Introduction to MEMS

[Slides taken and/or adapted from
- a seminar by dr. Cristina Bertoni
- a presentation given to the GE annual meeting
- slides by dr. Valeria Toffoli]

MEMS: micro electro-mechanical systems

• Silicon integrated circuit industry is able to produce devices in volume with **very high yield** at **low cost**

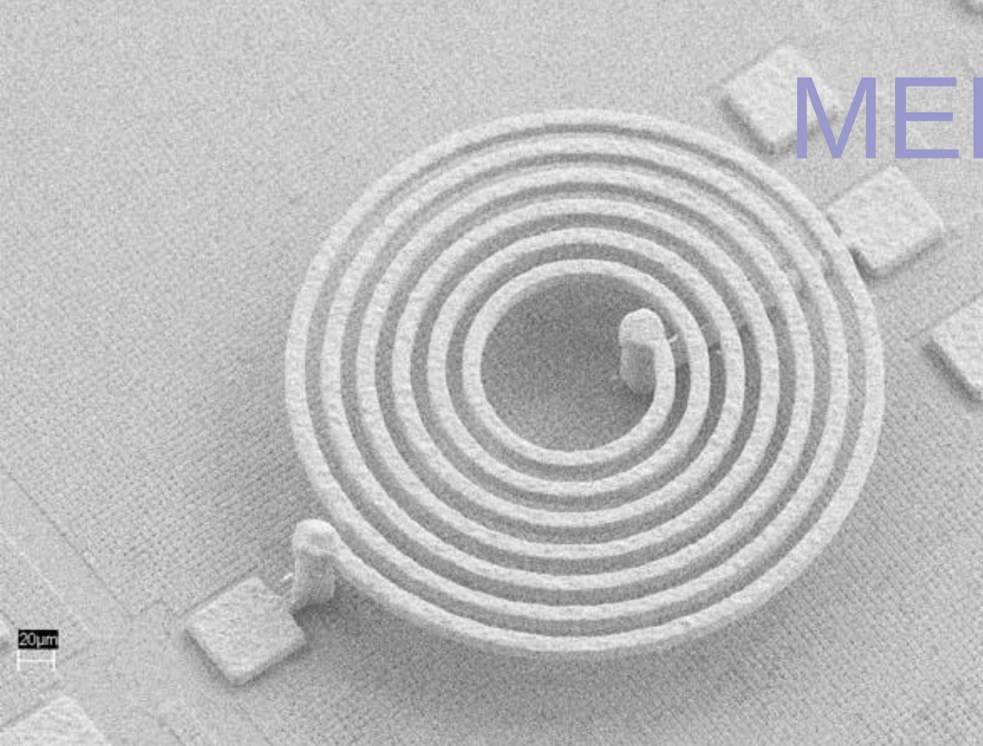
• Silicon has driven the semiconductor industry and allowed for progressive **reduction in size** for more than 3 decades

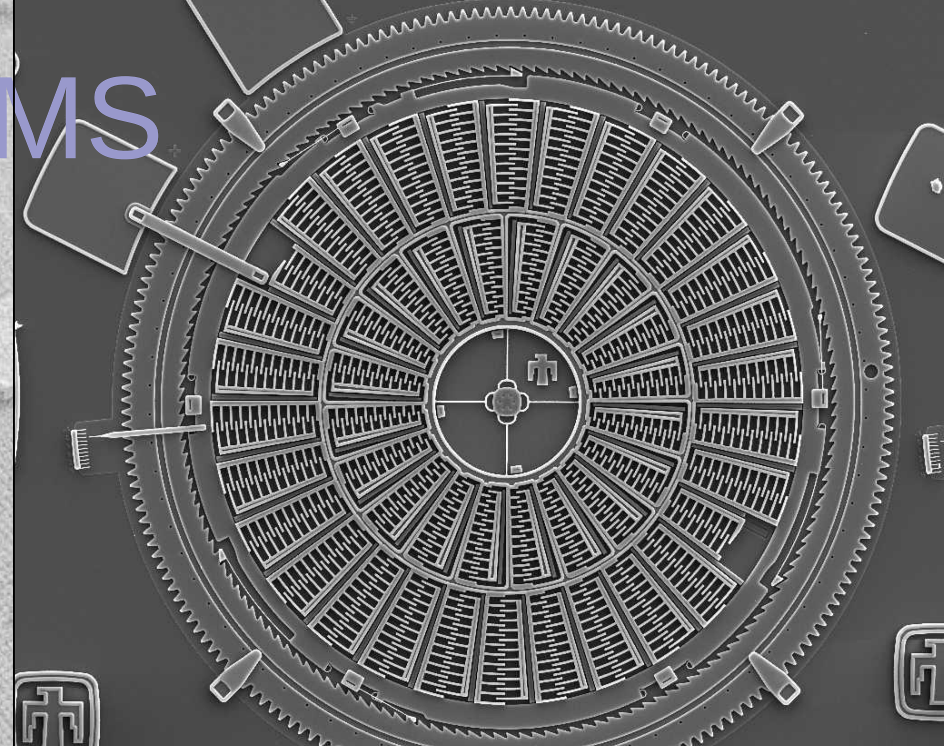
In **<u>MEMS</u>**:

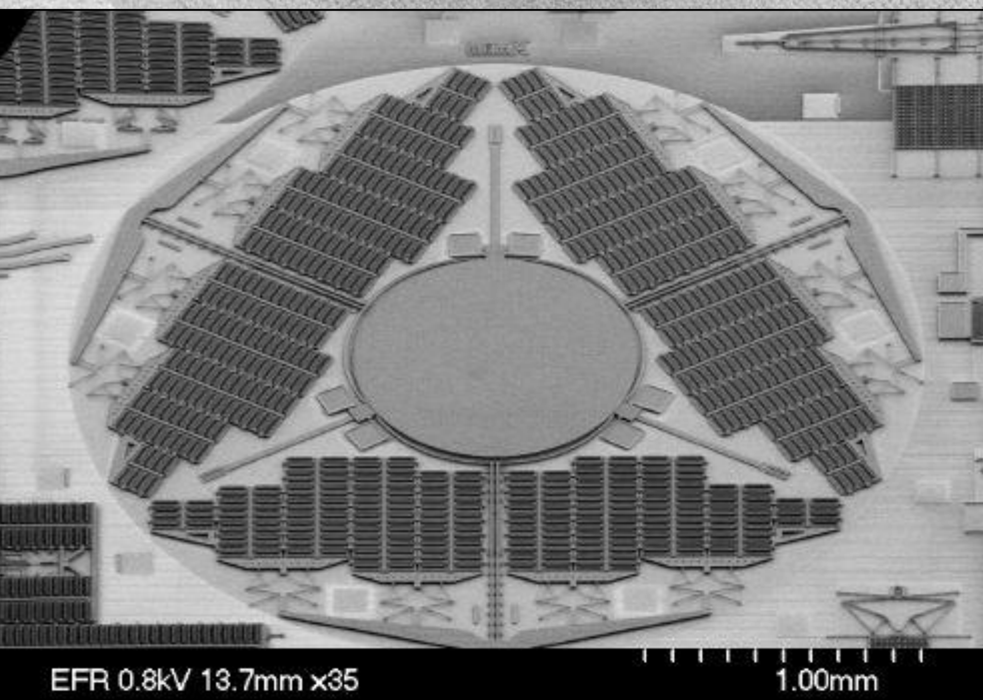
✓ Silicon technology is **<u>well-established</u>**

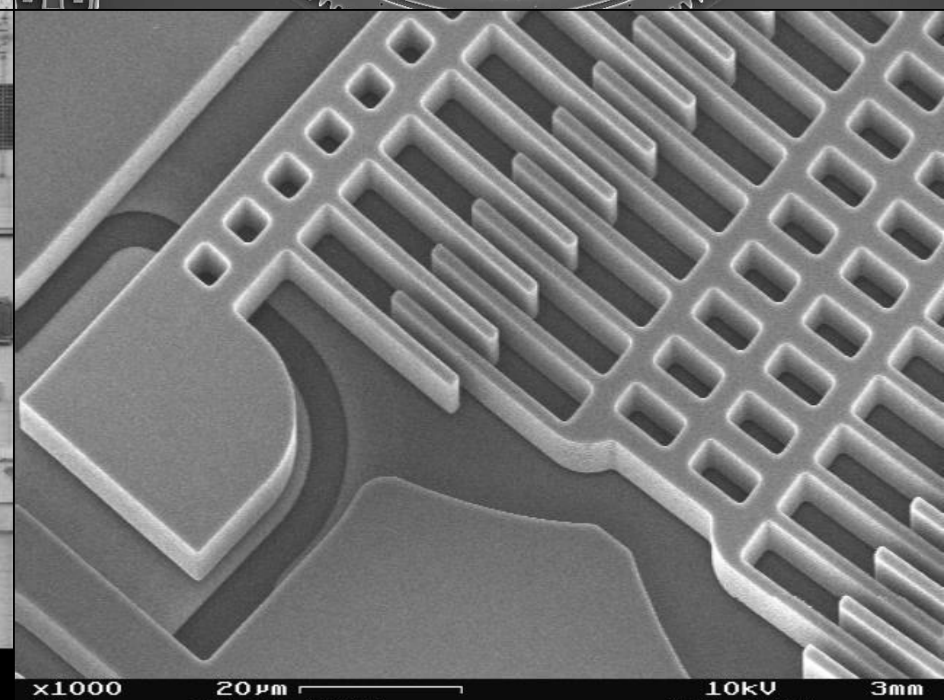
✓ Possibility of **<u>integration</u>** with microelectronics on a single chip

MEMS

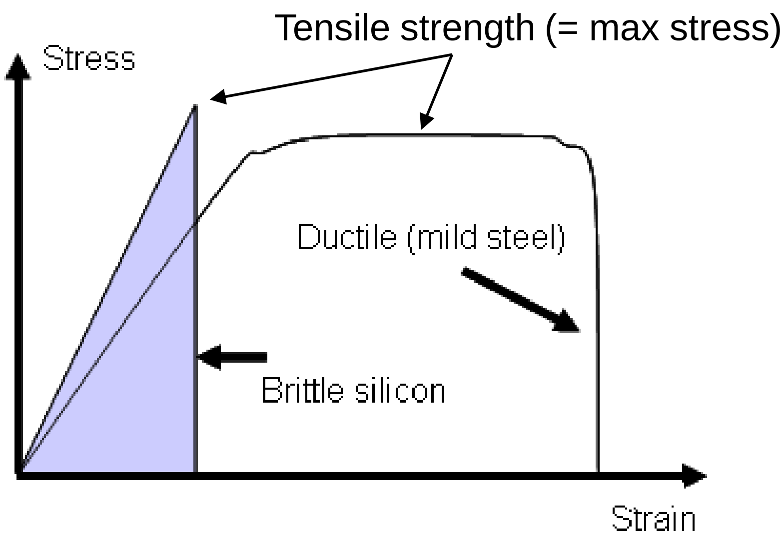








Mechanical properties of silicon



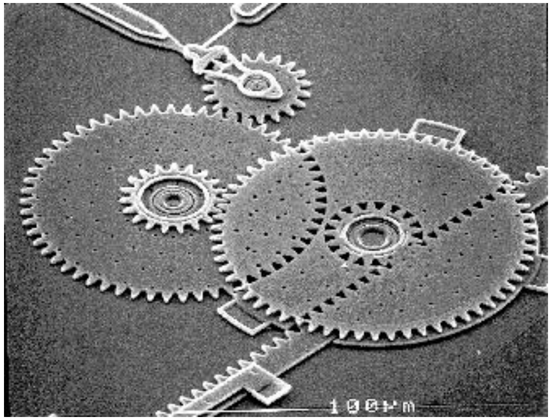
- Single-crystal Si (SCS) is almost a perfect material: **dislocations in SCS < metals**
- Materials usually deform above yield stress and fails completely at the ultimate stress
- in metals, ultimate stress >> yield stress
- in **silicon, yield stress ~ ultimate stress**

- SCS exhibits no plastic deformation or creep up to 800 ºC and so it has an **intrinsic mechanical stability**
- **No fatigue failure** when subject to a high number of cycles
- Absence of plastic behavior means that resonating structures of **exceedingly high Q** can be made

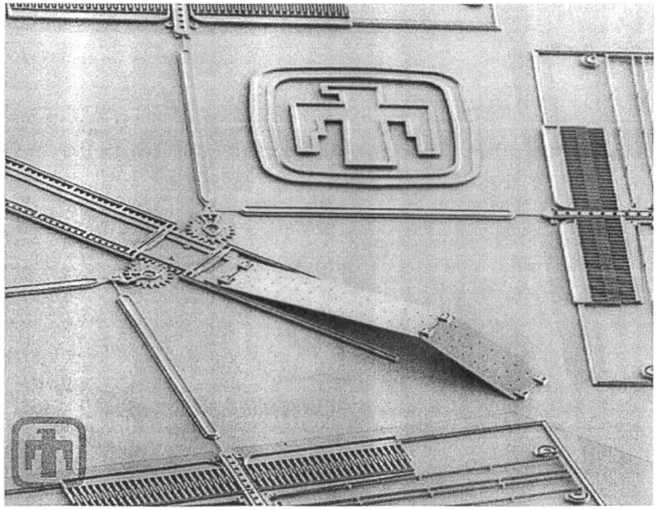
	Yield Strength (GPa)	Young's Modulus (GPa)	Density (g/cm^3)	Thermal Conductivity (W/cm ˚C)	Thermal Expansion (ppm/˚C)
Diamond	53	1035	3.5	20	1
SCS	>1	180	2.3	1.6	2.3
Steel	4.2	210	7.9	1.0	12.0
Aluminium	0.2	70	2.7	2.4	25

- Thermal expansion coefficient very important in packaging
- Remember that silicon properties depend on the direction in the crystal lattice, i.e. tensors may be required
- SCS Fracture Strength > 1.0 GPa

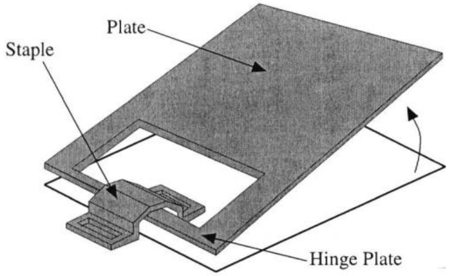
Other MEMS structures…



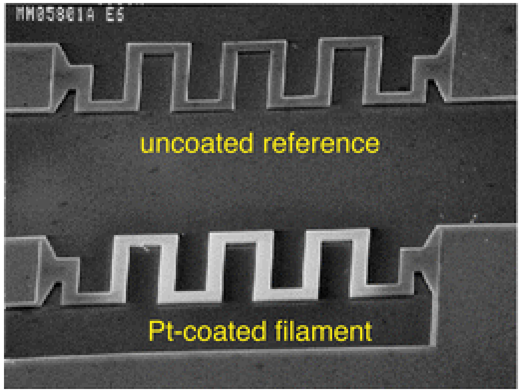
Microtransmission



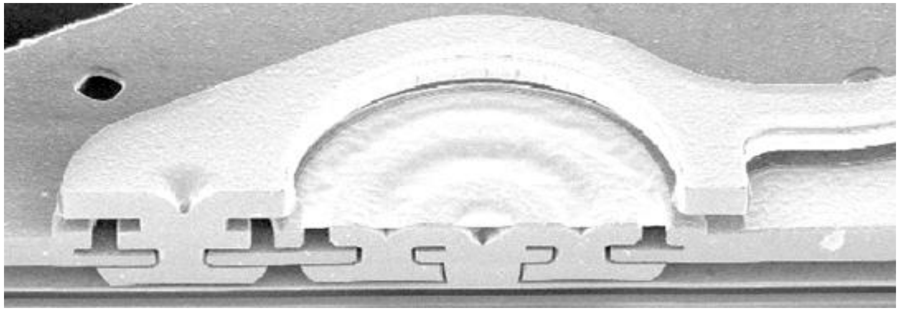
Micromirror



Out-of-plane hinge



Catalytic microsensor

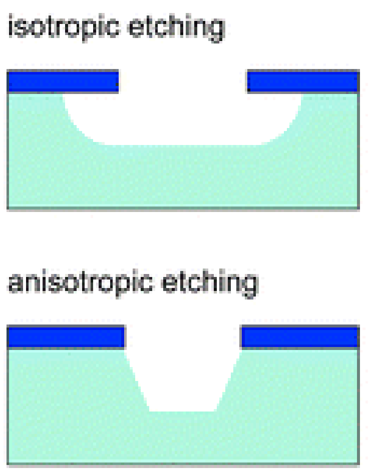


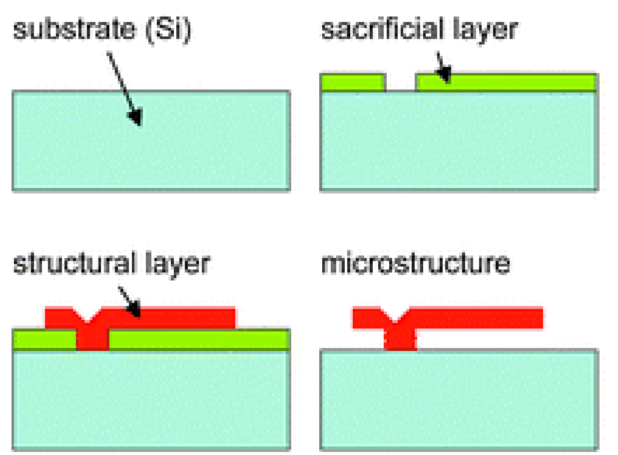
3-levels device cross-section

Silicon micromachining

Most MEMS fabrication techniques can be classified as

- *in* the substrate, **bulk micromachining**, or
- *above* the substrate, **surface micromachining**.

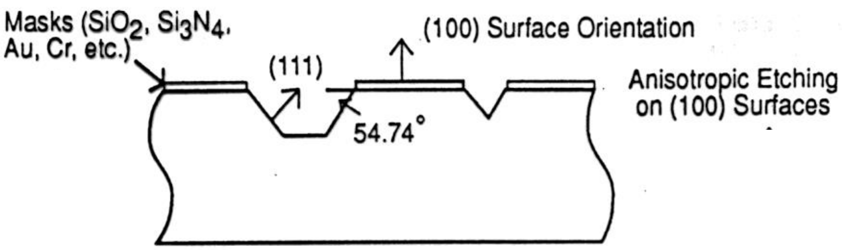




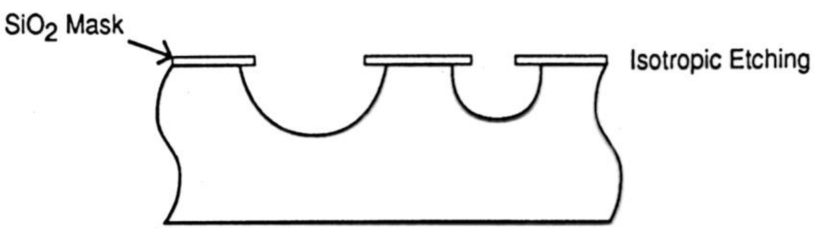
Bulk micromachining is a fabrication technique to selectively remove substrate to create MEMS devices

Surface micromachining is a fabrication technique for depositing various films on top of the substrate (substrate as a construction base material) and selectively remove parts of deposited films to create MEMS devices

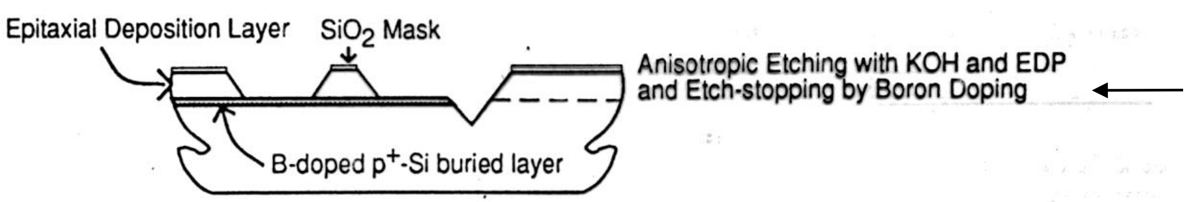
Wet etching



KOH (potassium hydroxide) is frequently used for **anisotropic etching:** the (111) surface direction of silicon crystal is etched at a very low speed compared with (100). Therefore, a (100) silicon wafer surface can be etched by KOH etchant with 54.74 deg slopes.

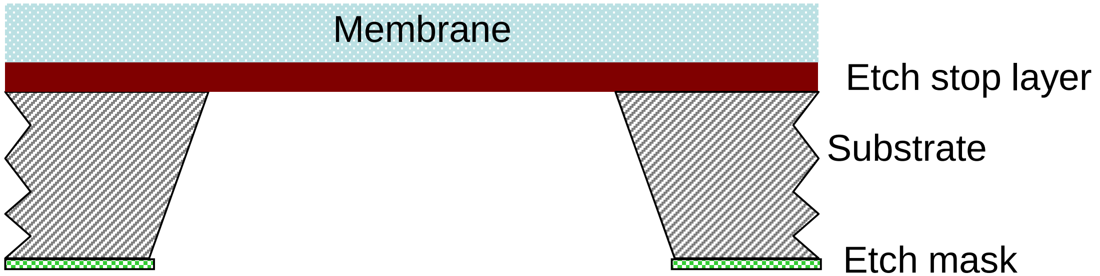


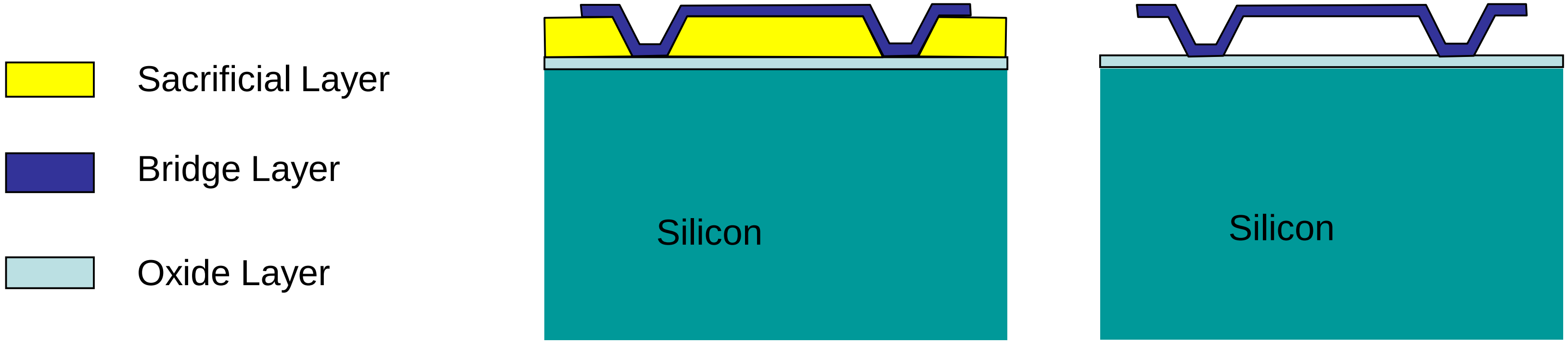
HNA ($HF+HNO_3+CH_3COOH$) is commonly used as an **isotropic etchant**: the etching speed does not depend upon the crystal axis



A deeply doped silicon layer can be used as an etch-stop layer.

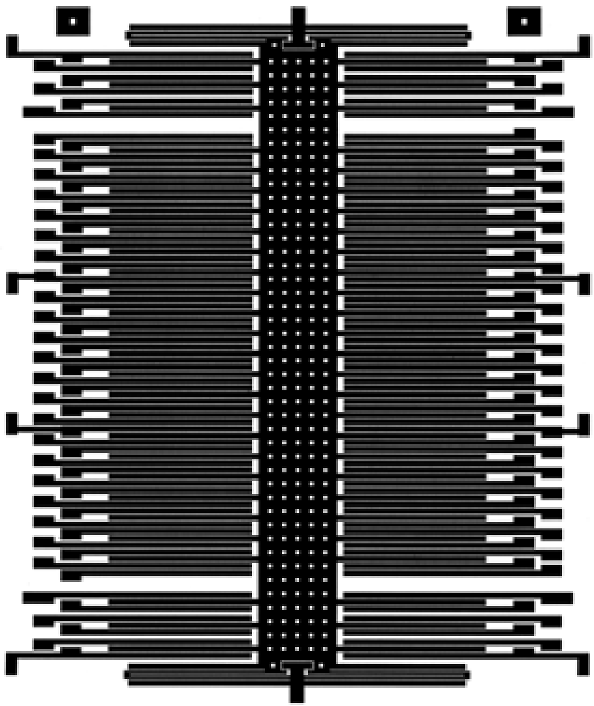
Approaches for the fabrication of membranes





IC + MEMS integration

- Typical MEMS/IC integration is done by fabricating **IC first**
- MEMS is post-processed on top of IC or pre-designated MEMS area on the IC

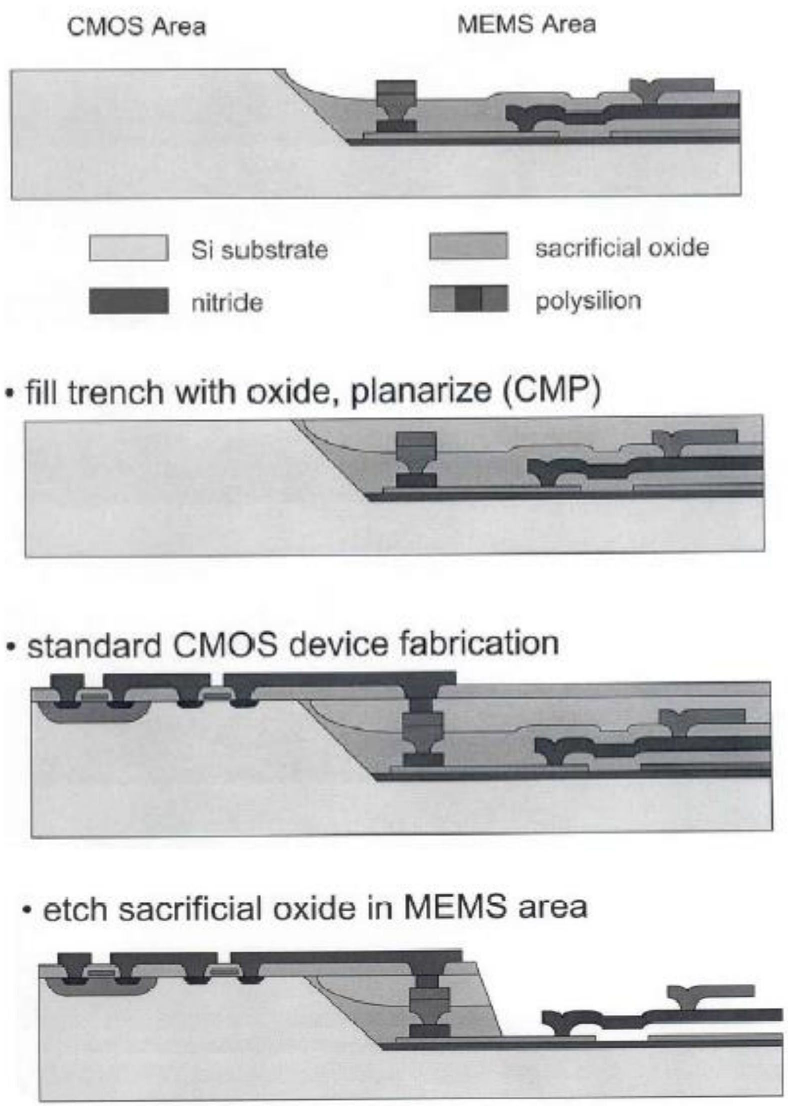


- Proper IC protection is needed
- Post-IC process temperature cannot exceed 450ºC to avoid IC degradation
  - o redistribution of dopants
  - o inter-diffusion of materials

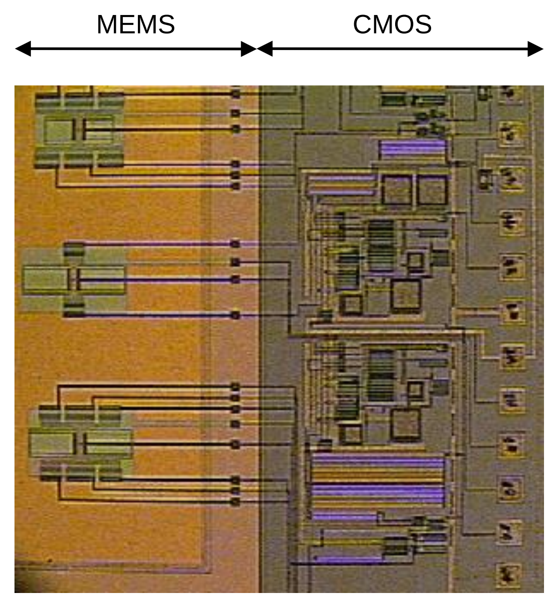
Analog devices ADXL-50, the industry first surface micromachined accelerometer including signal conditioning on chip

http://www.analog.com/library/analogDialogue/archives/30-4/acccel.html

IC + MEMS integration



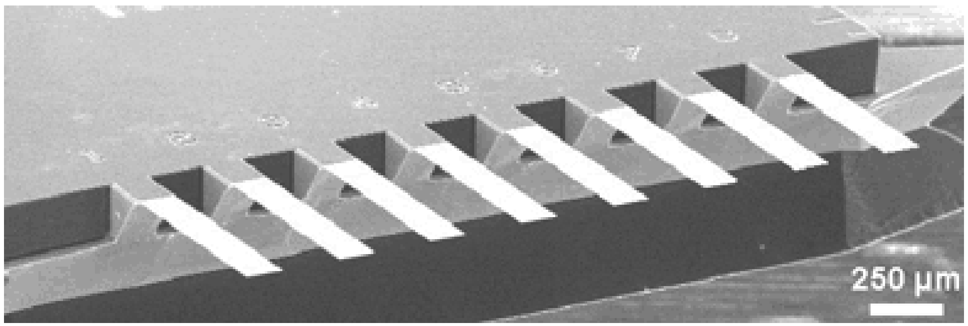
MEMS first approach developed at Sandia Labs

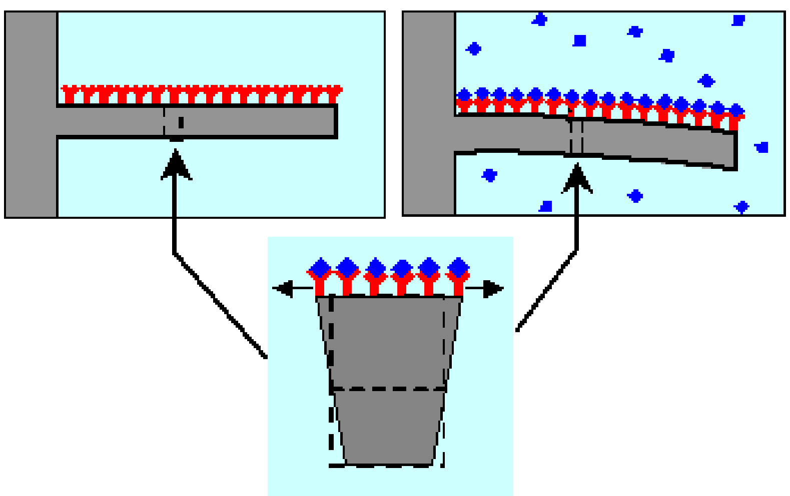


http://mems.sandia.gov/tech-info/mems-overview.html

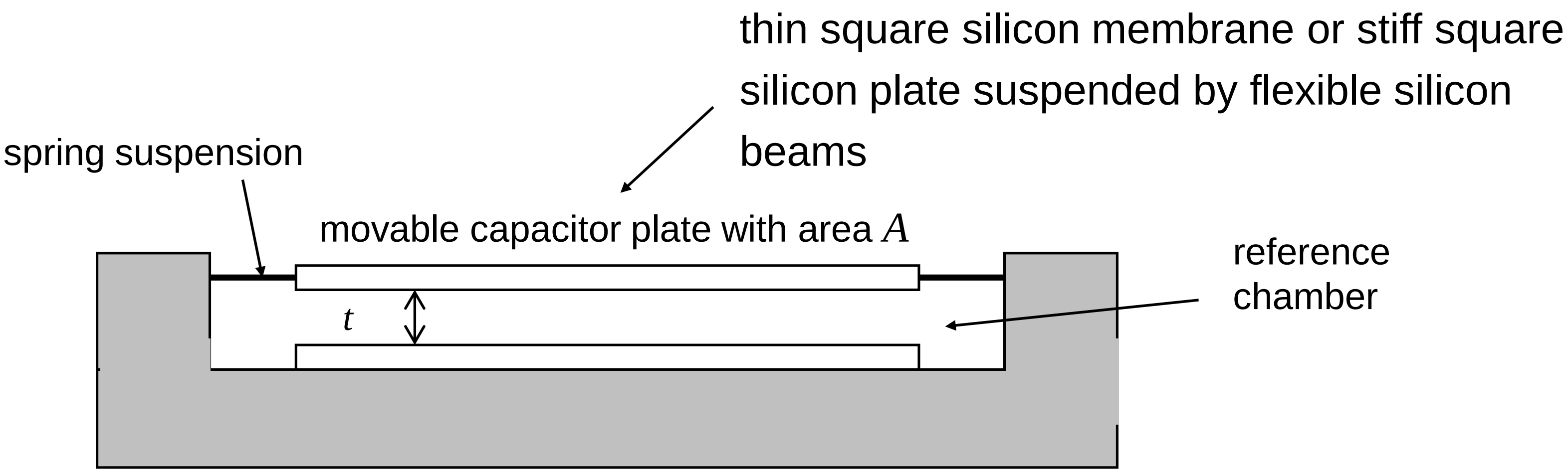
Cantilevers

- Widespread application in atomic force microscopy
- Biological and chemical sensors





Capacitors in MEMS



Use a capacitor with one fixed plate and one moving plate to give a variable capacitance

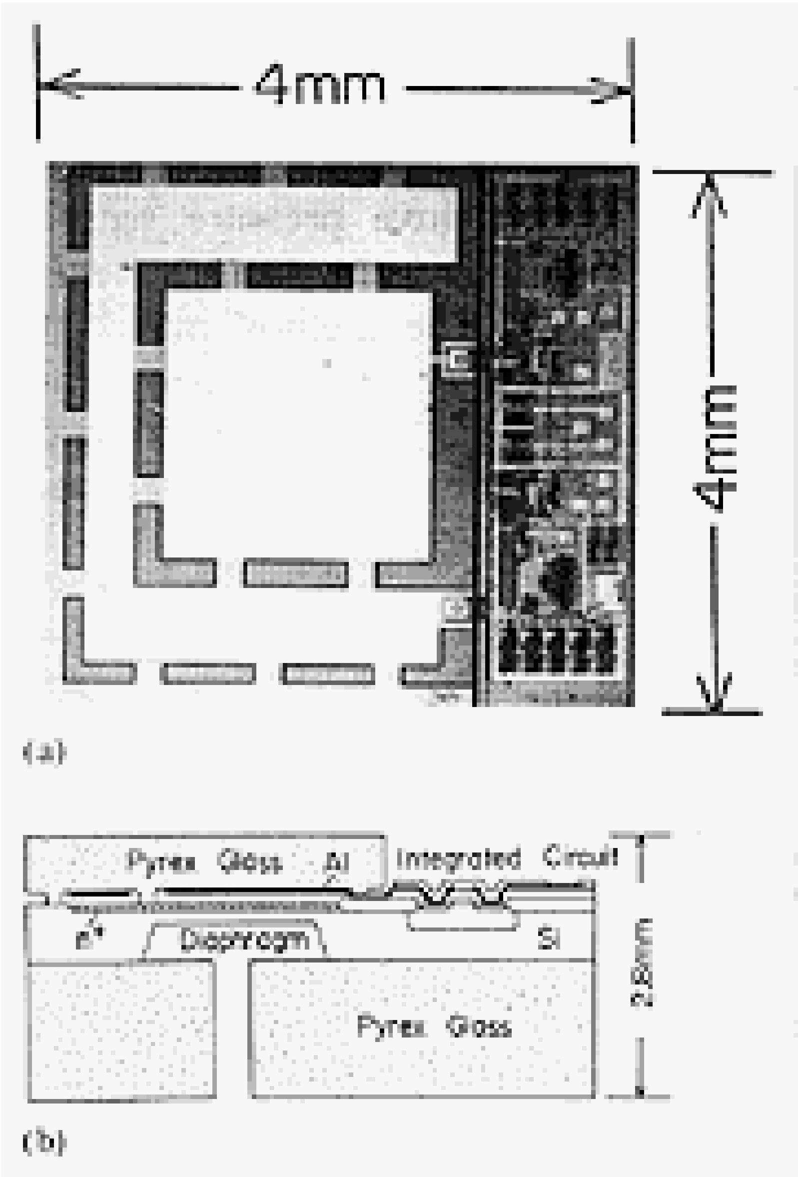
$$C = \varepsilon_0 \varepsilon_r \frac{A}{t}$$

(for a N_2 filled capacitor e_r ~1)

if $\Delta t \ll t$, the sensitivity to Δt is

$$\frac{\Delta C}{\Delta t} = -\varepsilon \frac{A}{t^2}$$

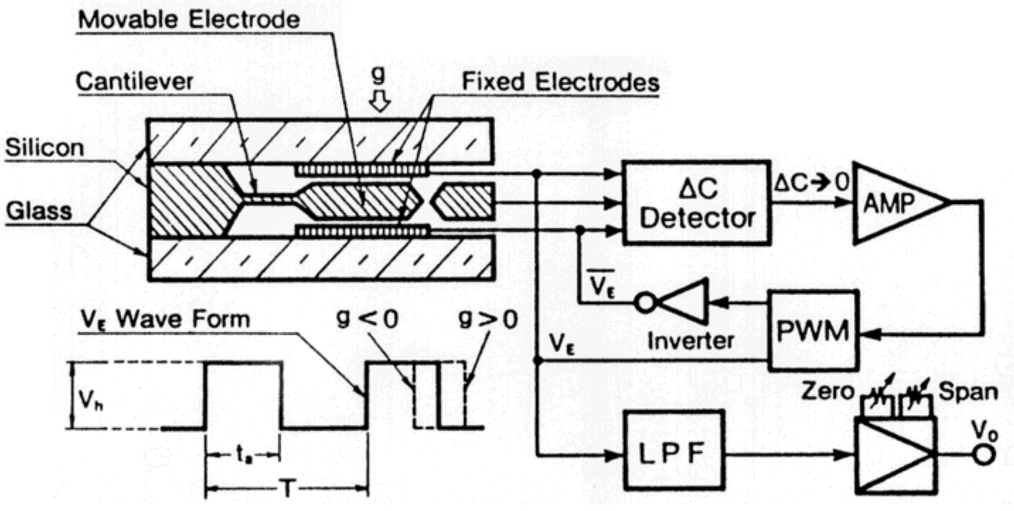
Examples of capacitors in MEMS



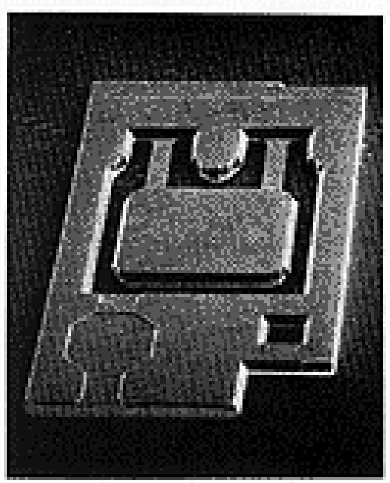
Photograph (top) and cross sectional diagram (bottom) of ***Toyota capacitive pressure sensor*** – employs bulk micromachining

Ref: www.tec.org/loyola/mems/c3_s2.htm

Examples of capacitors in MEMS



(a)



(b)

Cross section & block diagram (top) and photograph (bottom) of ***Hitachi capacitive accelerometer*** – employs bulk micromachining

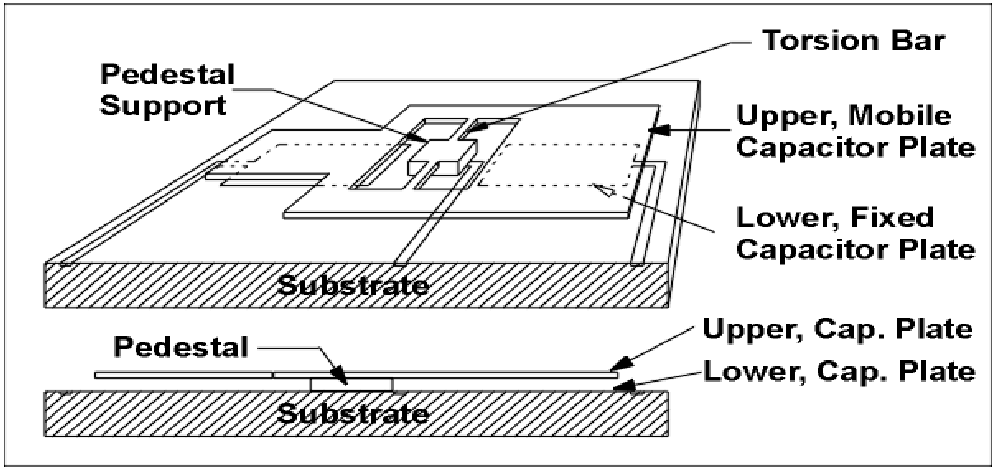
AMP = amplification

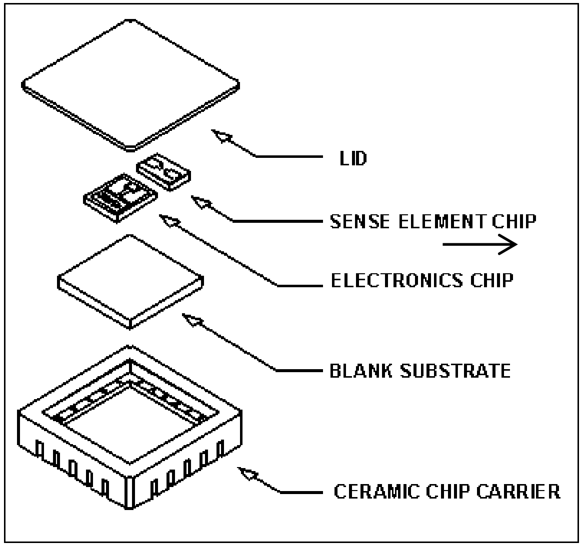
PWM = pulse width modulator

LPF = low-pass filter

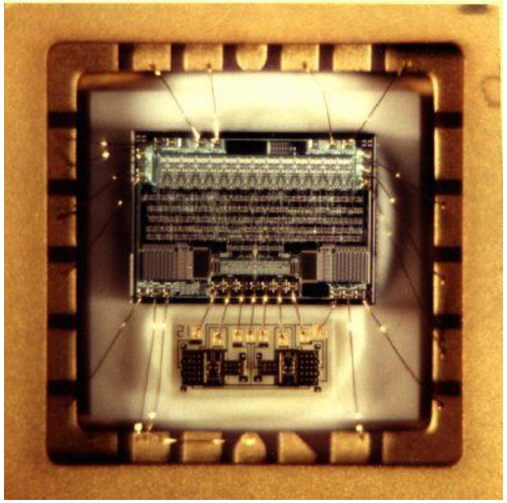
Ref: www.tec.org/loyola/mems/c3_s2.htm

Examples of capacitors in MEMS





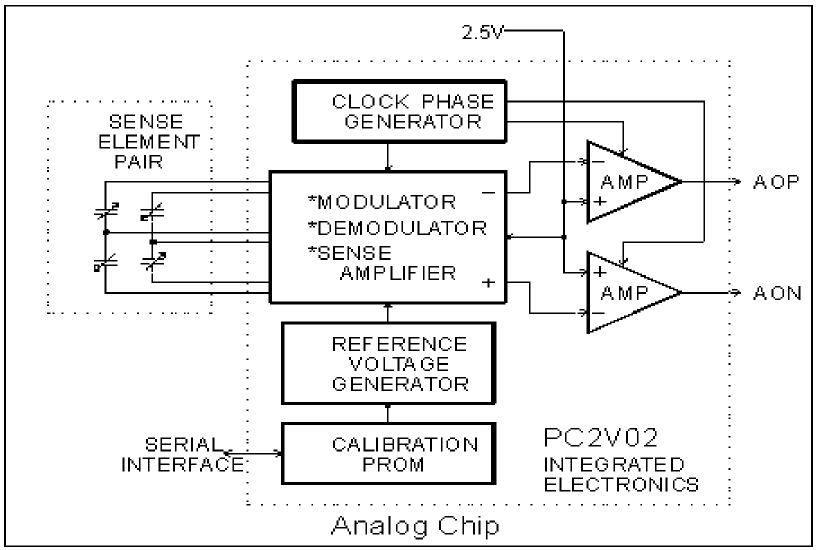
analogue or digital ASIC chip



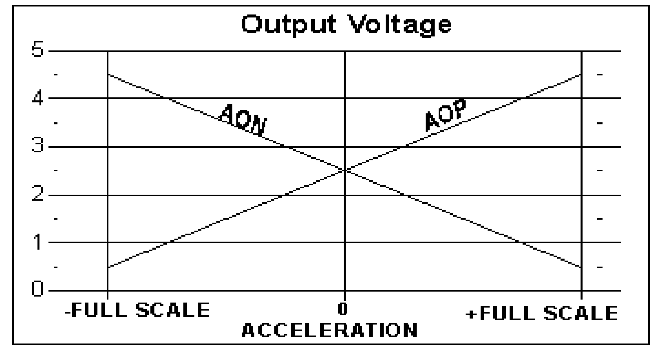
Silicon Designs Inc (SDI) torsional accelerometer uses an electroformed nickel structure

Ref: http://www.silicondesigns.com/tech.html

Examples of MEMS capacitor sensor circuits



Analogue ASIC for SDI accelerometer: it is basically a capacitance-to-voltage converter



The electronics produces a large voltage deviation (+/- 4 volts) that is linearly proportional to the applied acceleration

The output is measured differentially as AOP-AON

Inductors for RF MEMS

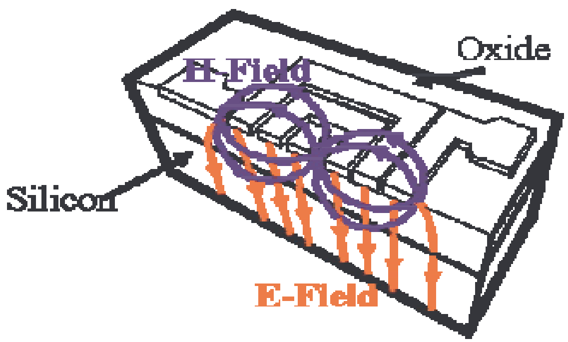


Figure 1. Planar inductor [8].

Planar inductors fabricated on substrates such as silicon suffer from many unwanted stray components that can compromise device performance. Stray capacitances tend to decrease the self-resonance while the conductivity of the substrate tends to reduce the Q-factor. Typical Q<10, f_r<1 GHz.

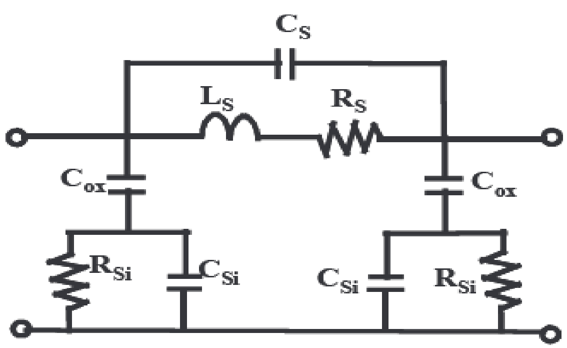
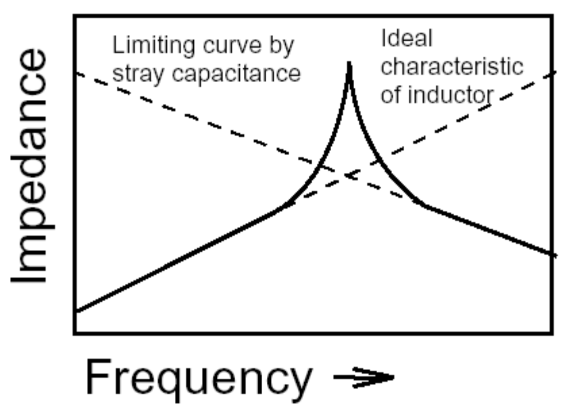
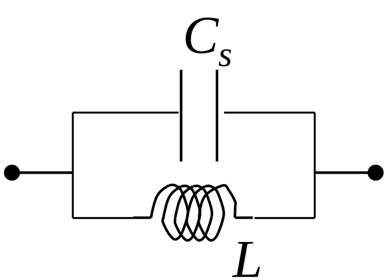


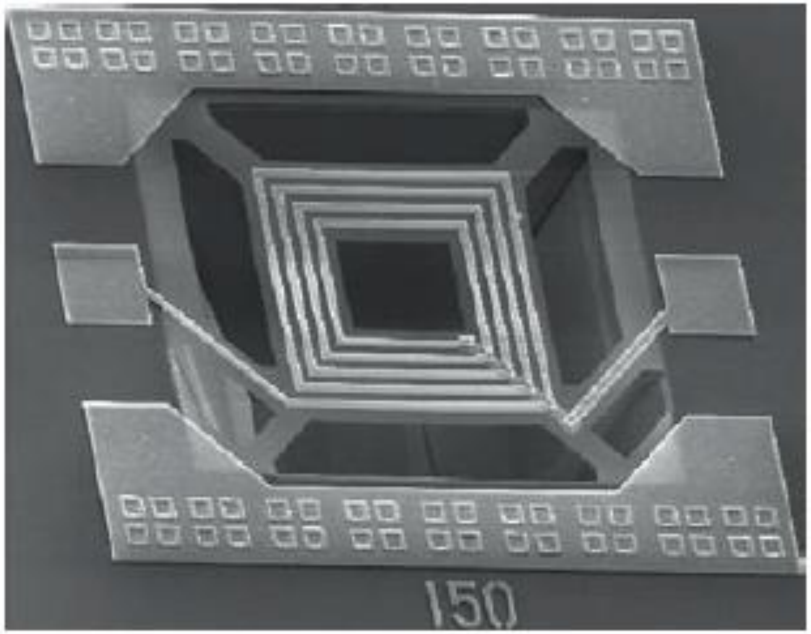
Figure 2. Equivalent circuit model of planar inducto

Impedance characteristic

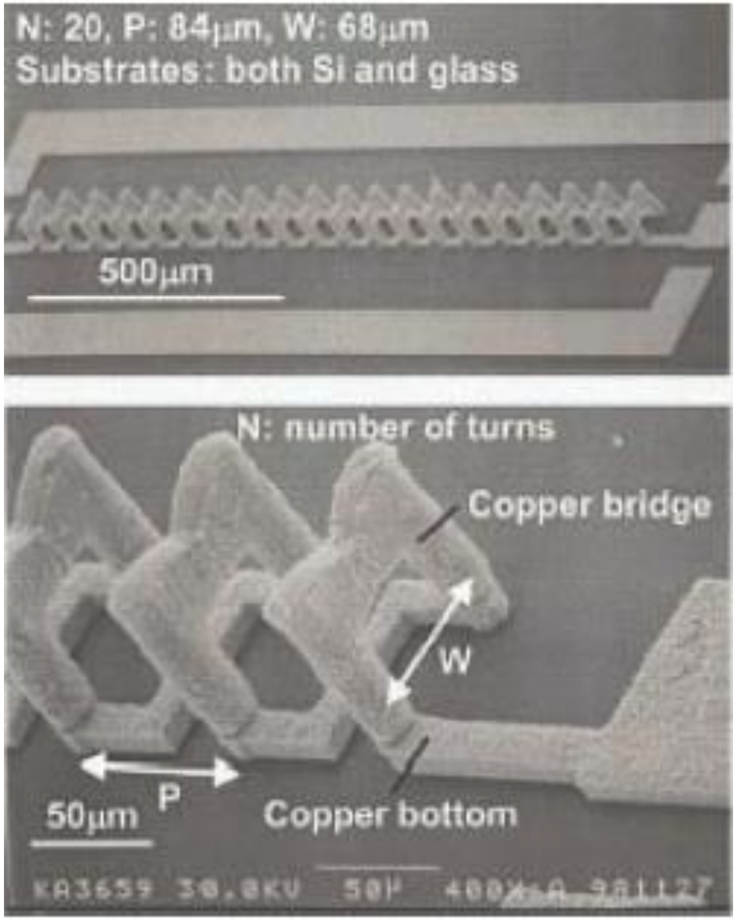




Inductors for RF MEMS



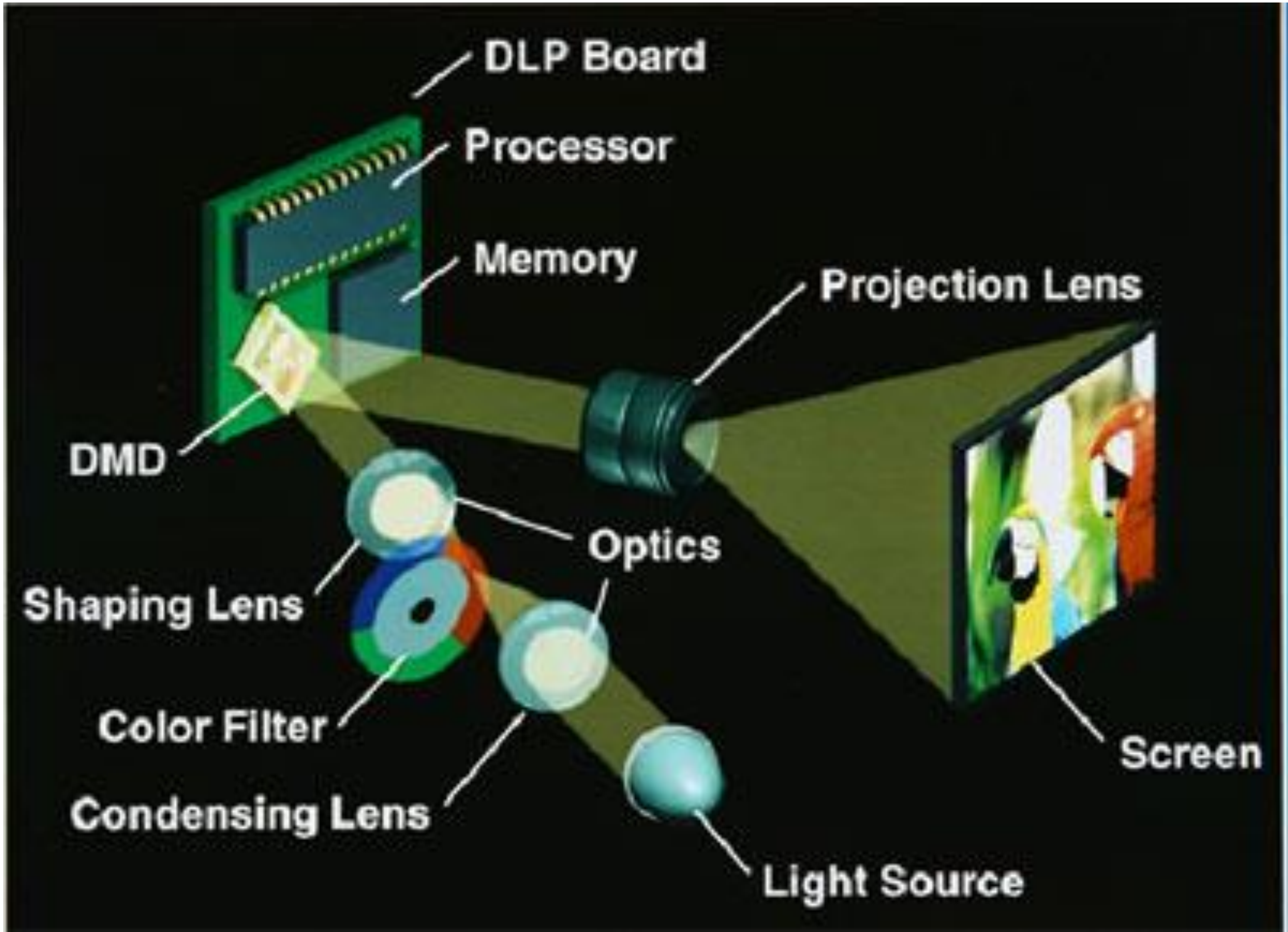
Bulk micromachined planar ***spiral*** inductor where the substrate has been locally removed from under the turns. Self-resonance f_r is increased from 800 MHz to 3 GHz thanks to substrate removal



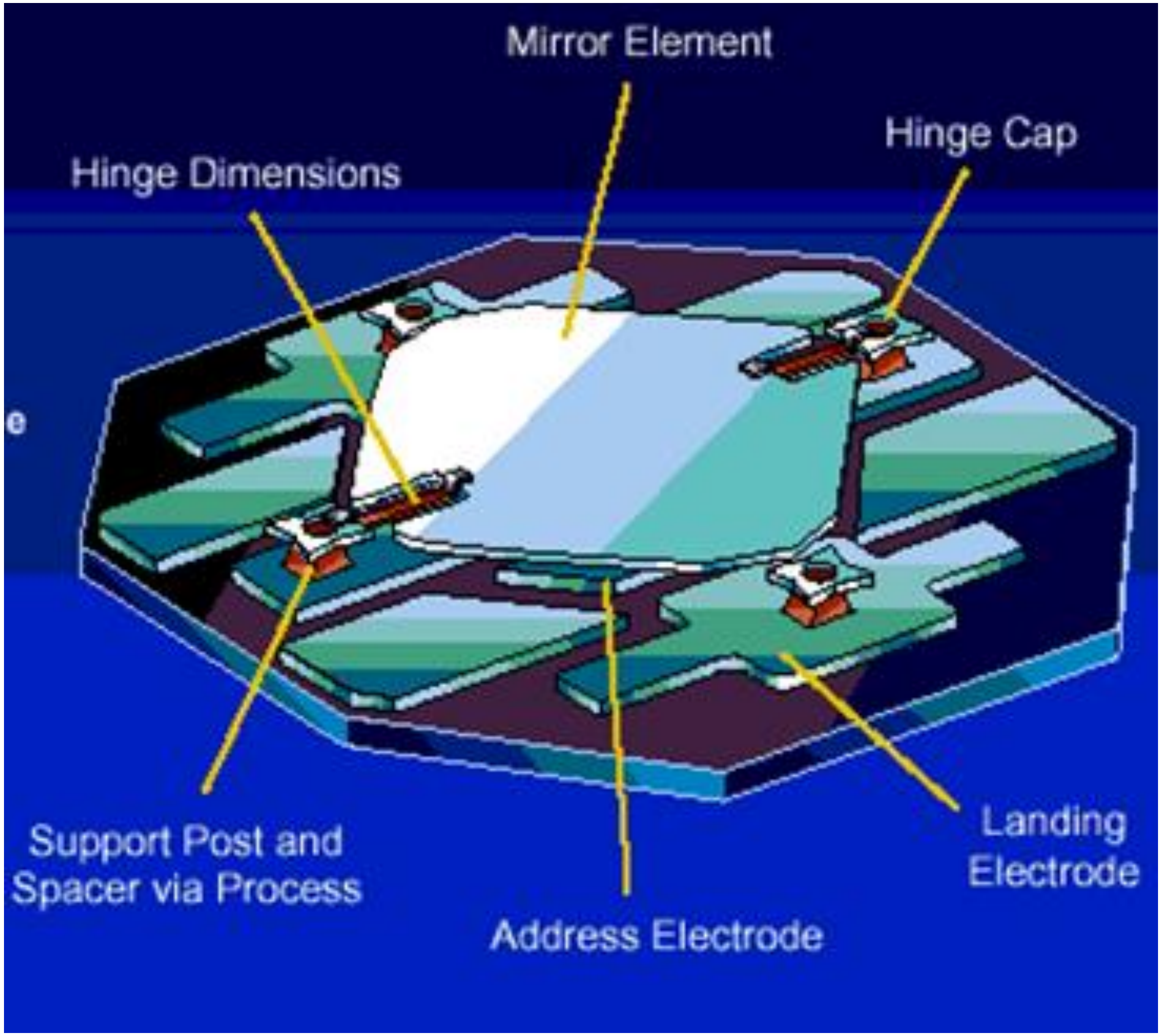
20-turn all-Cu air-core ***solenoid*** on Si. It reduces parasitic capacitances between metal traces and the substrate

Q = 16.7 at 2.4 GHz

TI's DLP technology



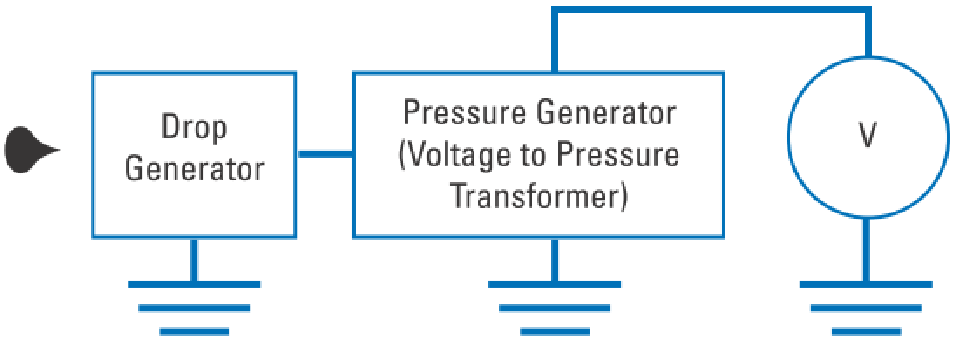
TI's DLP technology

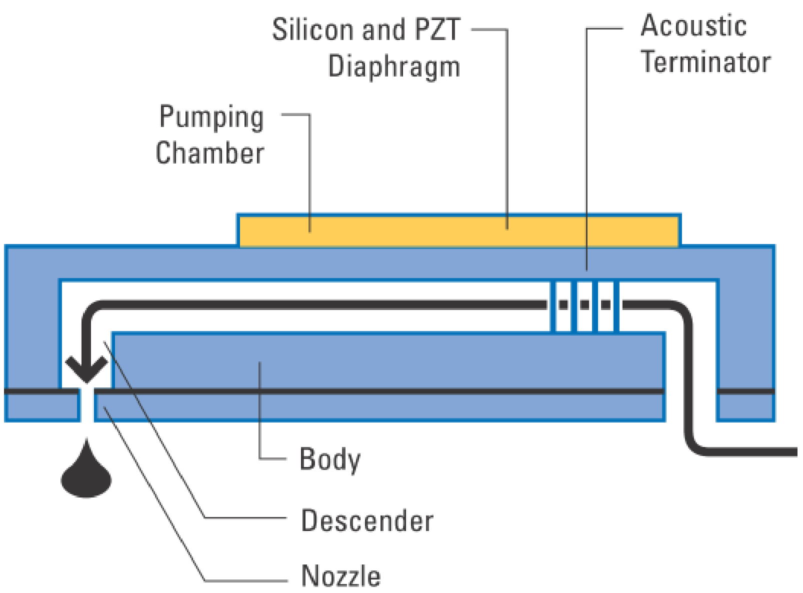


MEMS inkjet printer heads

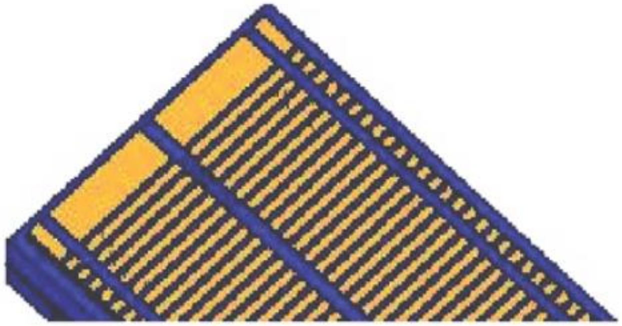
Single jet

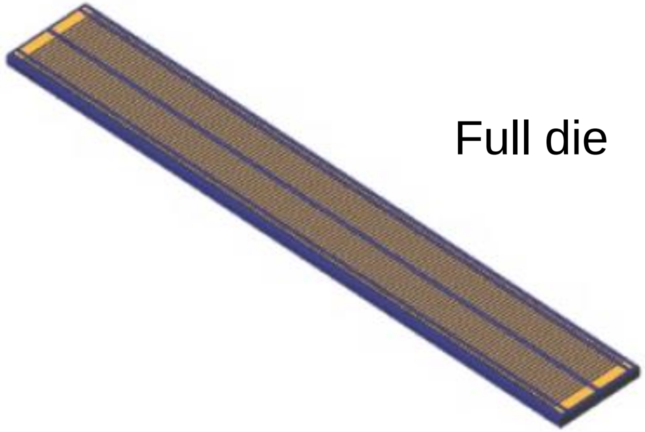
Simplified scheme





Layout of jets on a die





Full die

MEMS inkjet printer heads: processing steps

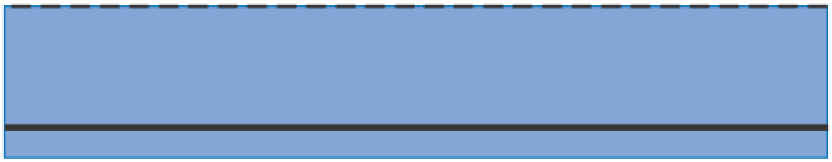


Figure 2a. Starting Wafer. Begin with a Silicon-on-Oxide (SOI) Wafer.

Figure 2b. Descender/Fill etch. Etch blind holes. This *Descender* will connect the pumping chamber to the nozzle. The Fill connects to fluid reservoir.

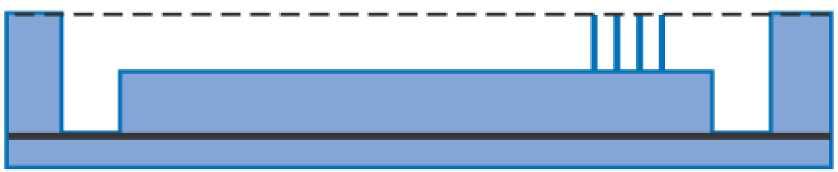


Figure 2c. Pumping Chamber/Filter Etch. Etch a rectangular pumping chamber with Acoustic Terminator at fill end.

Figure 2d. Nozzle/Fill Through Etch. Etch a *through hole* to complete nozzle and fill paths.

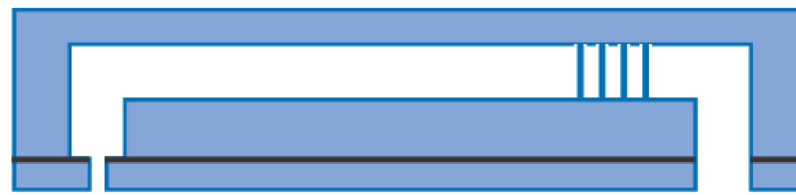


Figure 2e. Actuator Diaphragm Attach. Attach an SOI wafer with a Fusion Bond and remove the handle wafer away to leave a (12 -50 µm) diaphragm.

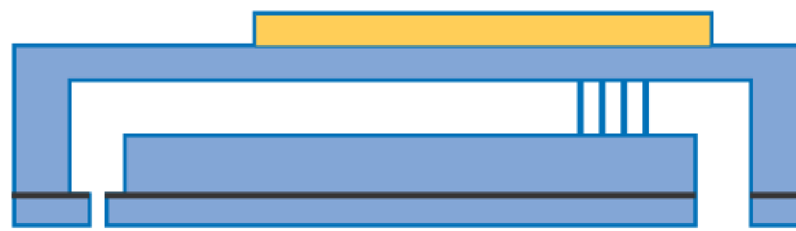


Figure 2f. PZT bond, grind and singulate. PZT, metalized on both sides is bonded to the membrane, ground to its final thickness (1- 50 µm) and sawn to singulate the individual jets.

MEMS inkjet printer heads: details

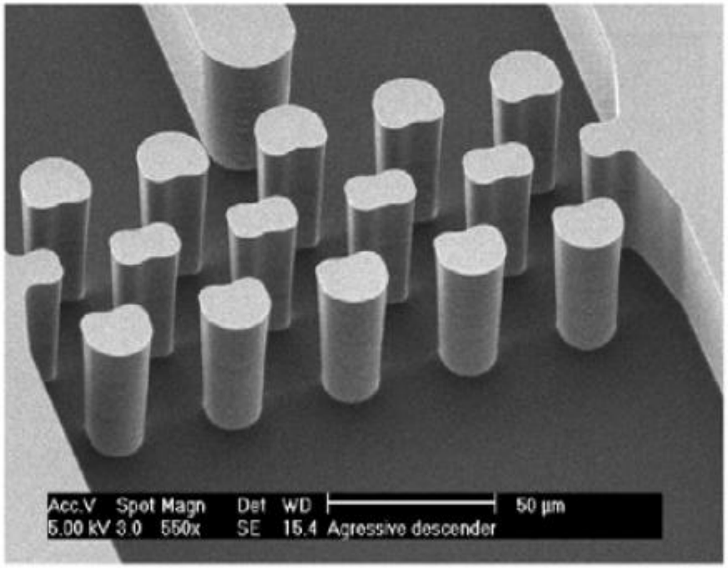


Figure 3a. Acoustic Terminator on fill side of Pumping Chamber

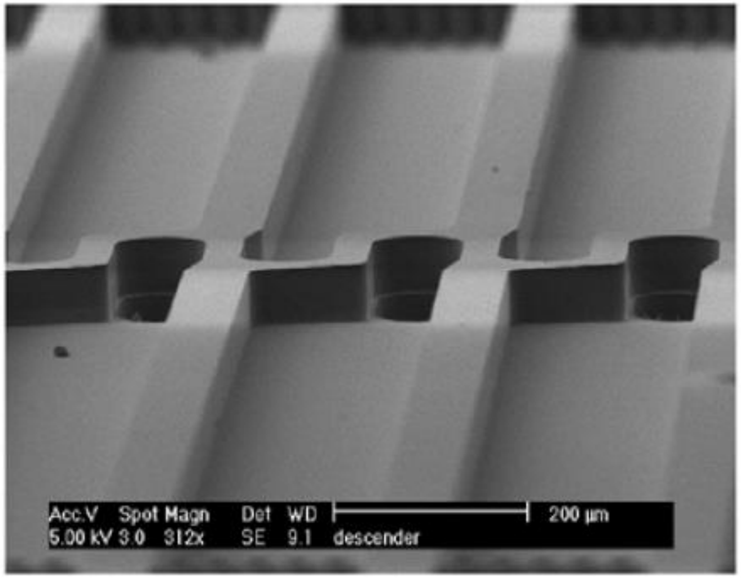


Figure 3b. View toward die center along Pumping Chamber

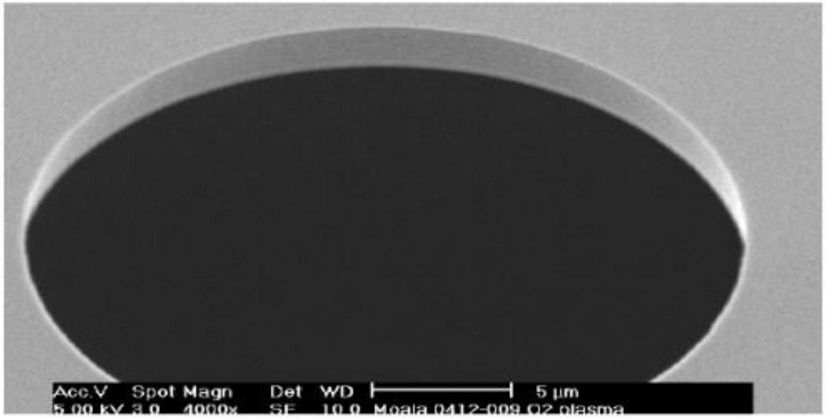
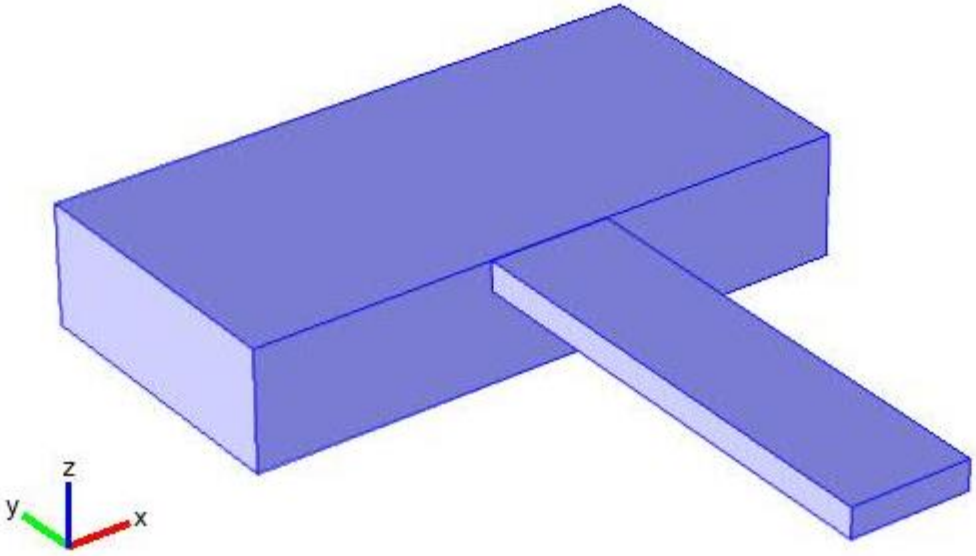
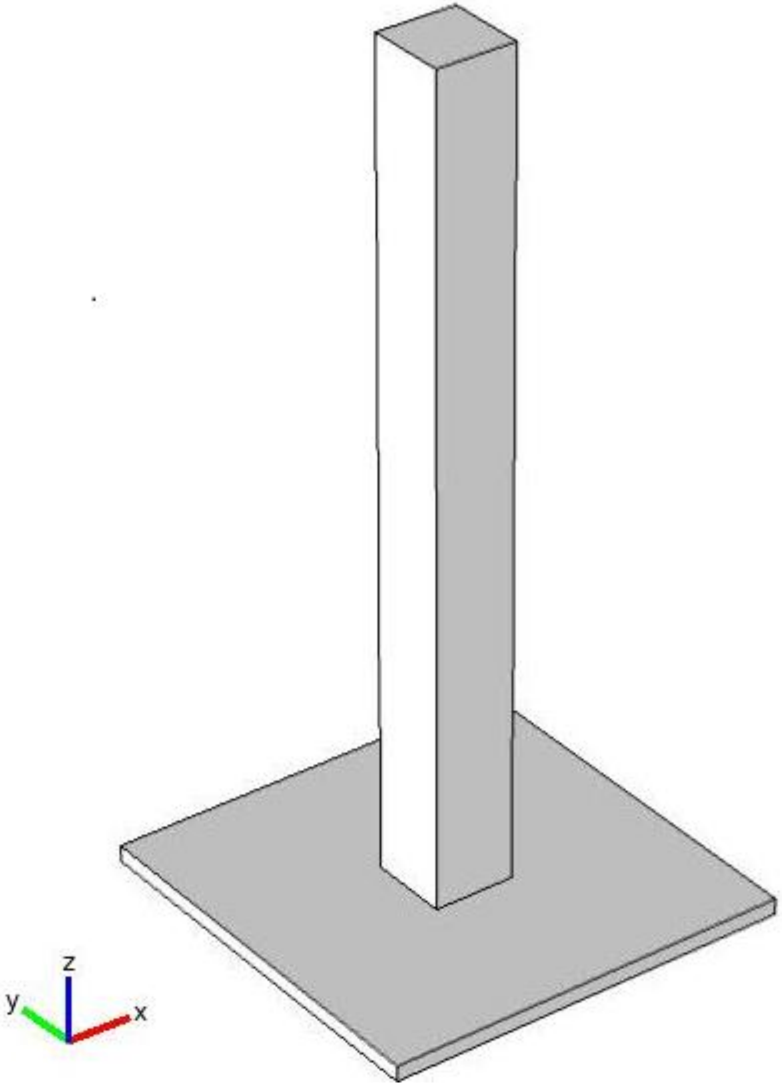


Figure 3c. Nozzle

Cantilevers and pillars





Asymmetrical twin cantilevers for single molecule detection

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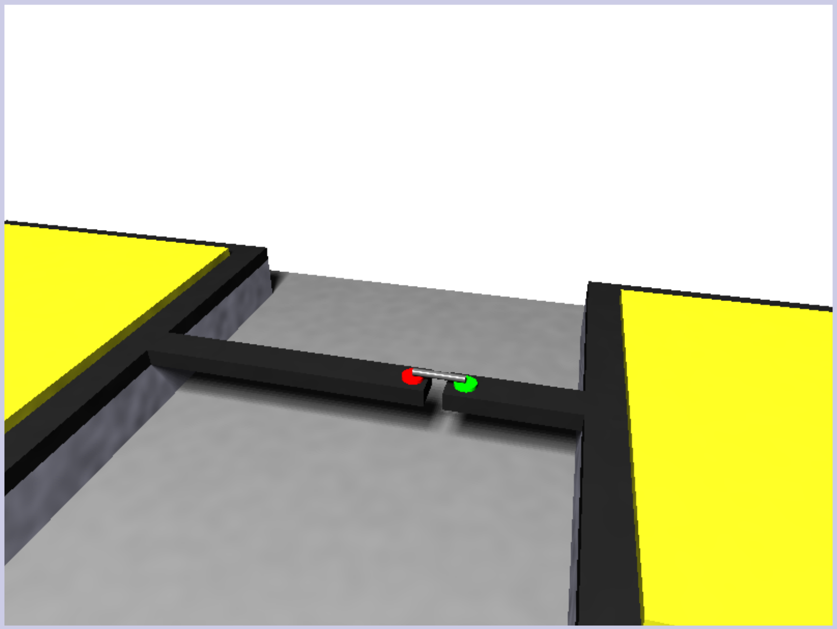
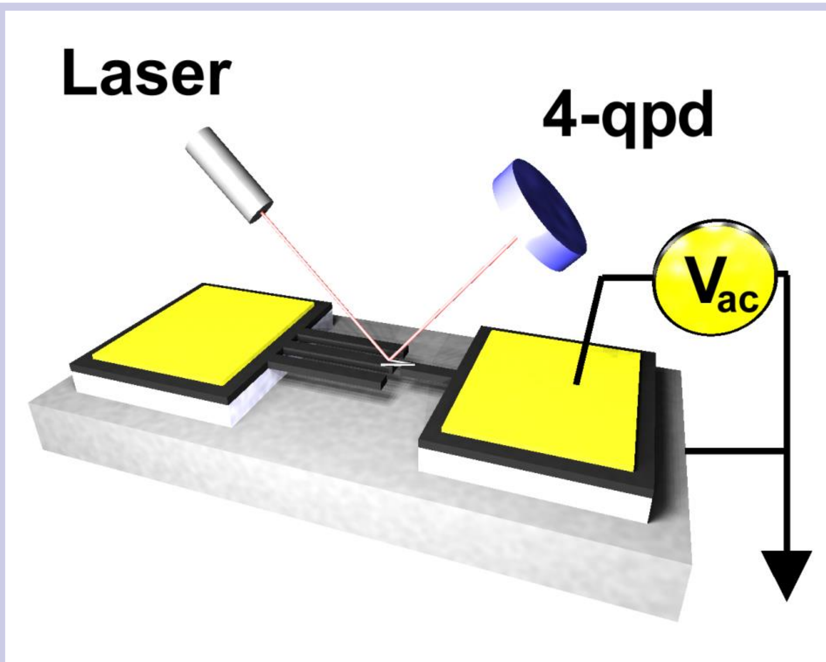
GE 2009 Riunione Annuale

Outline

- asymmetrical twin cantilevers
- detection of MW-CNTs
- fabrication of tunable nanometric gap
- selective functionalization of the gap





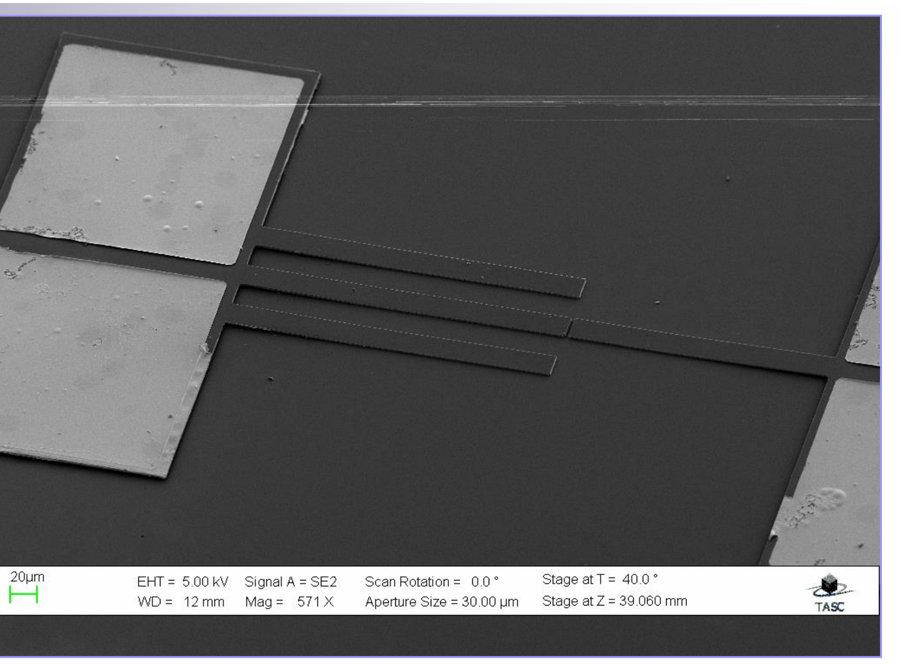
Asymmetrical twin cantilevers approach

We detect the mechanical cross-talk induced by the molecular link between a short *driver* cantilever and a longer *follower* one.

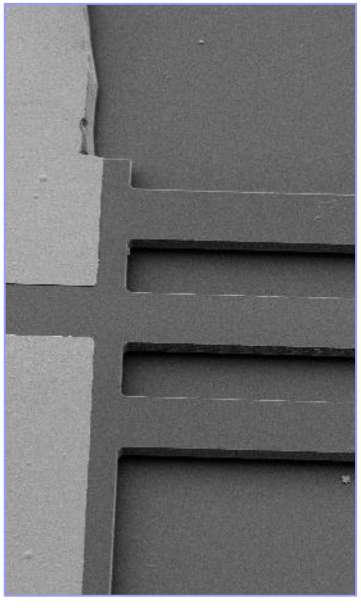
- The driver is actuated at the eigenfrequency of the follower
- the follower is excited through the molecular link
- motion is optically detected
- actuating force is as low as 0.5 pN with Q=10000
- dsDNA is denaturated with a force of about 60 pN

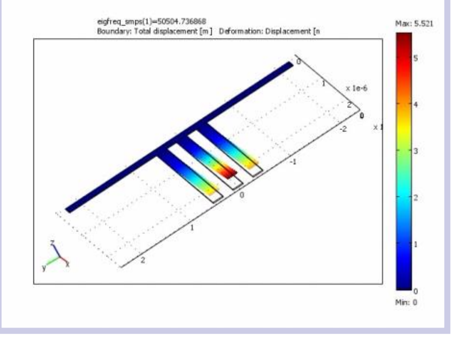
Triple *follower* and mode splitting

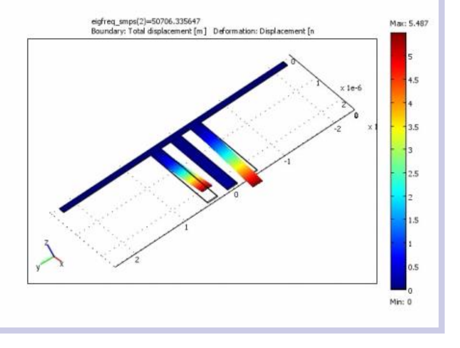
Three nominally identical followers are built
• only the central one faces the driver

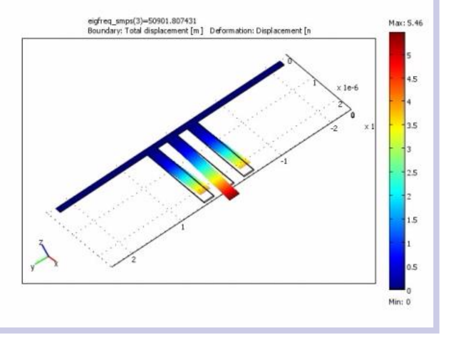


The production process causes an undercut that slightly links the three cantilevers
• the three resonators split their eigenfrequency into three modes



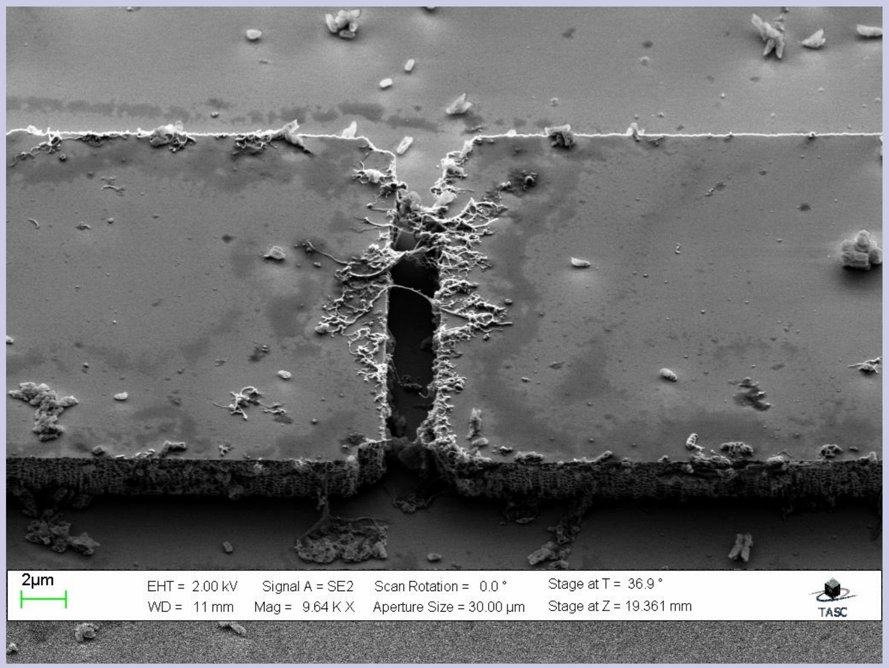


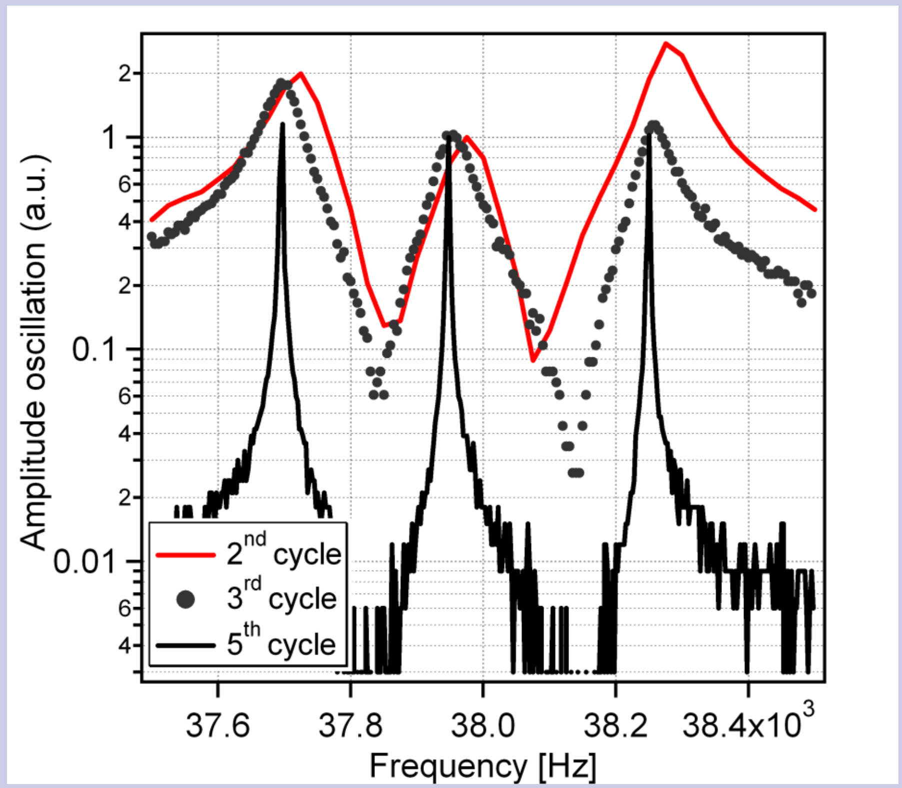




Preliminary tests with MW-CNTs

We placed MW-CNTs as test molecules across the gap by dielectrophoresis

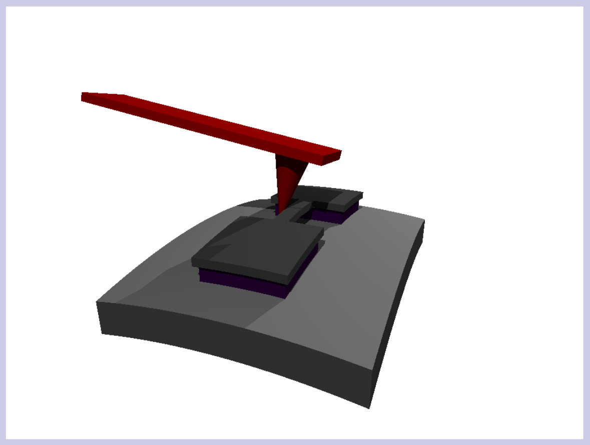


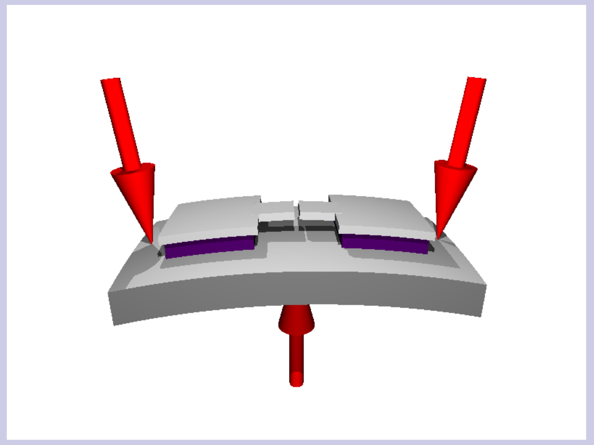


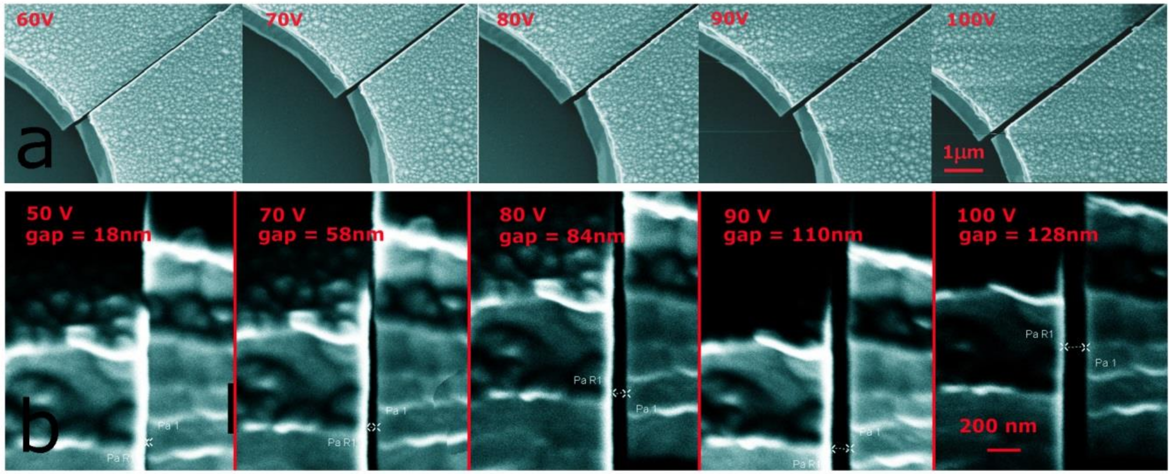
Gap formation and tuning

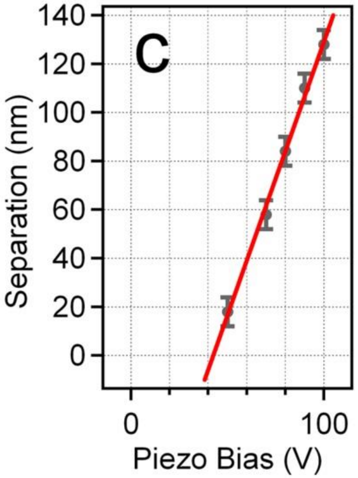
For molecular detection we need very flat edges
• the twin cantilevers are cleaved along the <111> plane by an AFM tip

The nanometric gap is tuned by mechanically bending the whole device





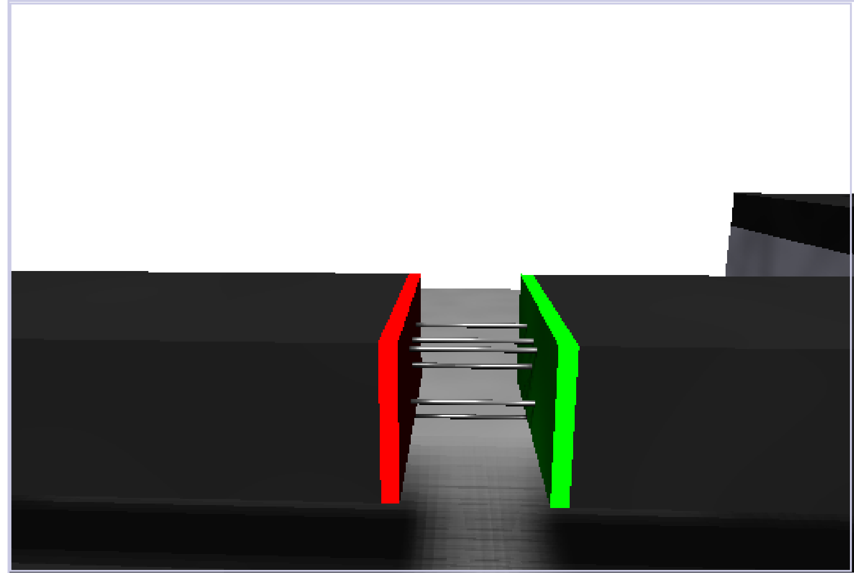


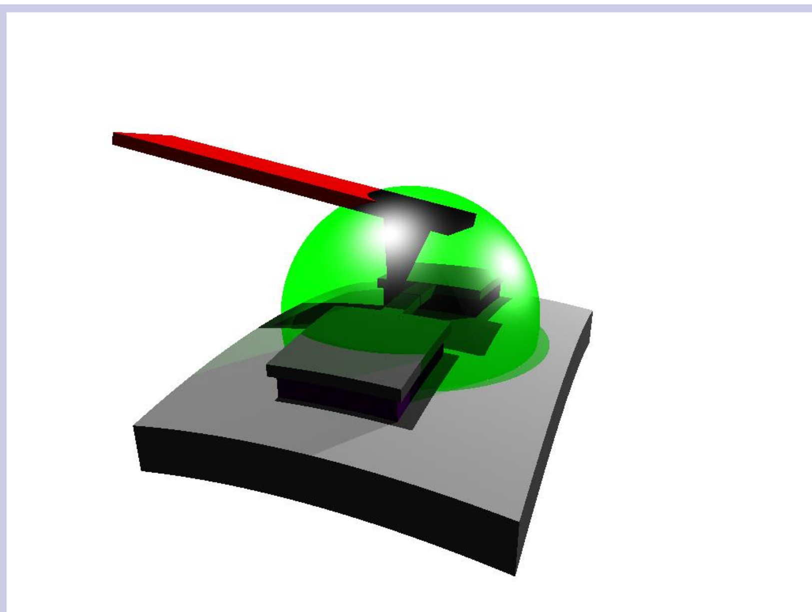


Resolution is 2.2 nm/V

Spatially defined functionalization

We need to selectively bind the molecules only at the twin cantilever terminations (better if on the facing surfaces)





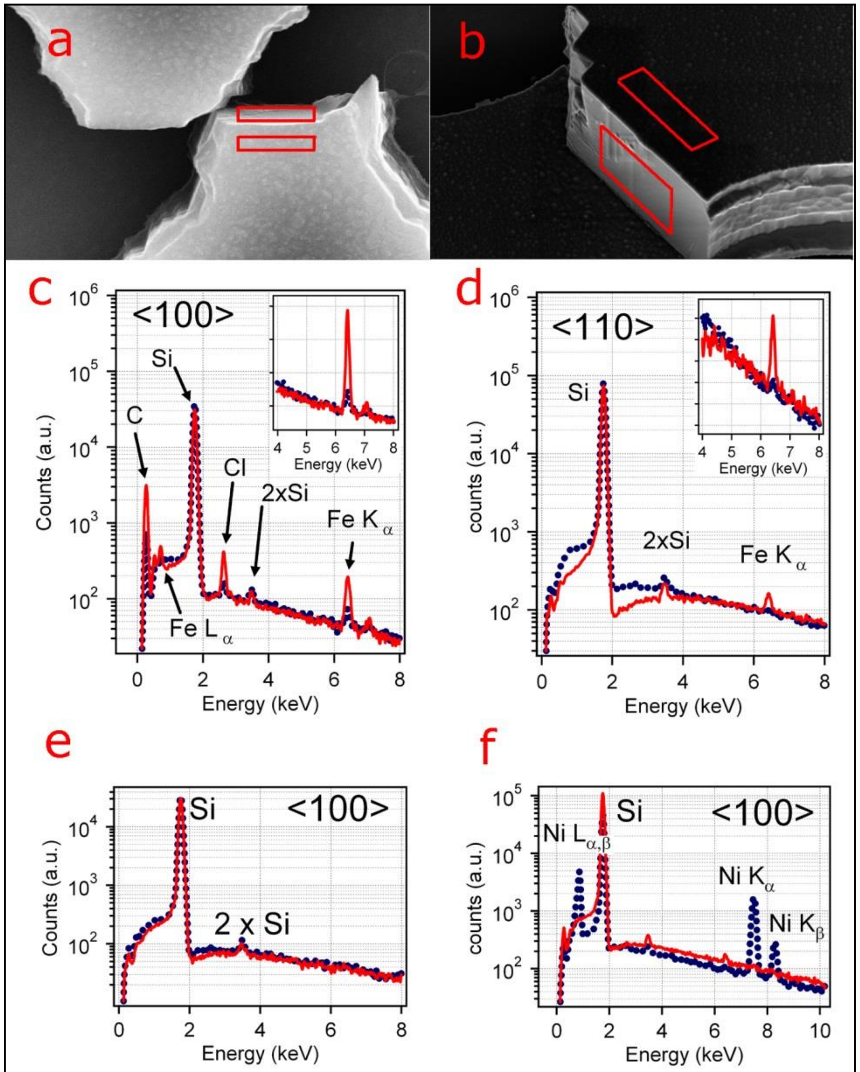
Proposed solution

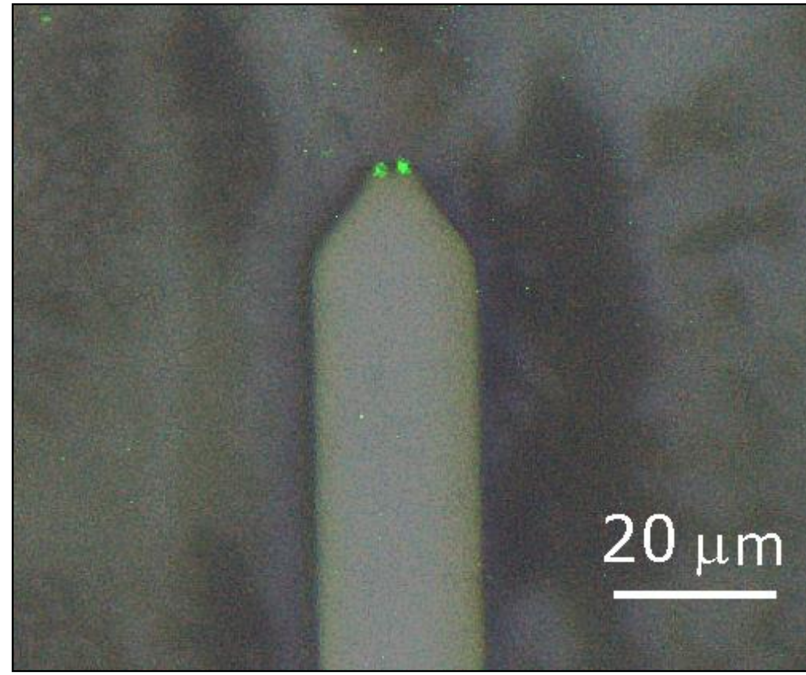
- cleaving in reactive environment, with no oxidation
- two molecules
    - vynilferrocene
    - fluorescein isothiocyanate (FITC)

Functionalization of the gap

Vynilferrocene solution and SEM-EDX analysis

FITC and fluorescence-optical microscopy analysis





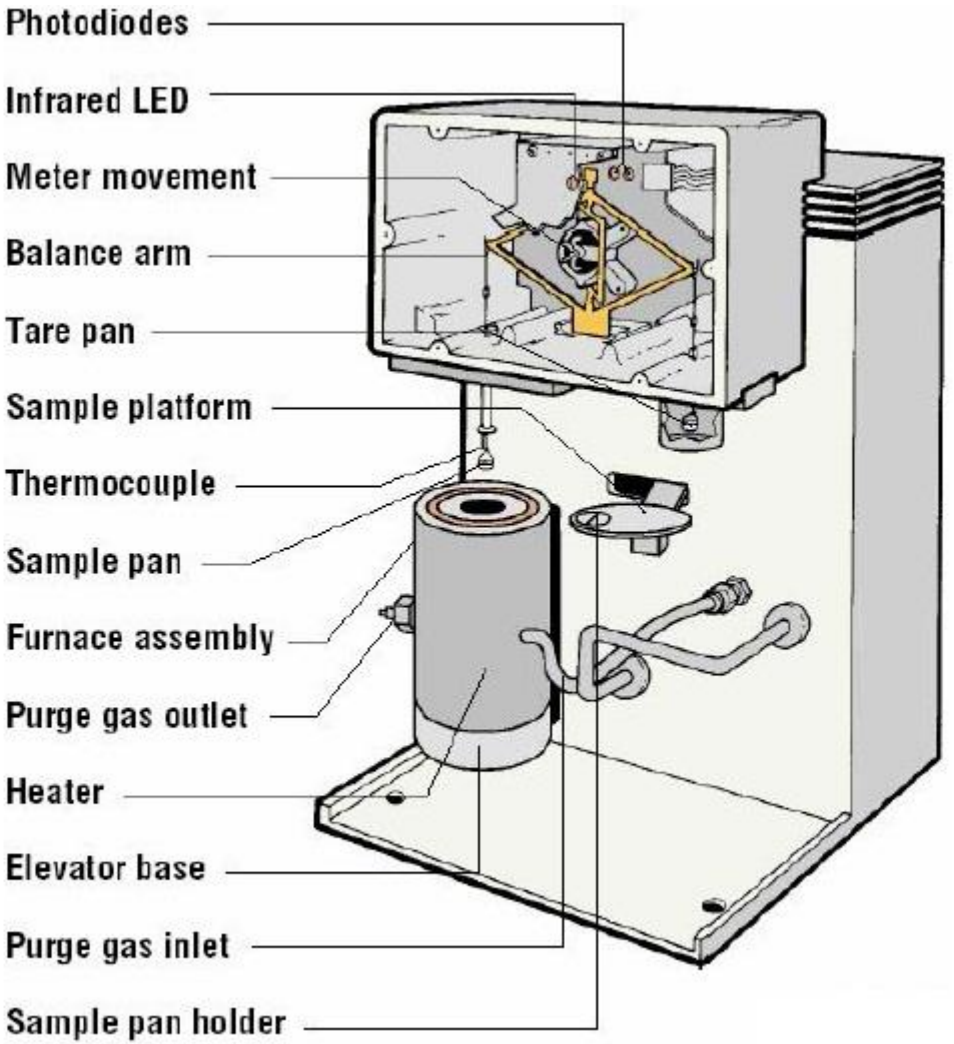
They both reacts only with the freshly exposed Si <111> surfaces

A MEMS based TGA

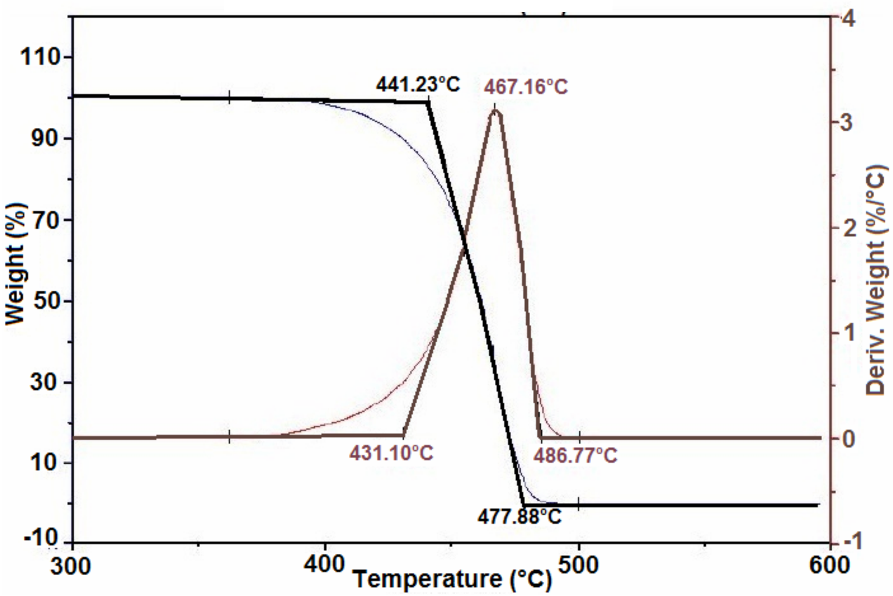
Sergio Carrato

DEEI, University of Trieste, Trieste, Italy

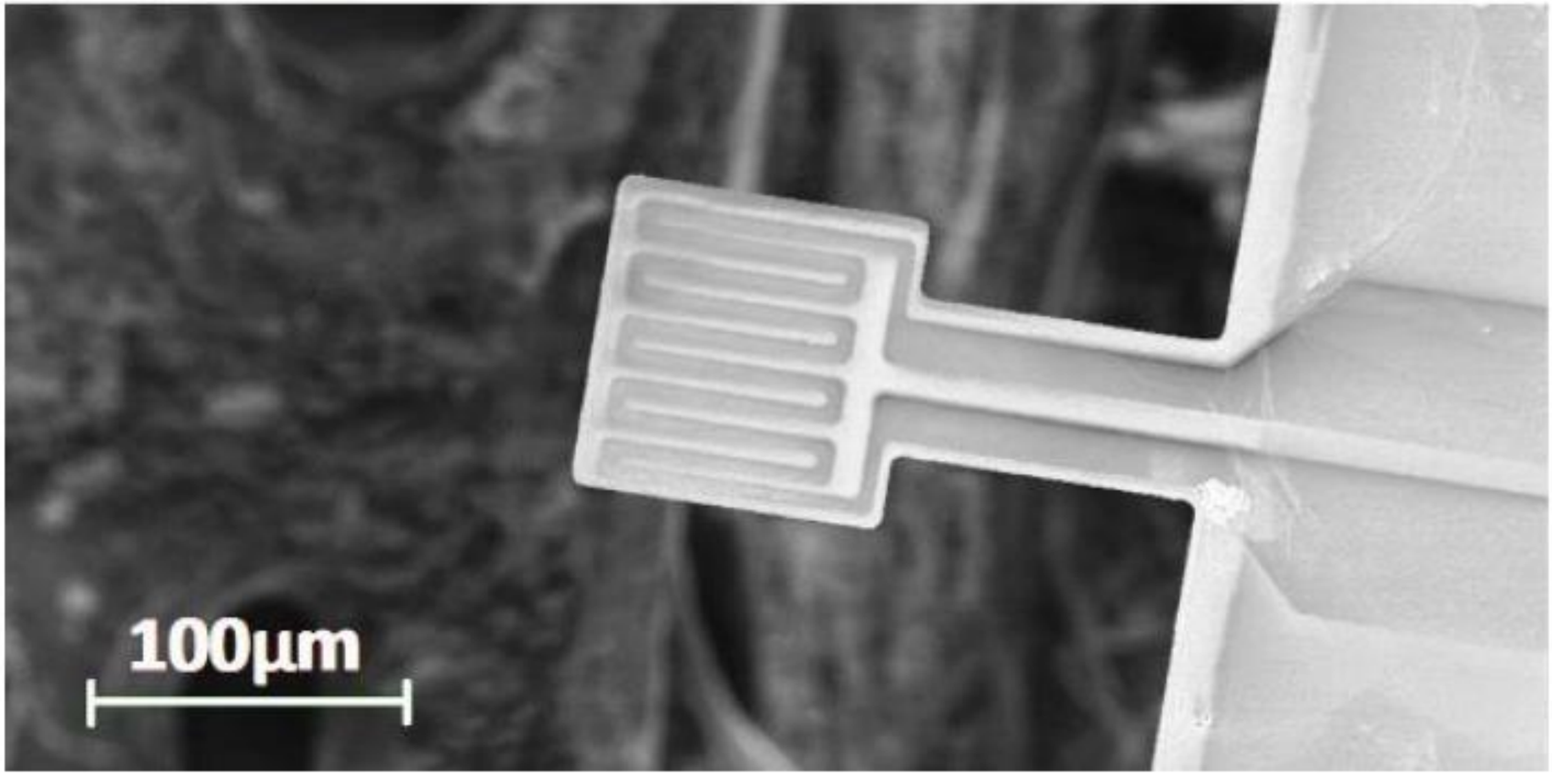
A commercial TGA



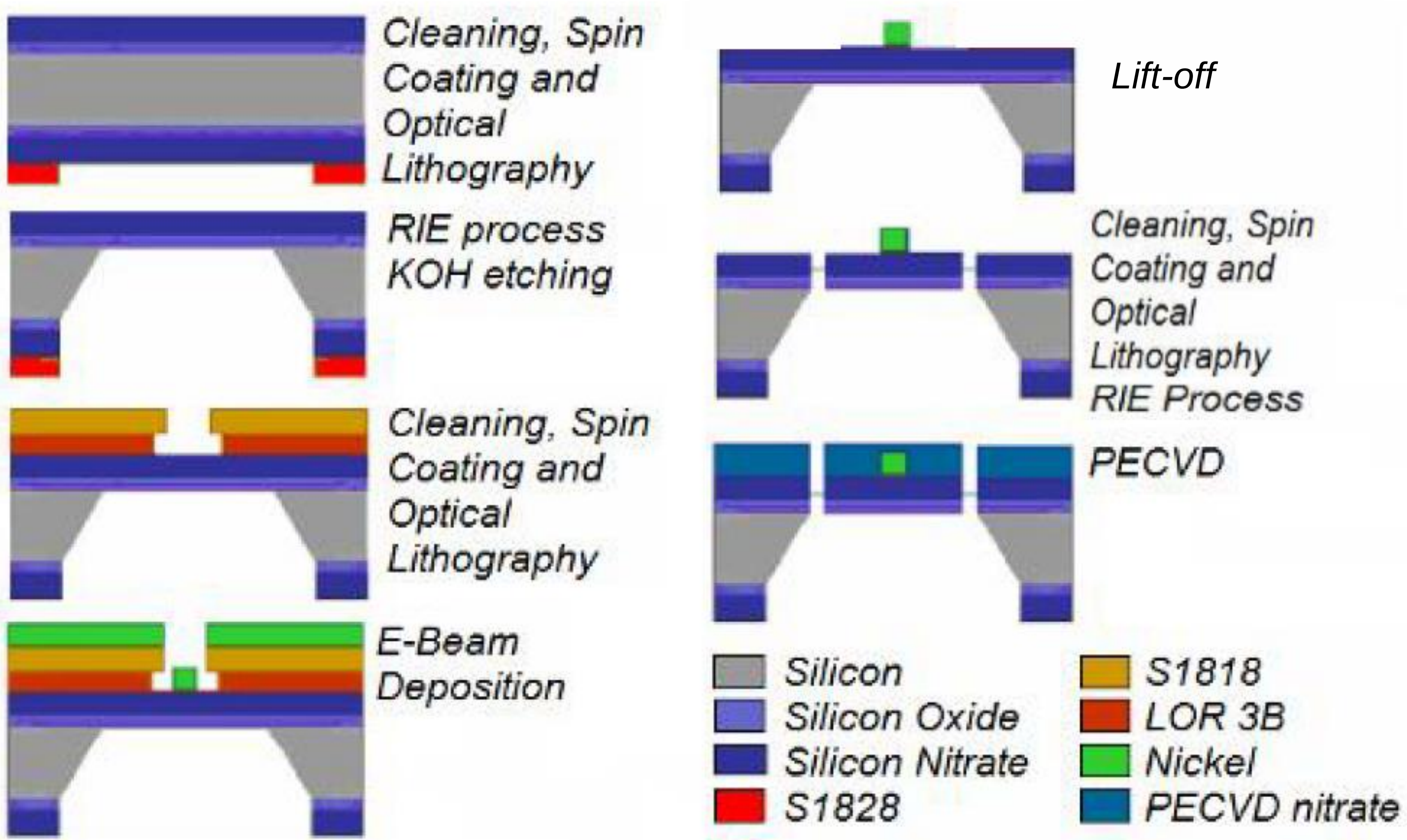
polythylene



Our TGA



Processing steps

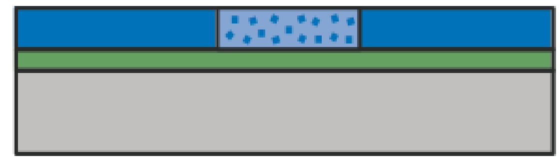


Processing step: lift-off

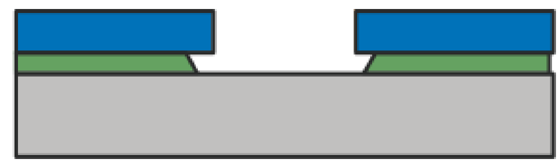
LOR lift-off resists are based on polydimethylglutarimide (PMGI) polymers and are well suited for a variety of lift-off processes, and as sacrificial release layers.

1. Coat and soft-bake LOR or PMGI.

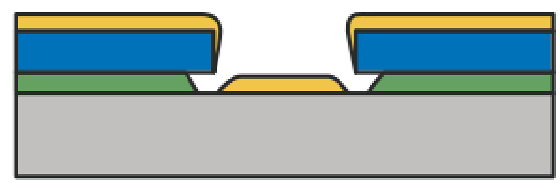
2. Coat and soft-bake imaging resist.



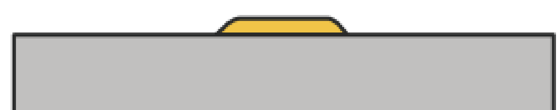
3. Expose imaging resist.



4. Develop resist and LOR or PMGI. LOR or PMGI develops isotropically, creating a bi-layer re-entrant sidewall profile.

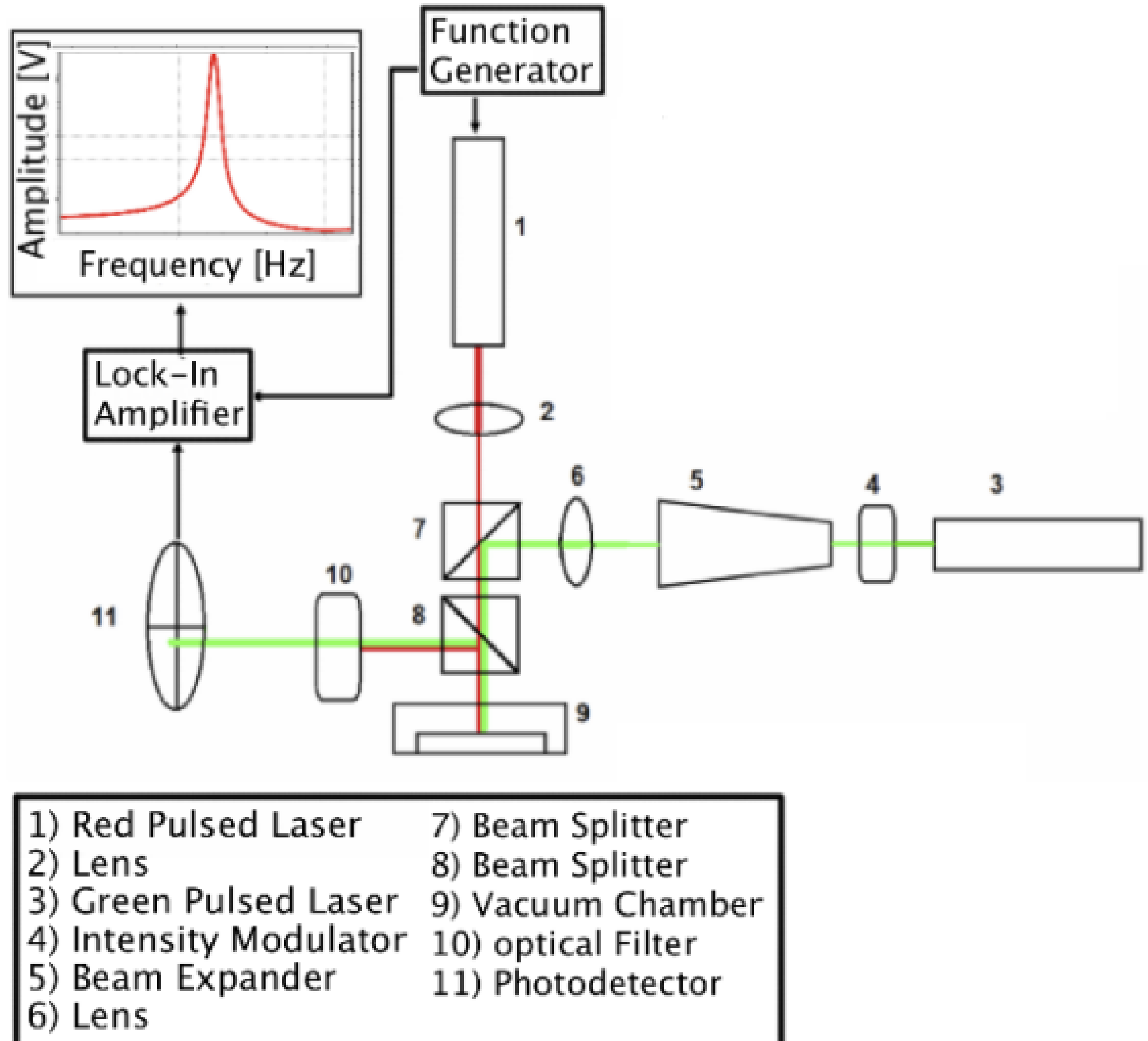


5. Deposit film. The re-entrant profile ensures discontinuous film deposition.



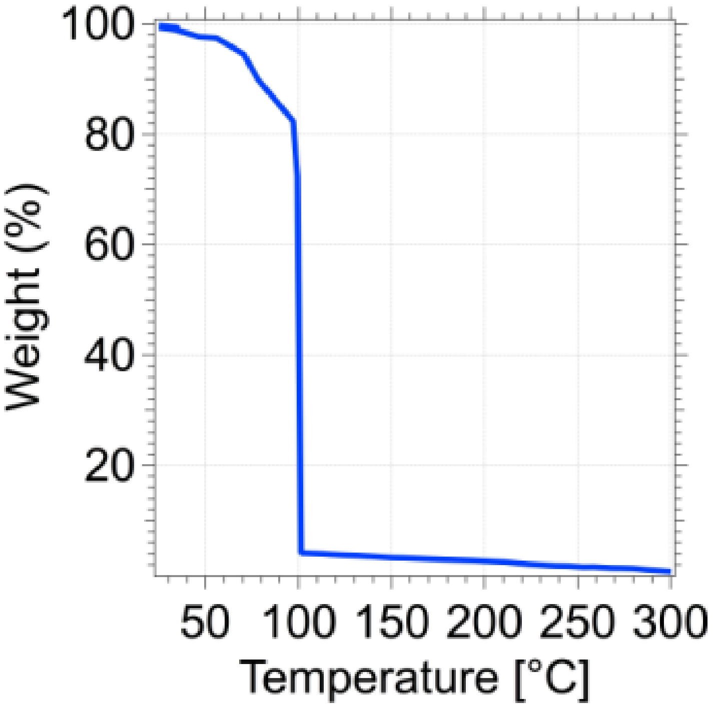
6. Lift off bi-layer resist stack, leaving only desired film.

Electronics



Advantages

- Faster heating
- Reduced contaminations
- High sensitivity
- Local heating
- Disposable devices

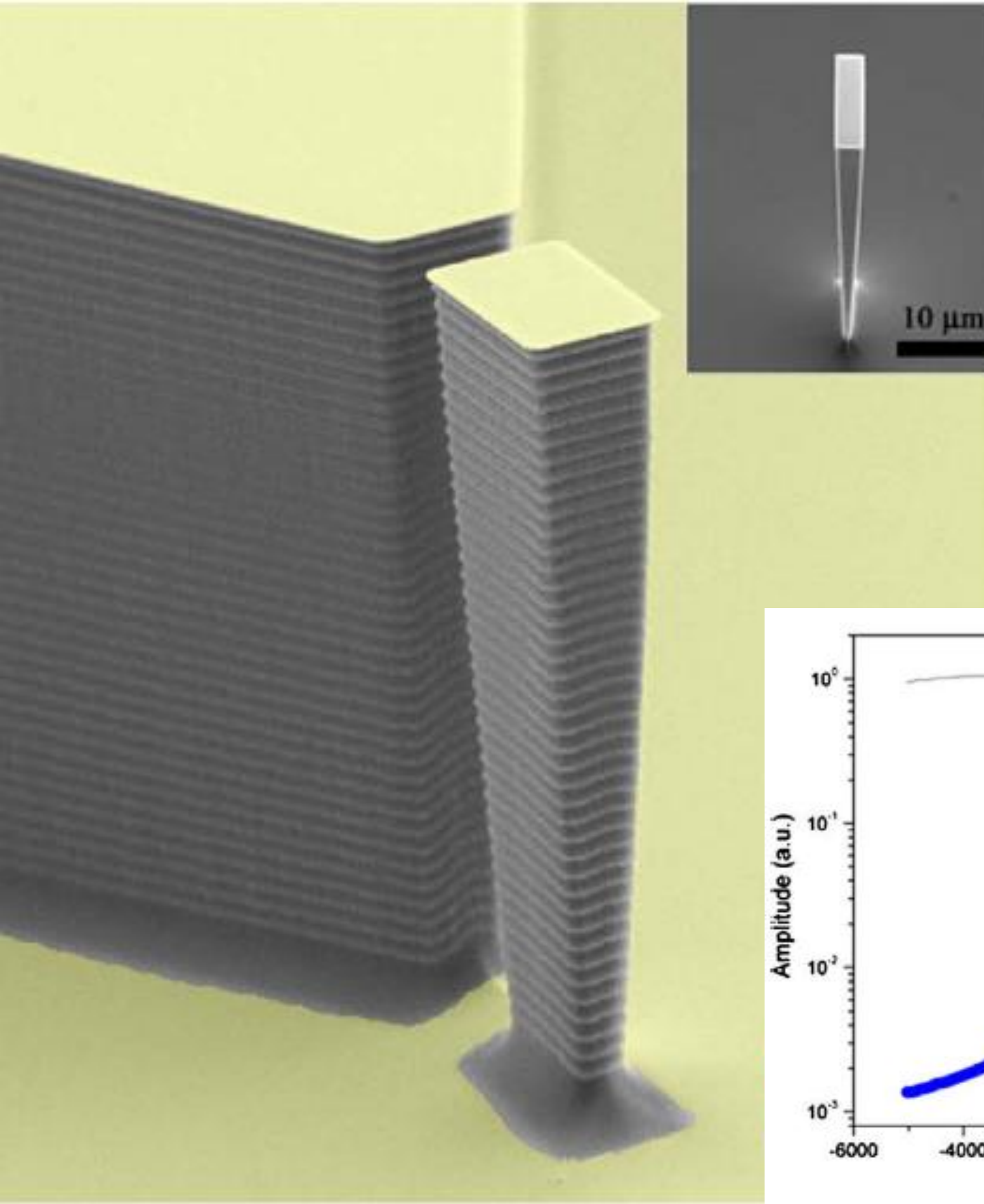


Test with water

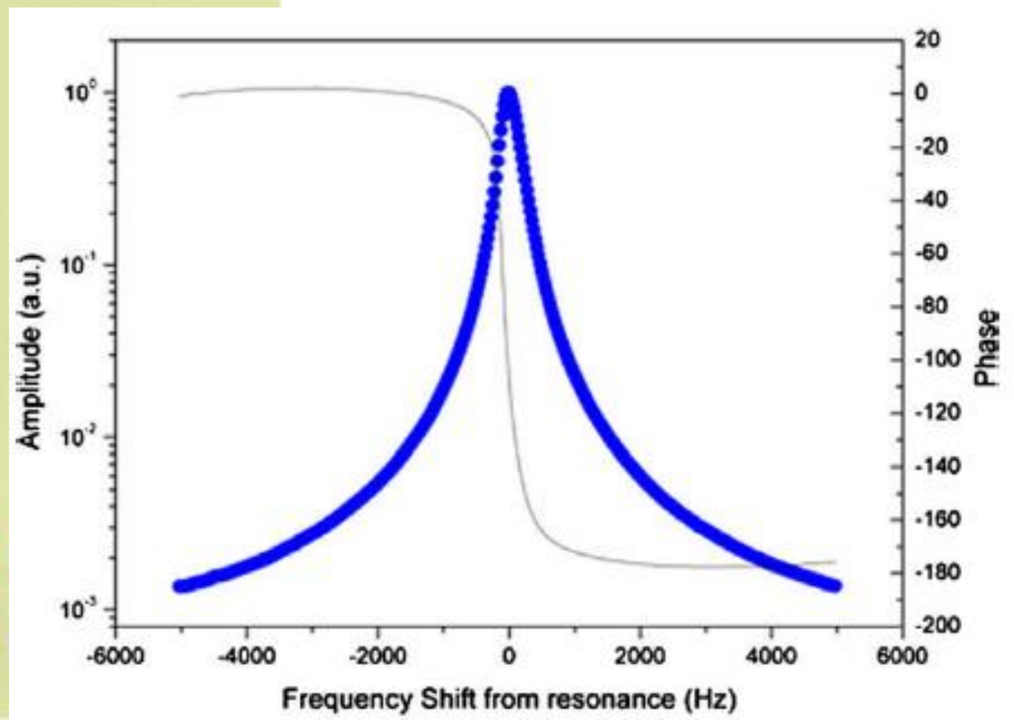
Actuation of silicon pillar micro-mechanical resonators by Kelvin polarization force

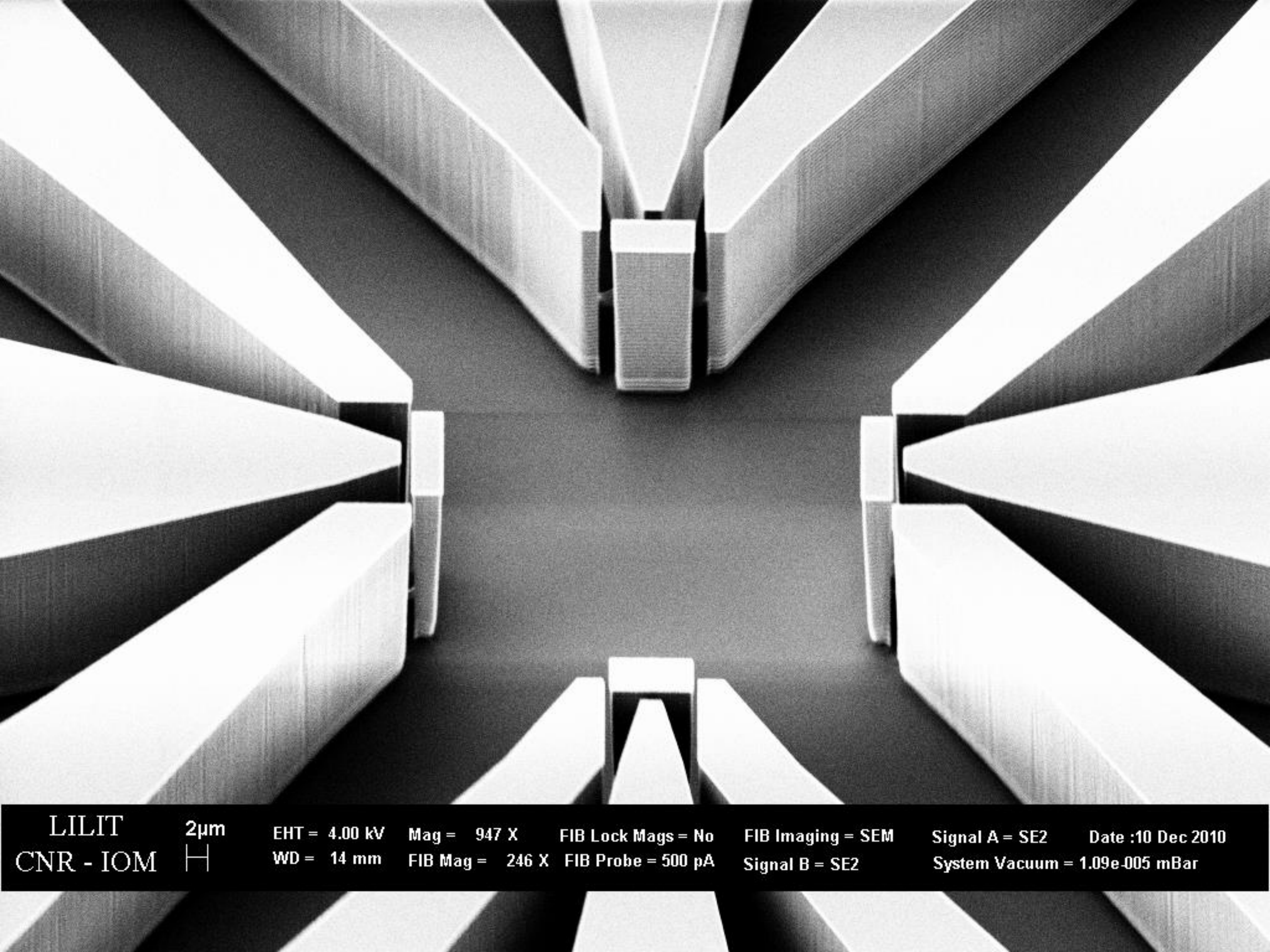
Carrato

DEEI, University of Trieste, Trieste, Italy

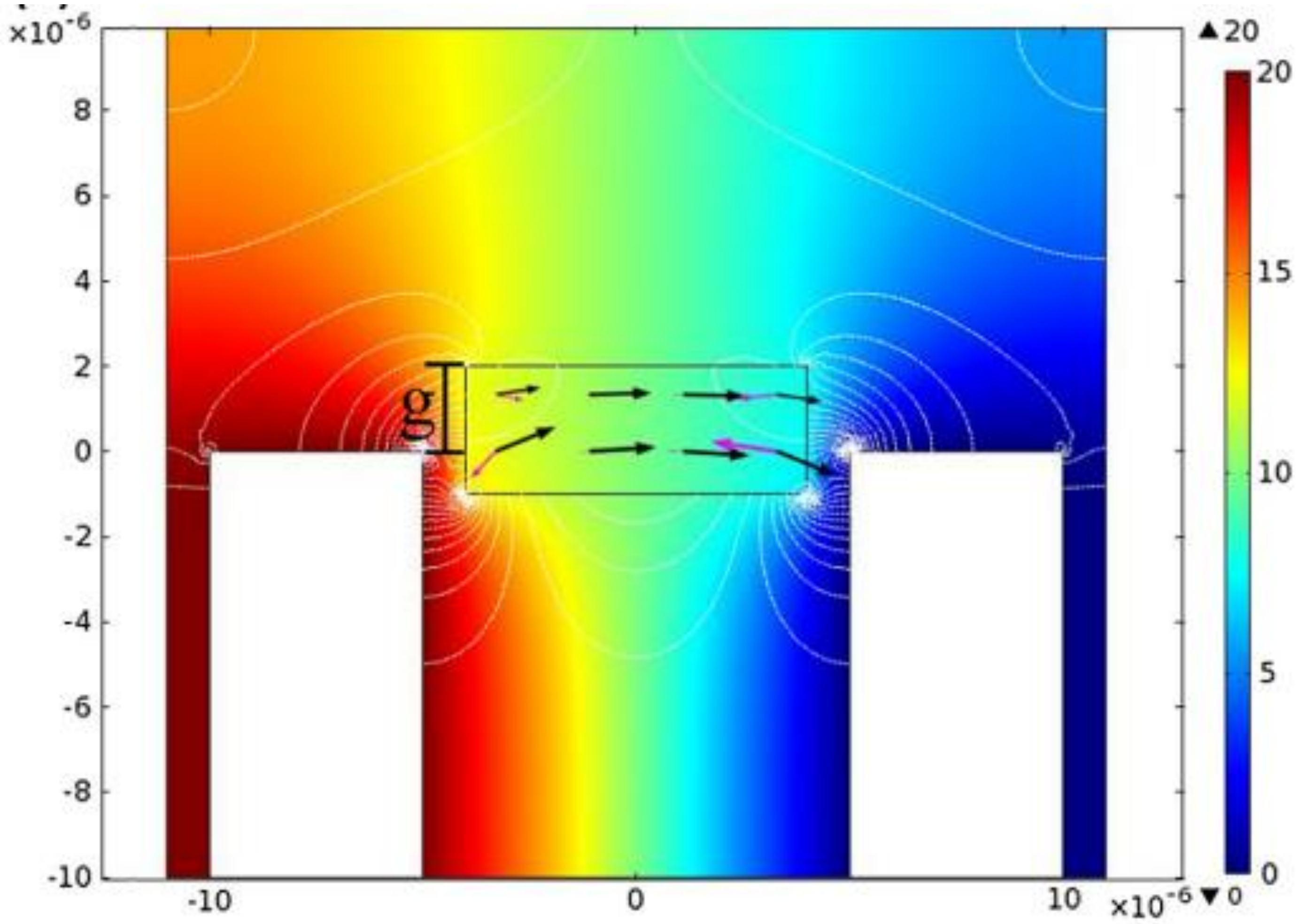

10 µm

Our pillar

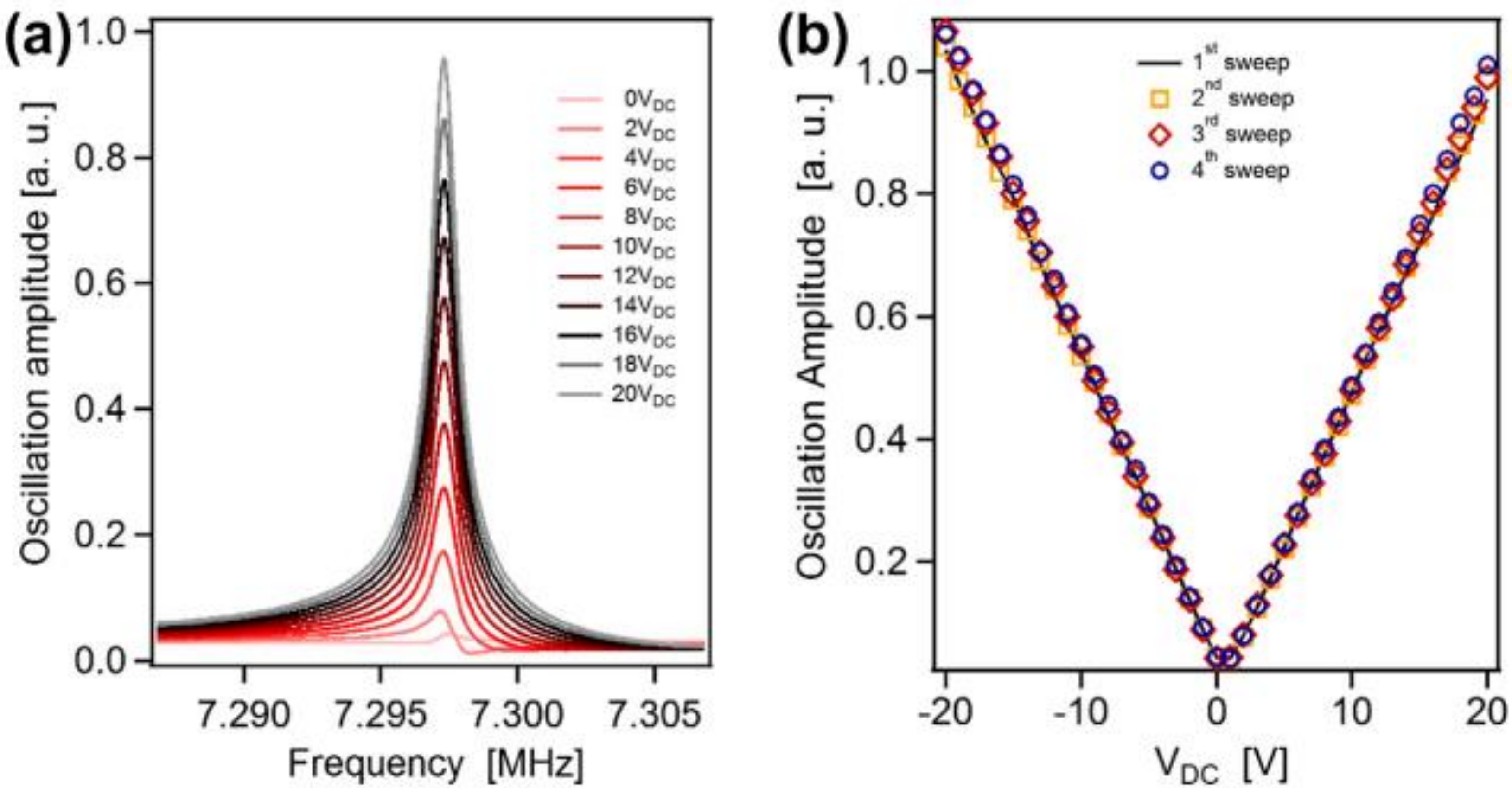

Amplitude (a.u.)
Phase
Frequency Shift from resonance (Hz)
-6000
-4000
-2000
0
2000
4000
6000
10⁰
10⁻¹
10⁻²
10⁻³
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200


LILIT
CNR - IOM
2µm
EHT = 4.00 kV
WD = 14 mm
Mag = 947 X
FIB Mag = 246 X
FIB Lock Mags = No
FIB Probe = 500 pA
FIB Imaging = SEM
Signal B = SE2
Signal A = SE2
Date :10 Dec 2010
System Vacuum = 1.09e-005 mBar

Electric potential



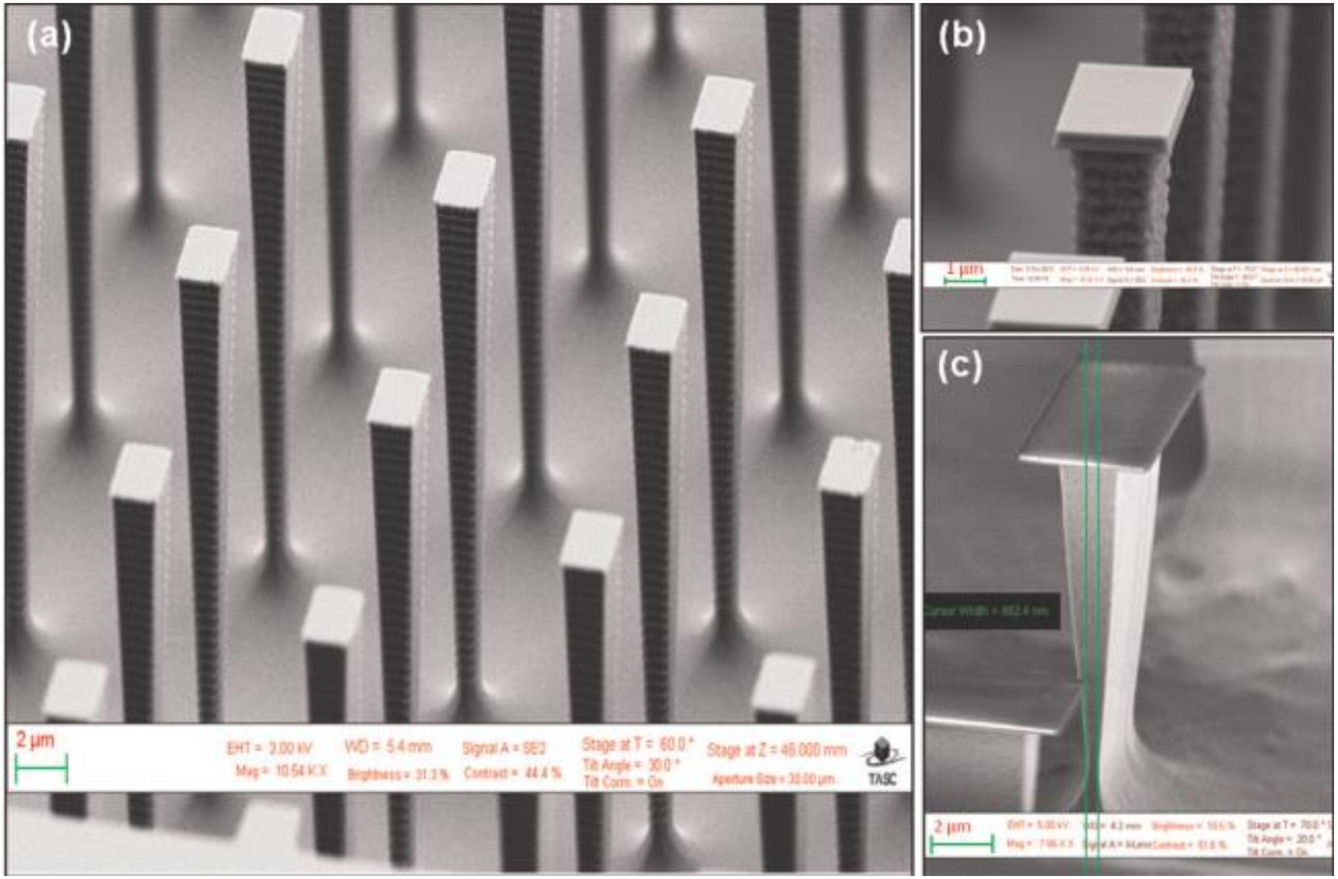
Resonance amplitude, and dependence on V_{DC}



Parallel optical read-out of micromechanical pillars applied to prostate specific membrane antigen detection

DEEI, University of Trieste, Trieste, Italy

SEM image of a micropillars array obtained from deep plasma etching of a patterned silicon wafer



Optical detection of pillar resonance