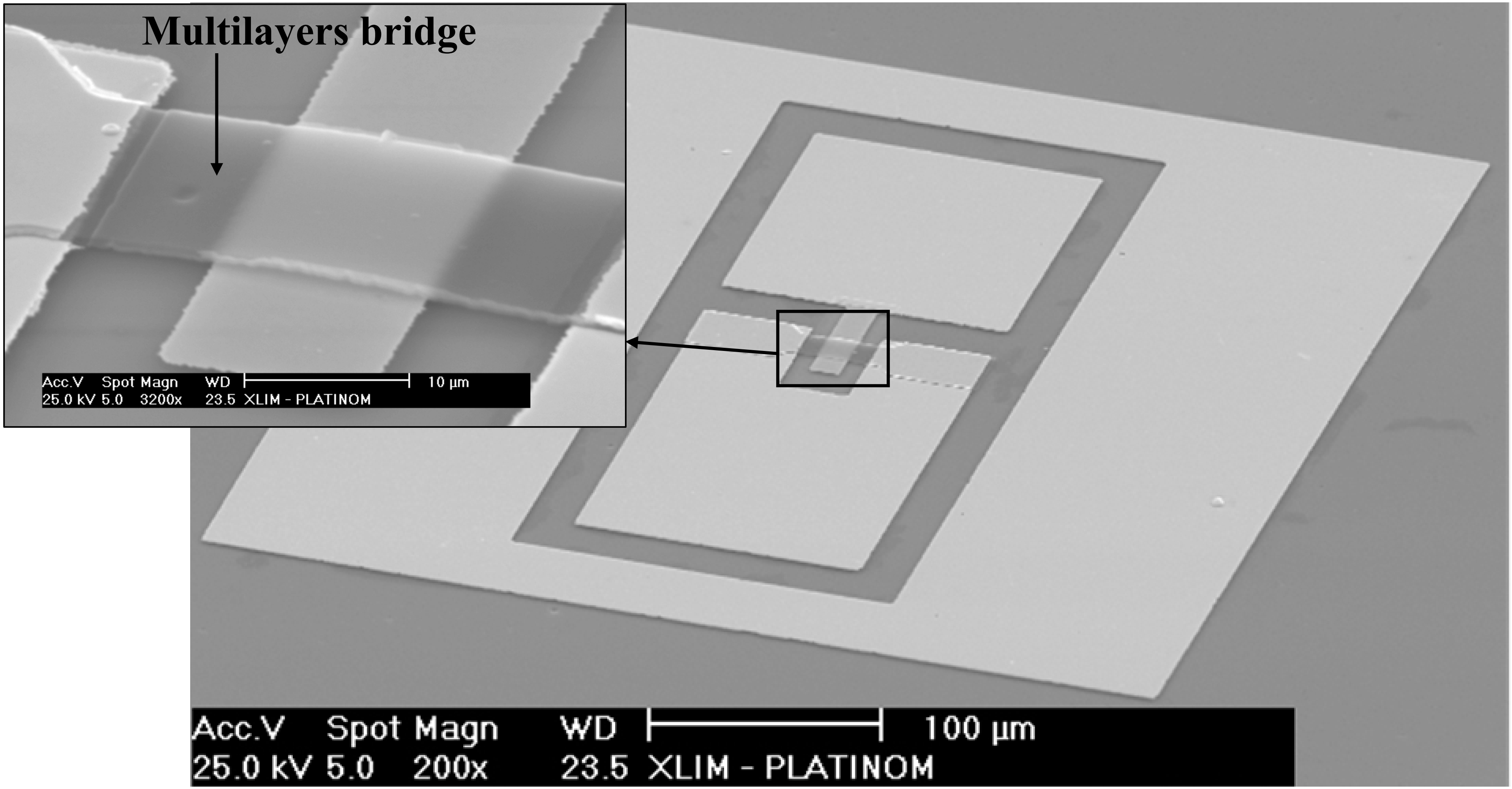
Simulated pull-in voltages



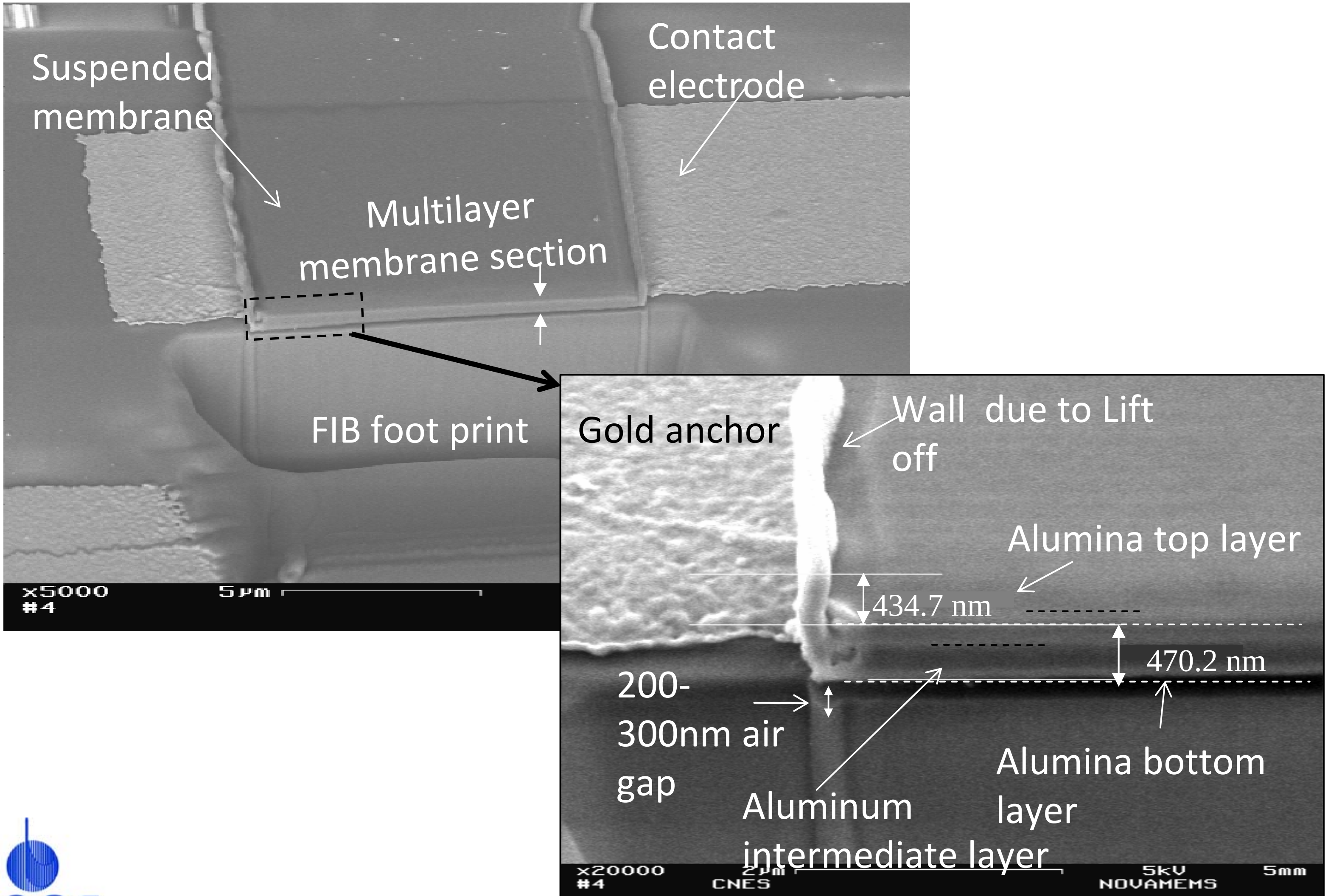
Multilayer beam =
Al_2O_3 (100 nm)
Al (x nm)
Al_2O_3 (100 nm)



Fabricated devices

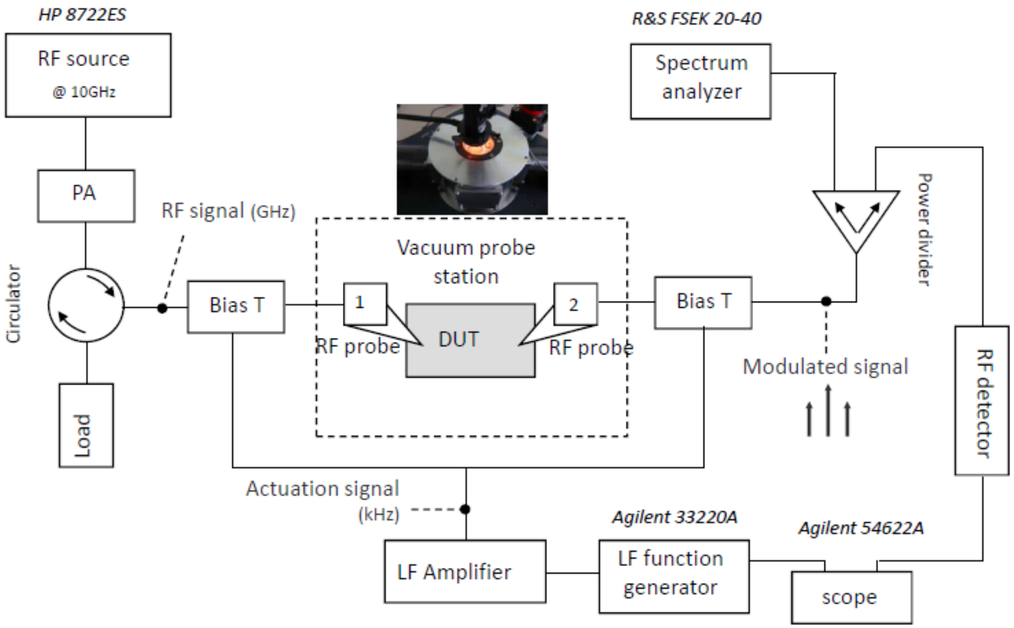


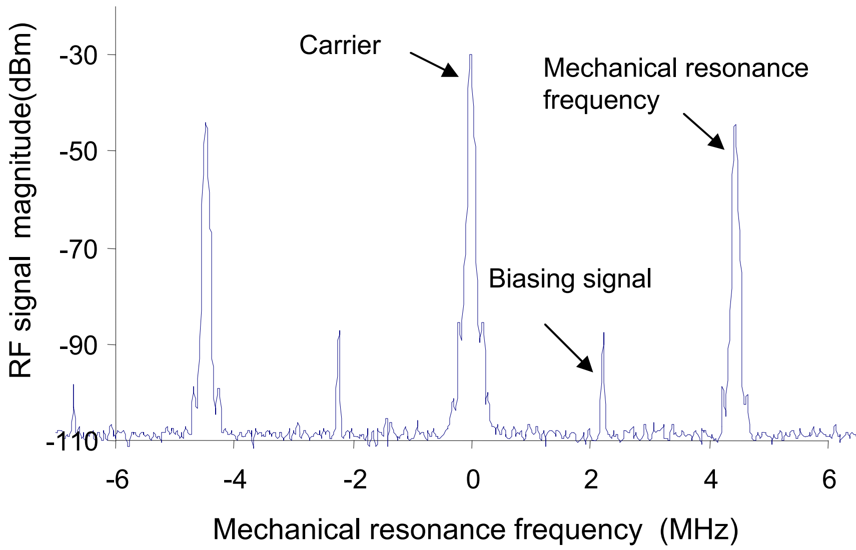
Fabricated devices



Mechanical resonance frequency measurement

Modulation detection on RF signal due to MEMS beam motion



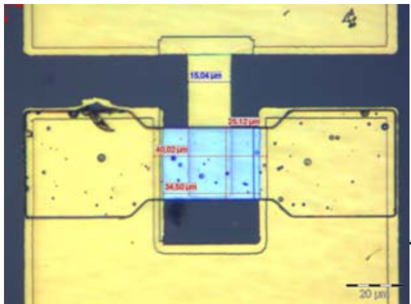


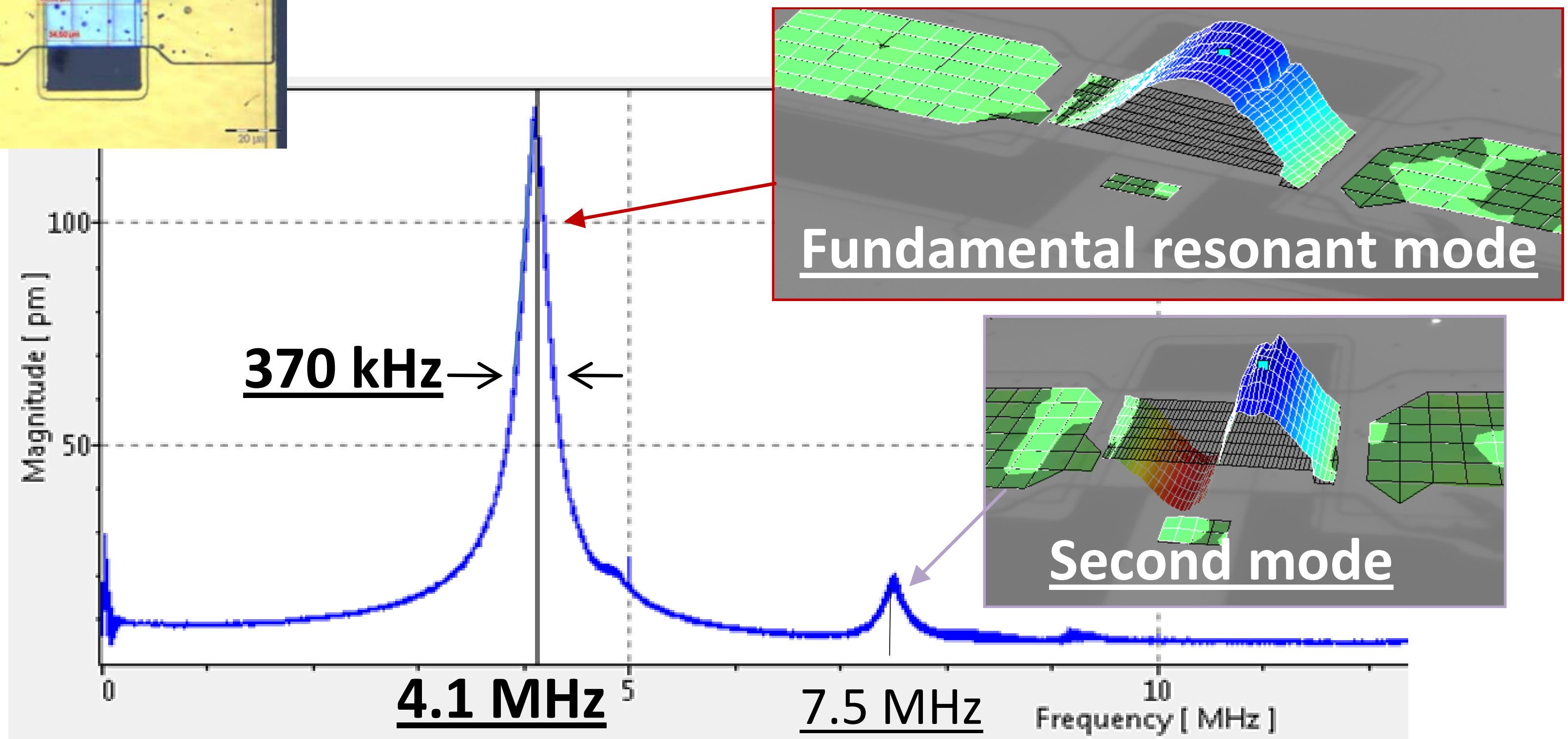
Beam lenght (µm)	f_0 mesured (MHz)	f_0 predicted (MHz)
35	3,2 – 4	3,5
30	4,2 – 5,6	4,8
25	5,1 – 7,2	6,5
20	9,2 – 11,5	10,5

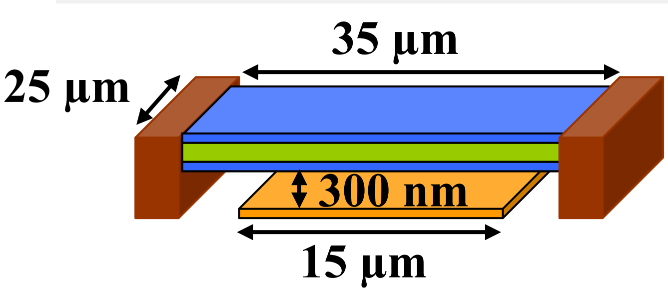
Measurements in good agreement

Mechanical resonance frequency measurement

Laser Doppler vibrometry measurement

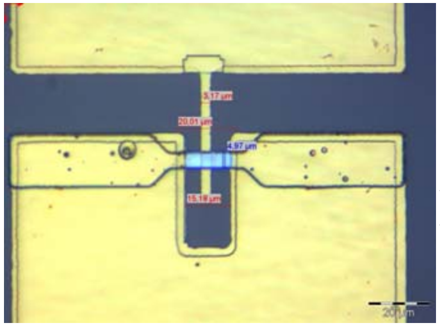




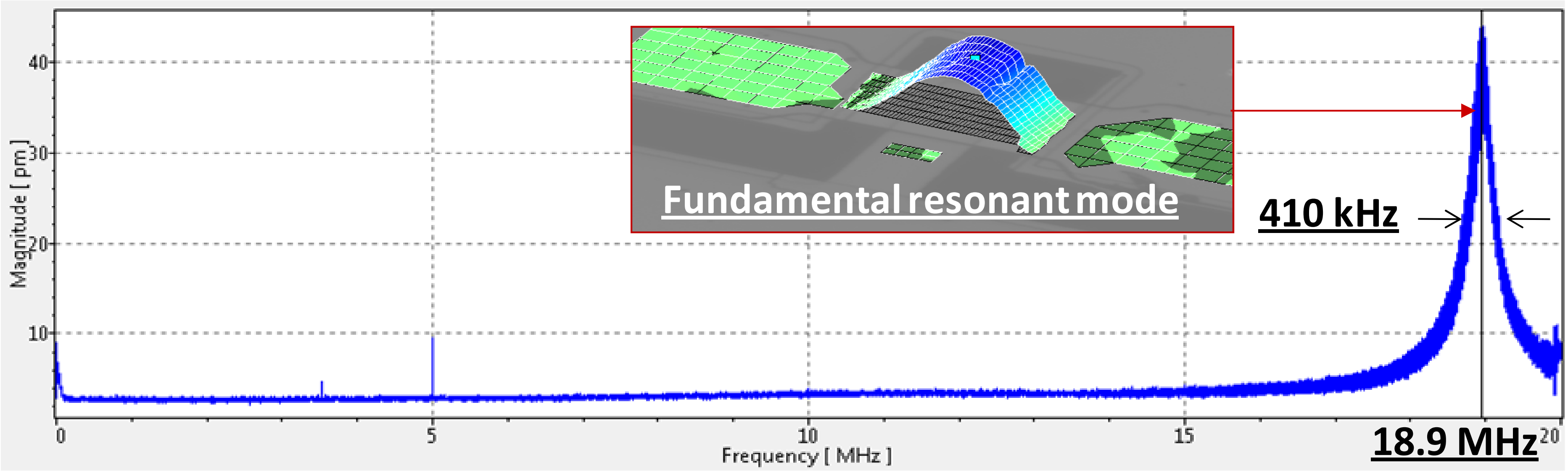


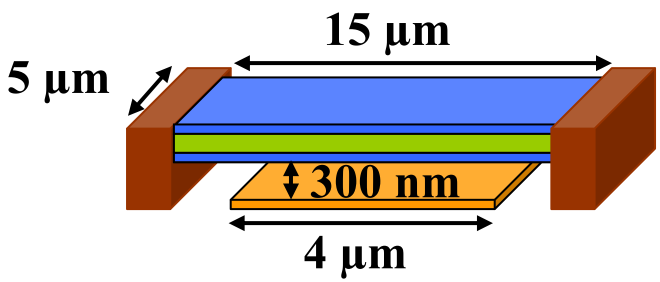
simulated $f_0 = 3.5$ MHz

Mechanical resonance frequency measurement



Length decreases → High mechanical resonance frequency

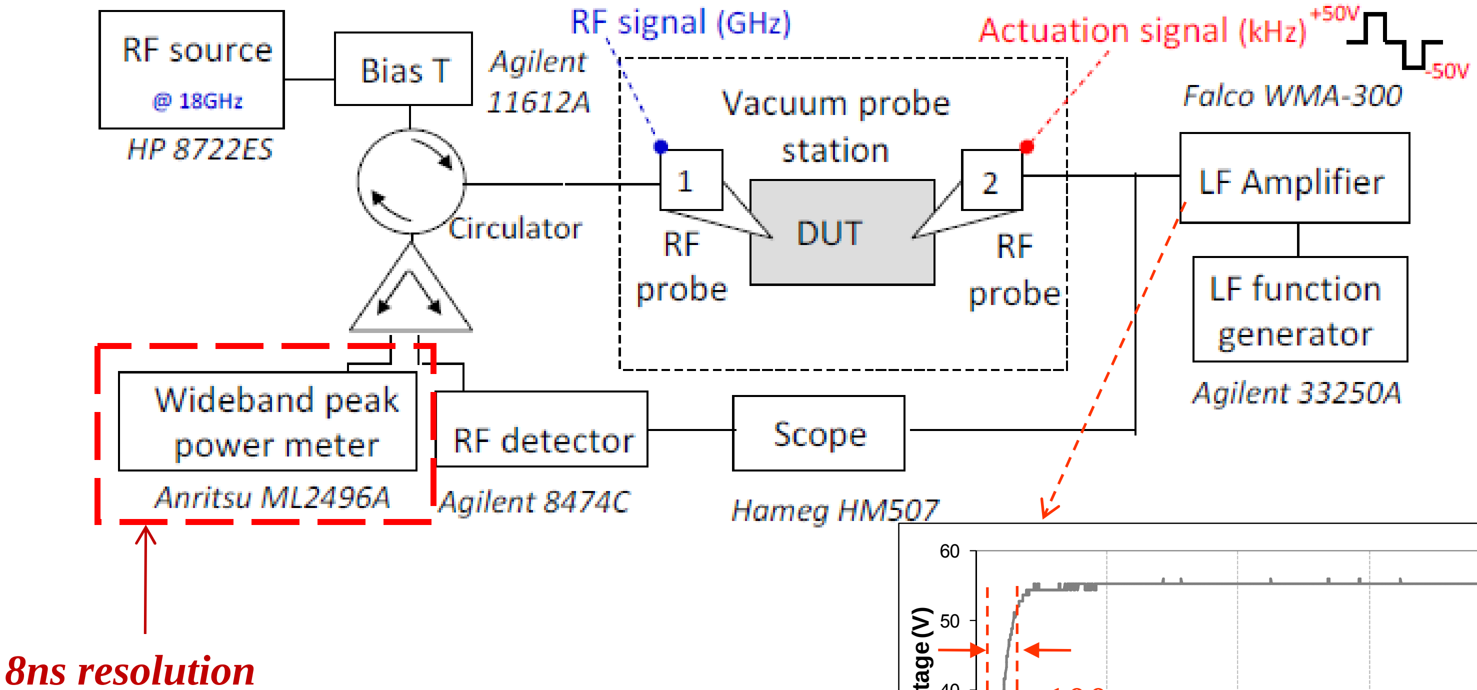


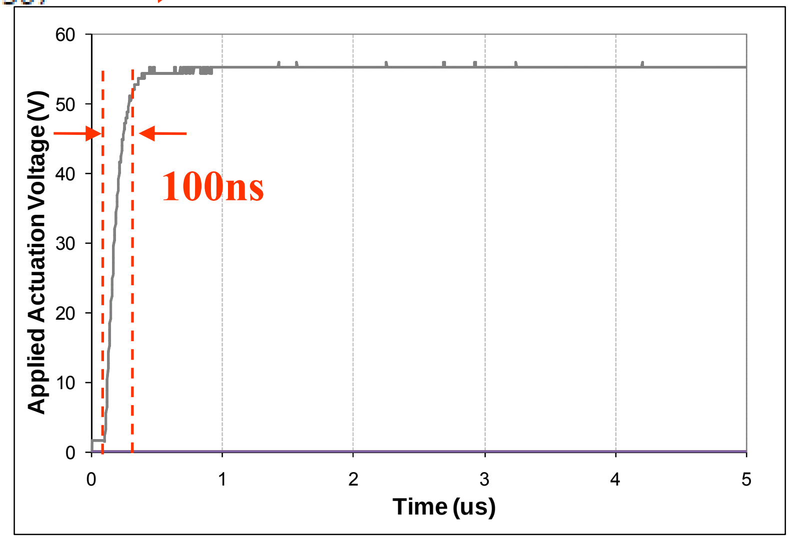


simulated f_0 = 18.7 MHz

Switching speed test bench

RF signal amplitude modulation when MEMS component is actuated





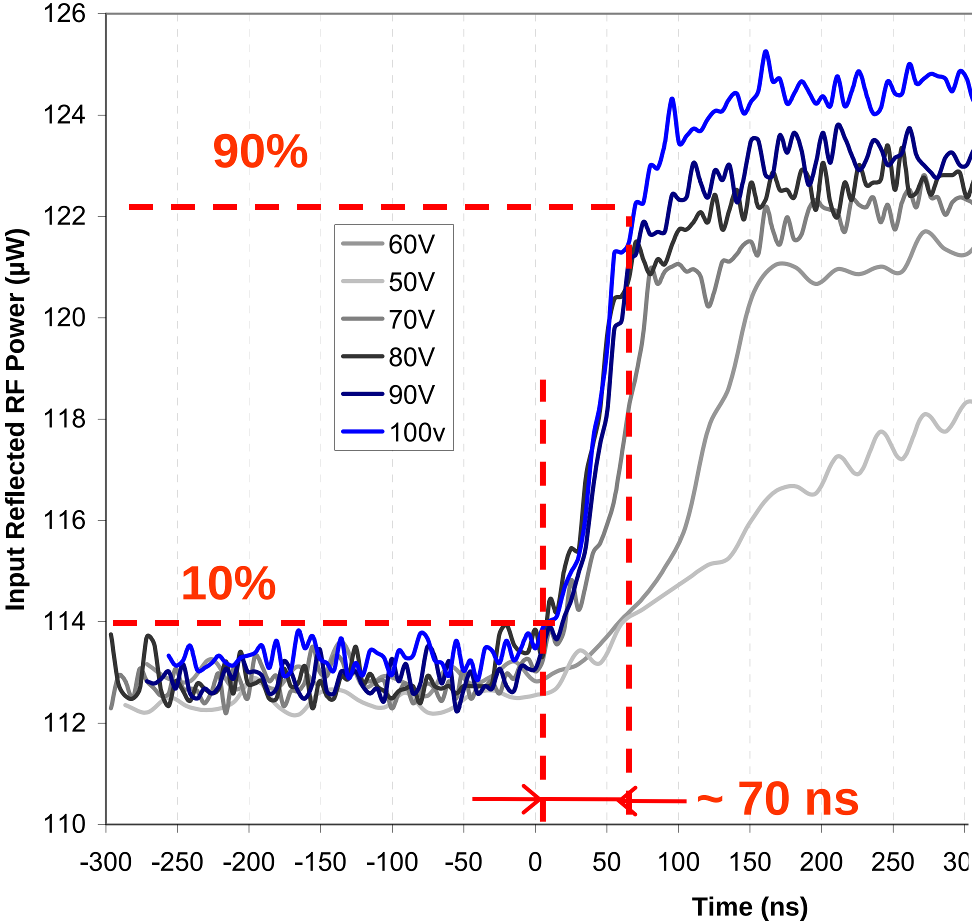
* @ 1.2xV_p

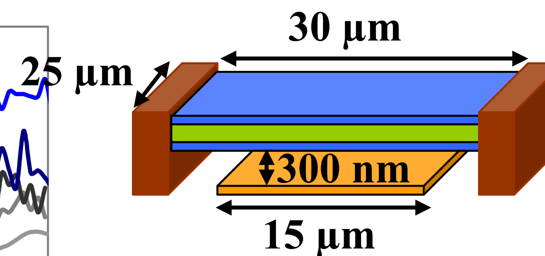
Switching speed measurement

Beam length (µm)	Mechanical resonance frequency (MHz)	Measured pull-in voltage (V)	Computed switching time (ns) @ 1.5xV_p	Measured switching time (ns) @ 1.5xV_p
15	**18. 9**	76	26 *	**40** *
20	**10.5**	54	44	**65**
25	**6.5**	30	72	**75**
30	**4.7**	40	99	**110**
35	**3.5**	42	111	**130**

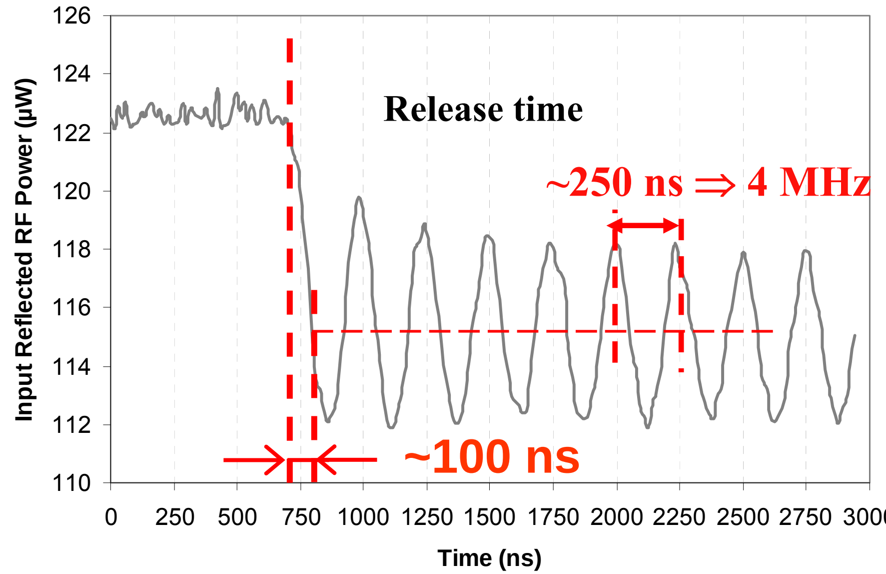
*** @ 1.2xV_p**

Switching time vs biasing voltage (1)





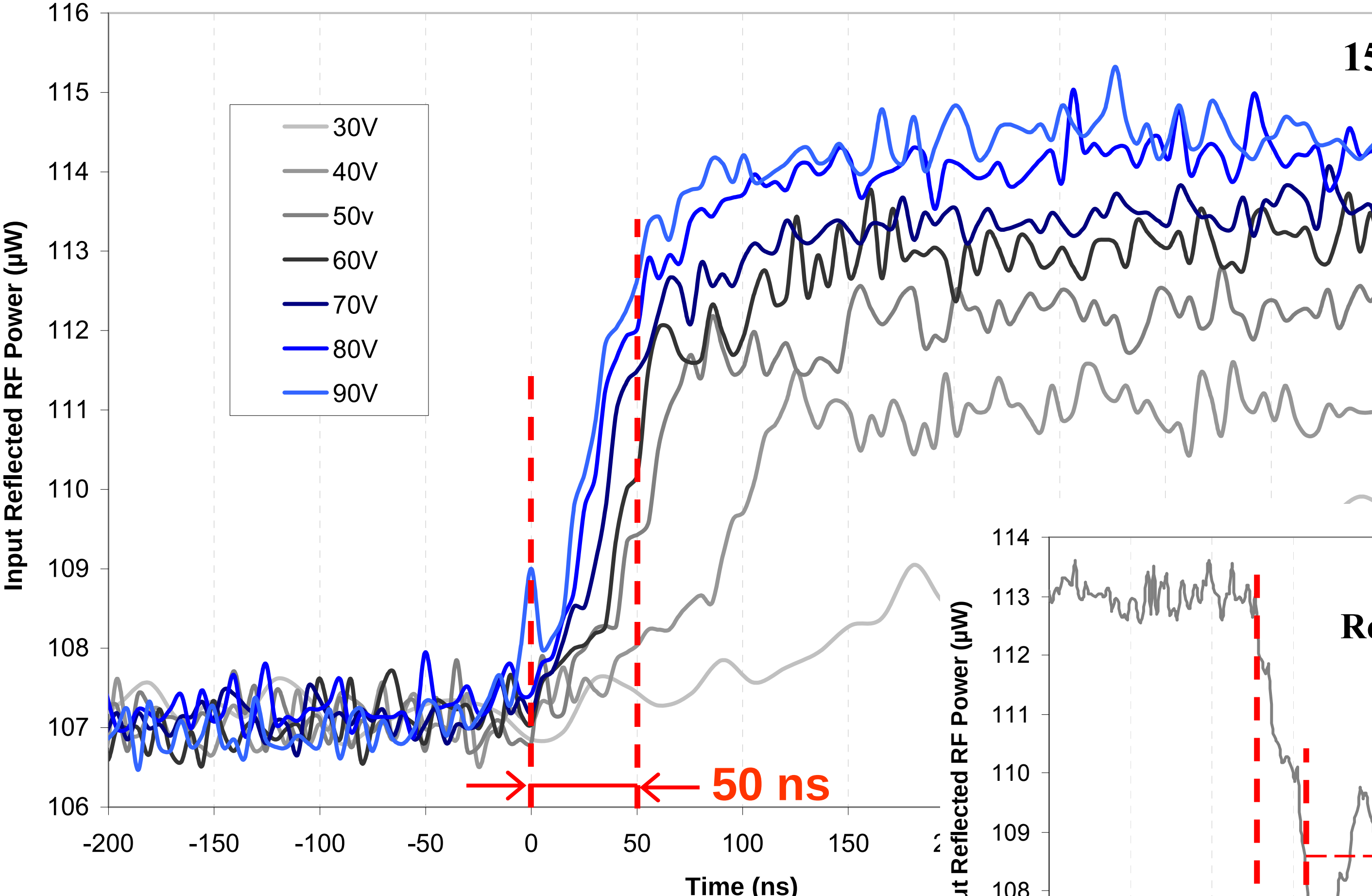
Predicted switching time @ 2Vp : **75 ns**

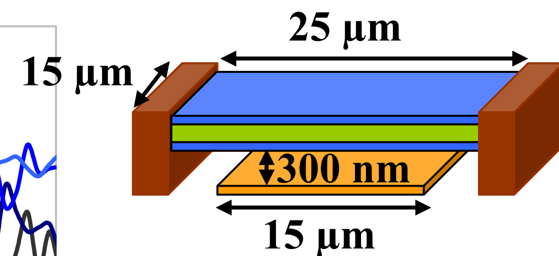


Vacuum measurement conditions

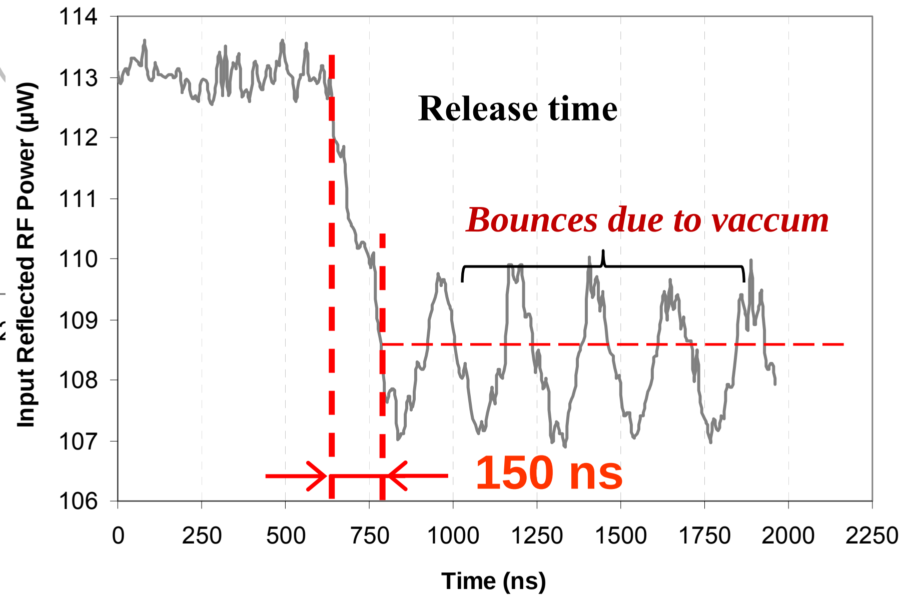
Measurements in good agreement

Switching time vs biasing voltage (2)



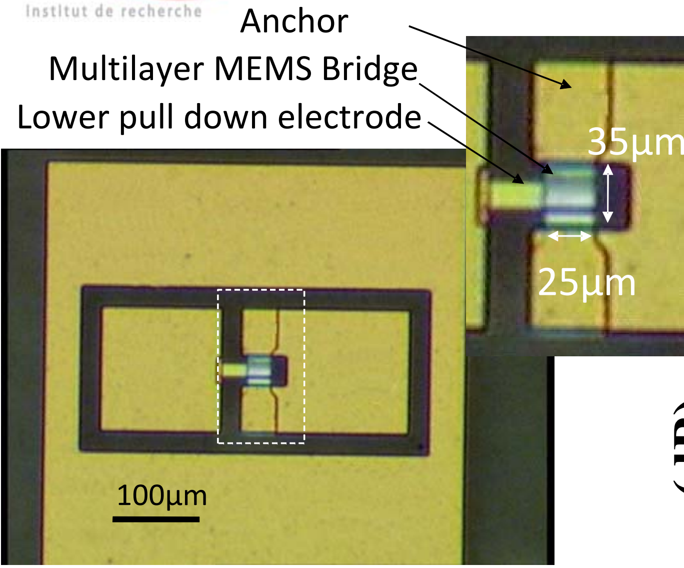


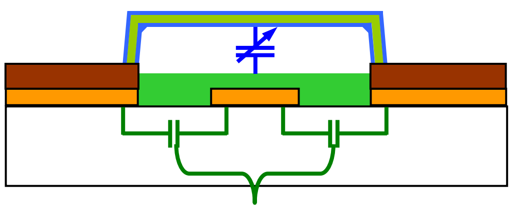
Predicted switching time @ 2Vp : **54 ns**



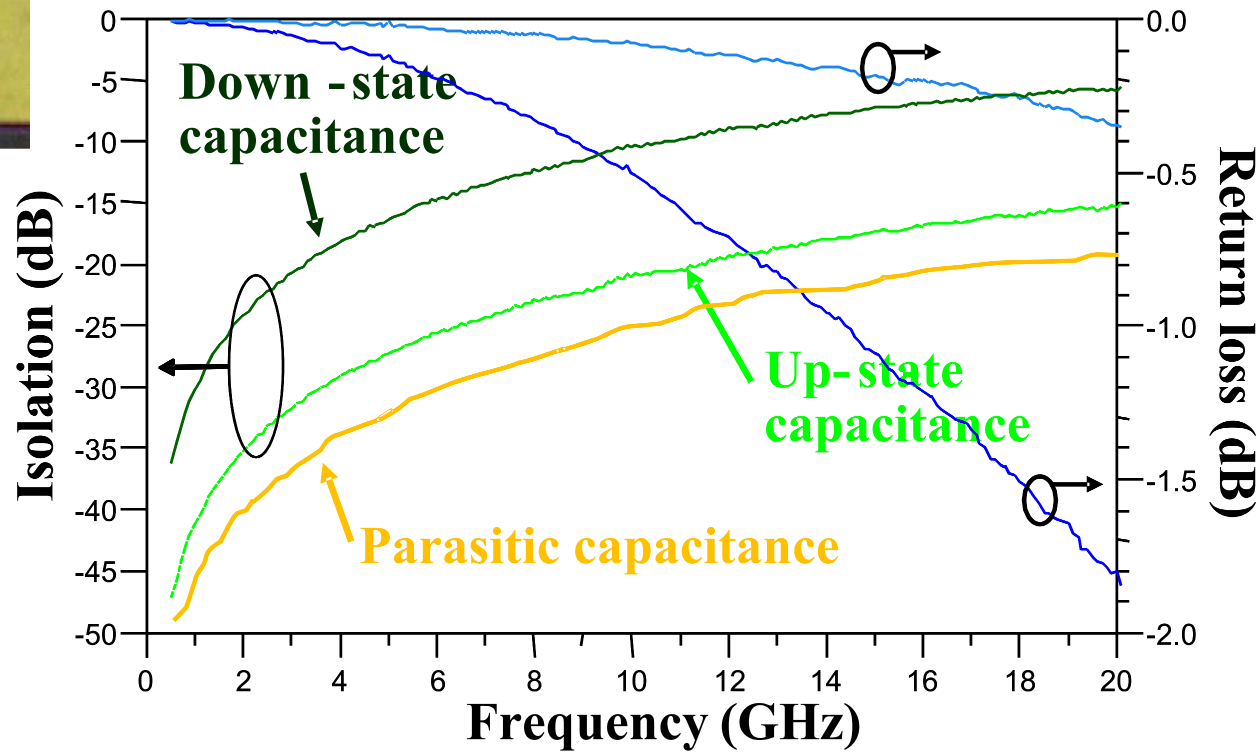
Vacuum measurement conditions

Switched capacitor RF performance





$C_{parasitic} = 7$ fF
$C_{up} = 19$ fF
$C_{down} = 110$ fF



Impedance ratio $C_{down} / C_{up} = 5.8$

Reliability potential superior capabilities

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Intrinsic beam release pressure:

$P_r = F_r / S$ (S: contact surface on lower electrode)

with $F_r = k\,(g0-g)$ ~~$+ ks\,(g0-g)3$~~ $\approx k.g0$

(g0: initial gap, g steady state gap and ks torque constant $k_s = \frac{\pi^4 E w t}{8 l^3}$

(1) w=l/2, welectrode = l/2 g_0=1µm, t=0,35 µm except*

l (µm)	300*	100	80	60	40	20	10
F_r (µN) (1)	6,4	9,0	10,7	14,2	24,3	78,9	297,4
P_r (kPa)	2,3*/0,3(2)	3,6	6,7	15,8	60,8	790	11 900

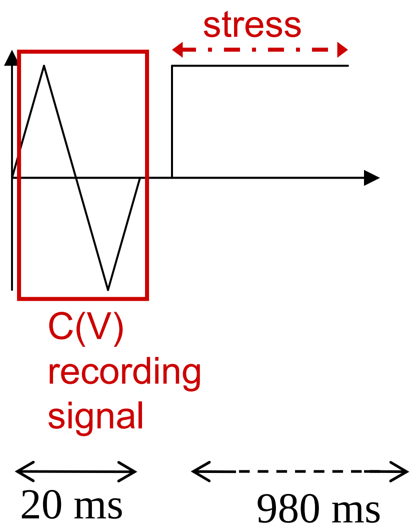
*Raytheon (g_0=4µm, w=100µm, t=0,5µm)

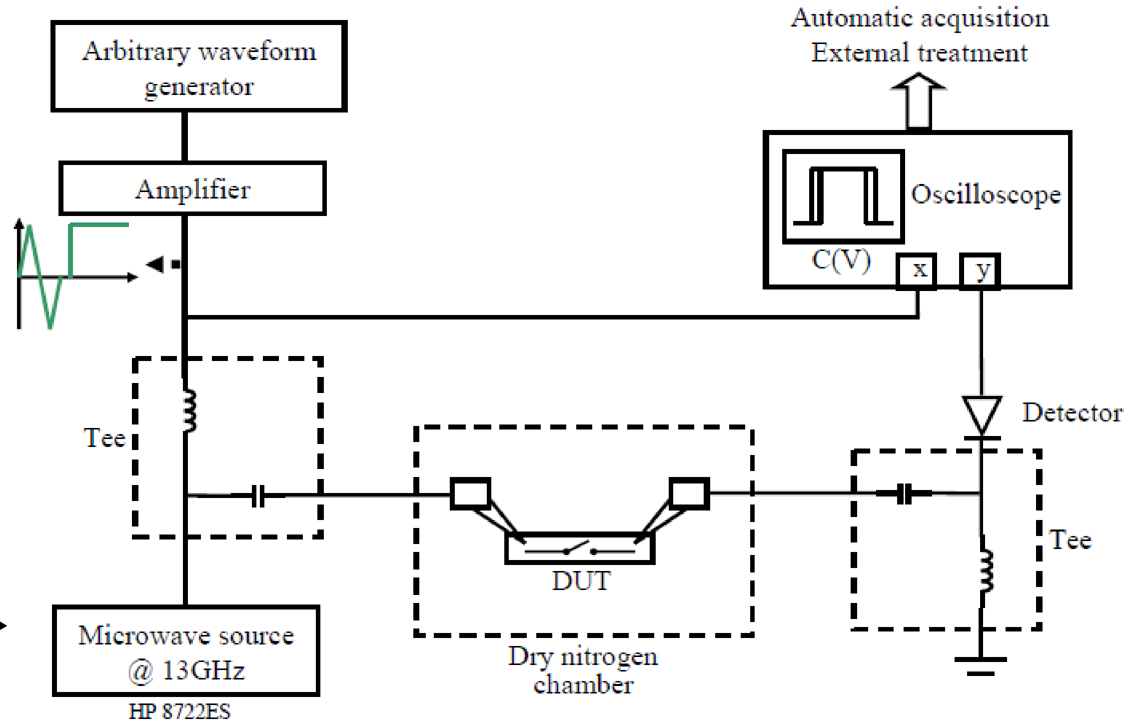
Miniature design will be less sensible to dielectric charging issues in the electrostatic actuator

Reliability tests and used test bench

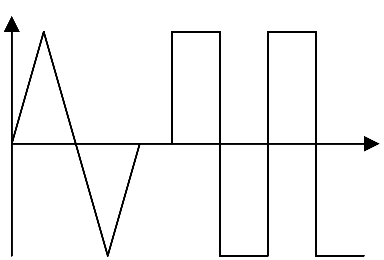
Applied biasing stress:

Monopolar stress





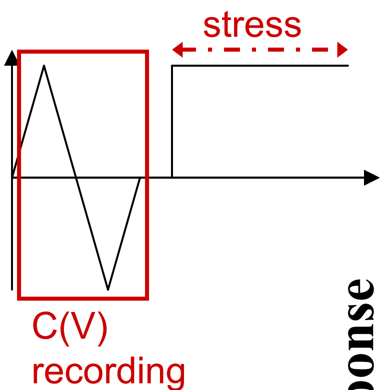
Bipolar (10Hz) stress

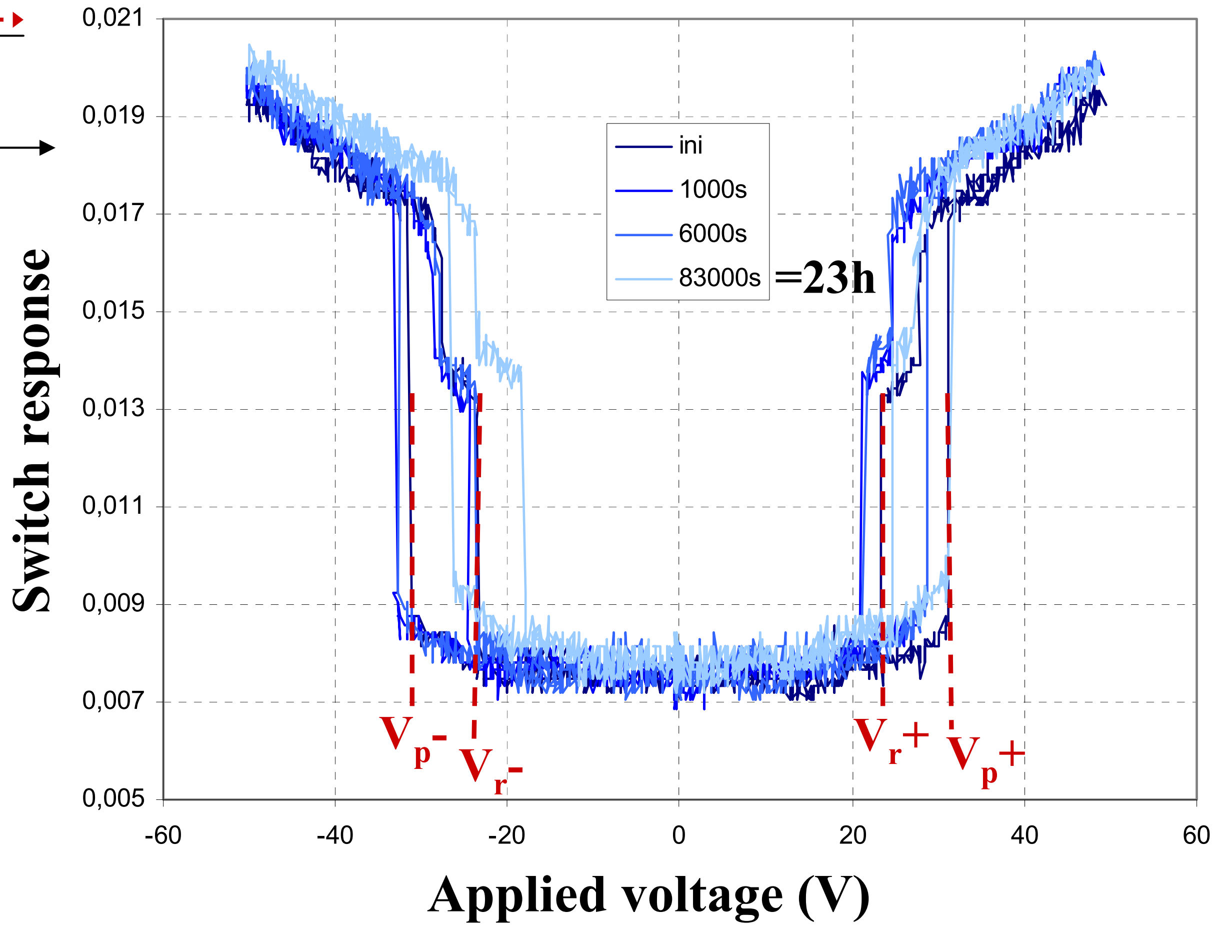


Continuous applied stress with periodic C(V) recording (every second):

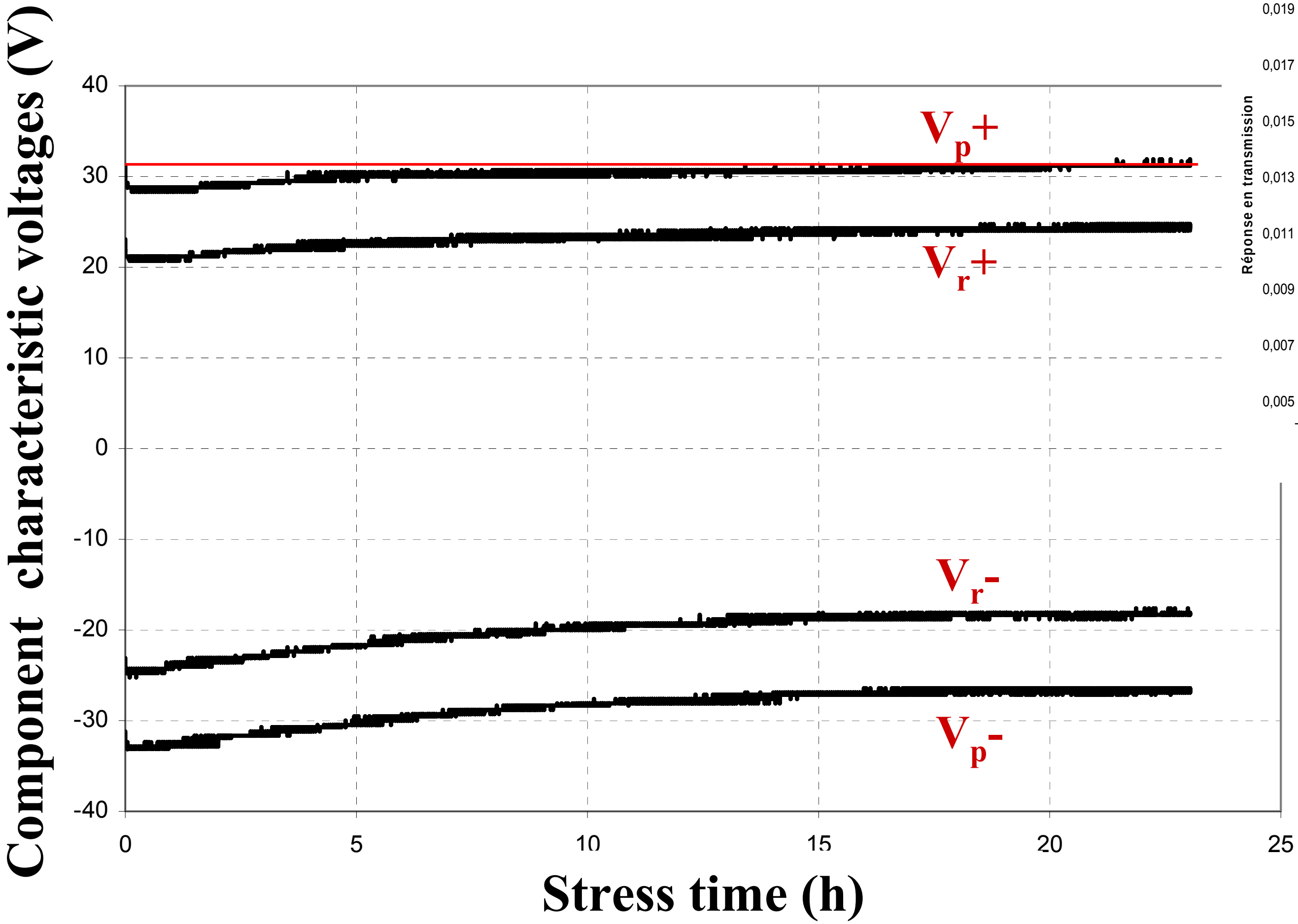
MEMS components are 98% of the time actuated down

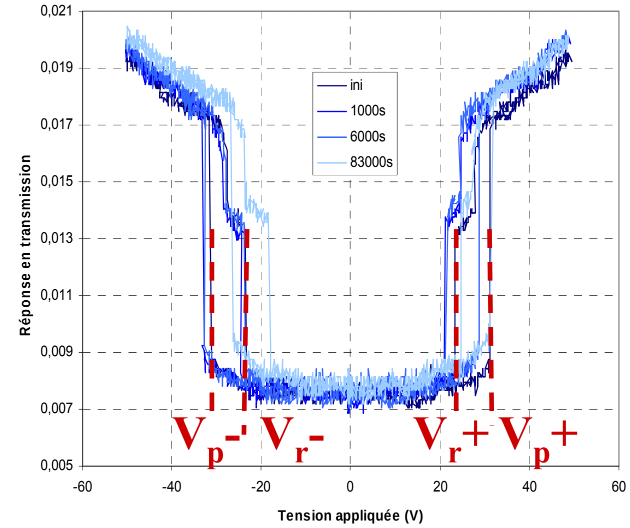
Monopolar stress effect:





Reliability performance (2)

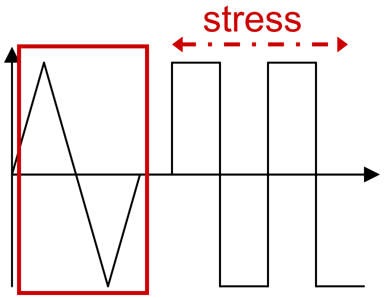


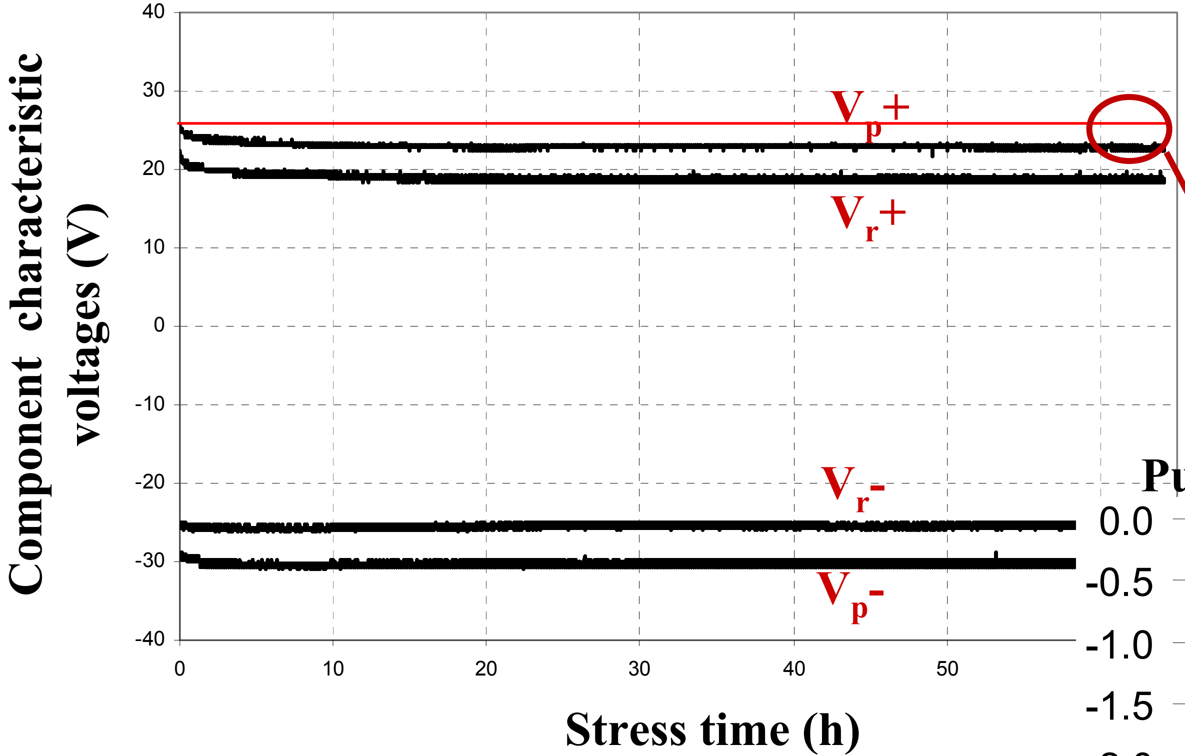


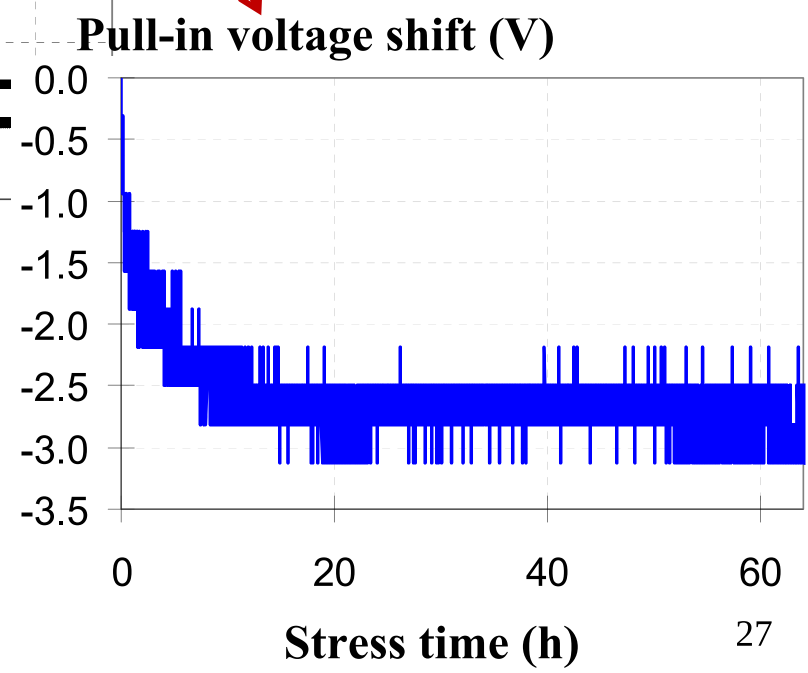
Very small recorded drift :4.5V after 23hours let down

Reliability performance (3)

Bipolar stress effect:







Recorded drift of 3V

after 60hours let down

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Conclusion and Prospects

	Raytheon	Miniature multilayer MEMS
Length	270 - 350 µm	15 - 35 µm
Width	50 - 200 µm	5 - 25 µm
Thickness	0.5 µm	0.4 µm
Gap	3 - 5 µm	0.3 µm
Mechanical resonance frequency	55 - 150 kHz	3500 - 18000 kHz
Switching time	3 - 5 µs	50 -100ns
Capacitance ratio	100	5-6

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