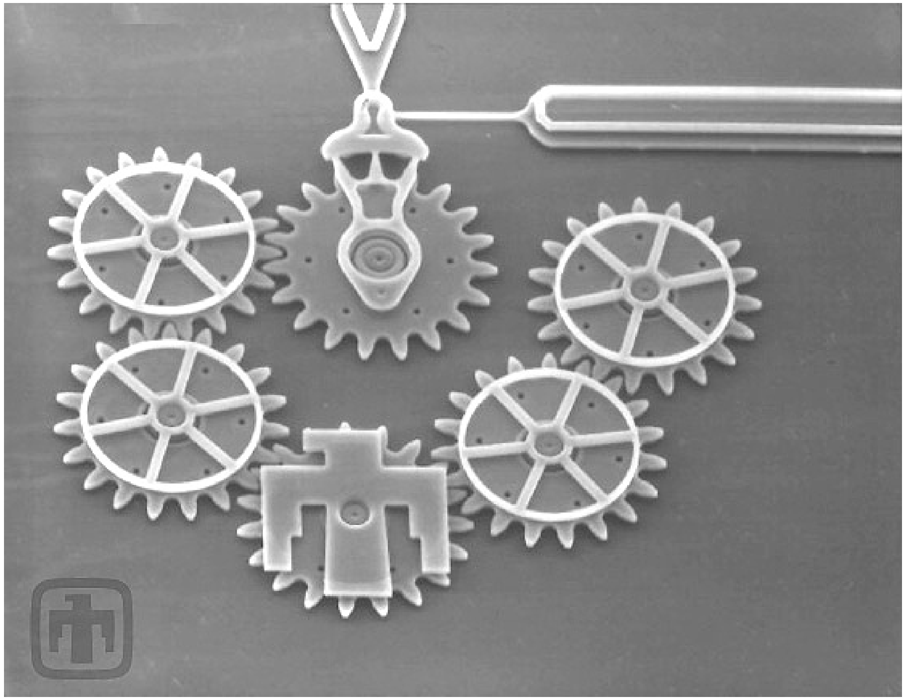
Micro-Electro-Mechanical Systems (MEMS)

Sensors
Actuators
Cantilevers
Gears
Accelerometers
Gyroscopes
Microphones
Capacitive comb drives
RF MEMs



International Technology Roadmap for Semiconductors
2013 Edition

Micro-Electro-Mechanical Systems (MEMS) are mechanical sensors and actuators that are fabricated using techniques similar to those used for integrated circuits. They are micrometer-sized mechanical structures, such as cantilevers, combs, membranes, and channels that are often integrated with logic circuitry. MEMS can act as sensors, receiving information from their environment, or as actuators, responding to decisions from the control system to change the environment.

A MEMS device typically contains a micro-electro-mechanical sensor or actuator element packaged together with an integrated circuit (IC). The IC provides an electronic interface to the sensor or actuator, signal processing / compensation, and analog and or digital output. The micro-electro-mechanical sensor or actuator can be integrated monolithically or co-integrated with the IC. Monolithic integration refers to a MEMS device that is integrated on the IC chip, while co-integration refers to a MEMS device that is on a separate chip and packaged together with the IC.

International Technology Roadmap for Semiconductors
2013 Edition

A major challenge to roadmapping MEMS technology has been the diversity of applications for MEMS, which include pressure sensors, ink jet printer cartridges, accelerometers, digital light projectors, bolometers, gas sensors, surgical tools, microphones, portable medical diagnostic systems, and more.

- Accelerometers
- Gyroscopes
- Inertial Measurement Units (IMUs)
- Microphones
- RF MEMS

Bridges and cantilevers

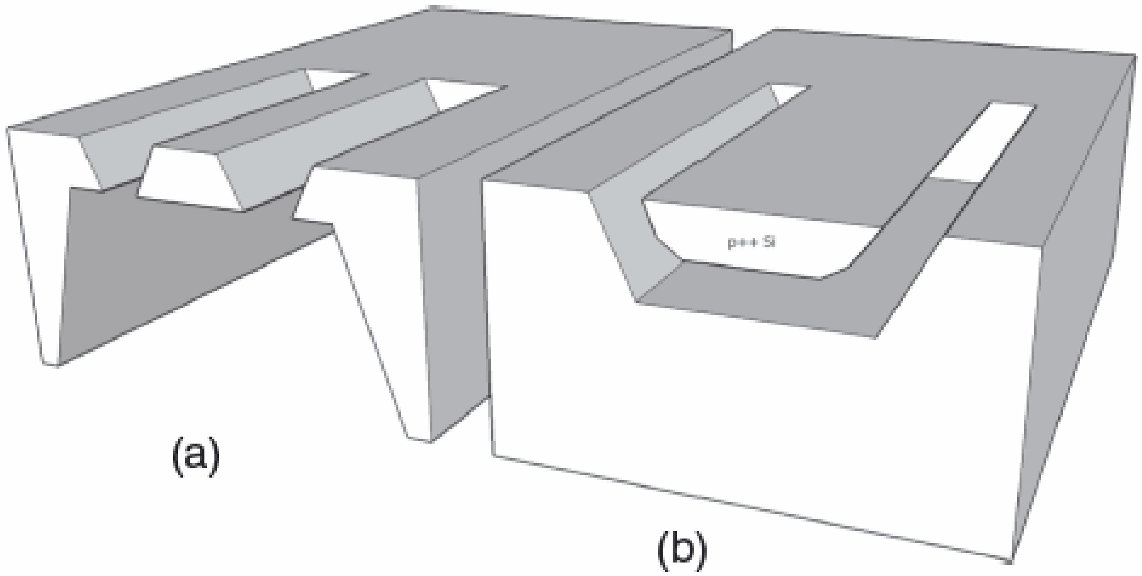


Figure 30.1 Silicon microbridges: (a) front-side KOH definition and timed back-side KOH release; (b) front-side bridge definition by p^{++} diffusion and front-side KOH release

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Bridges and cantilevers

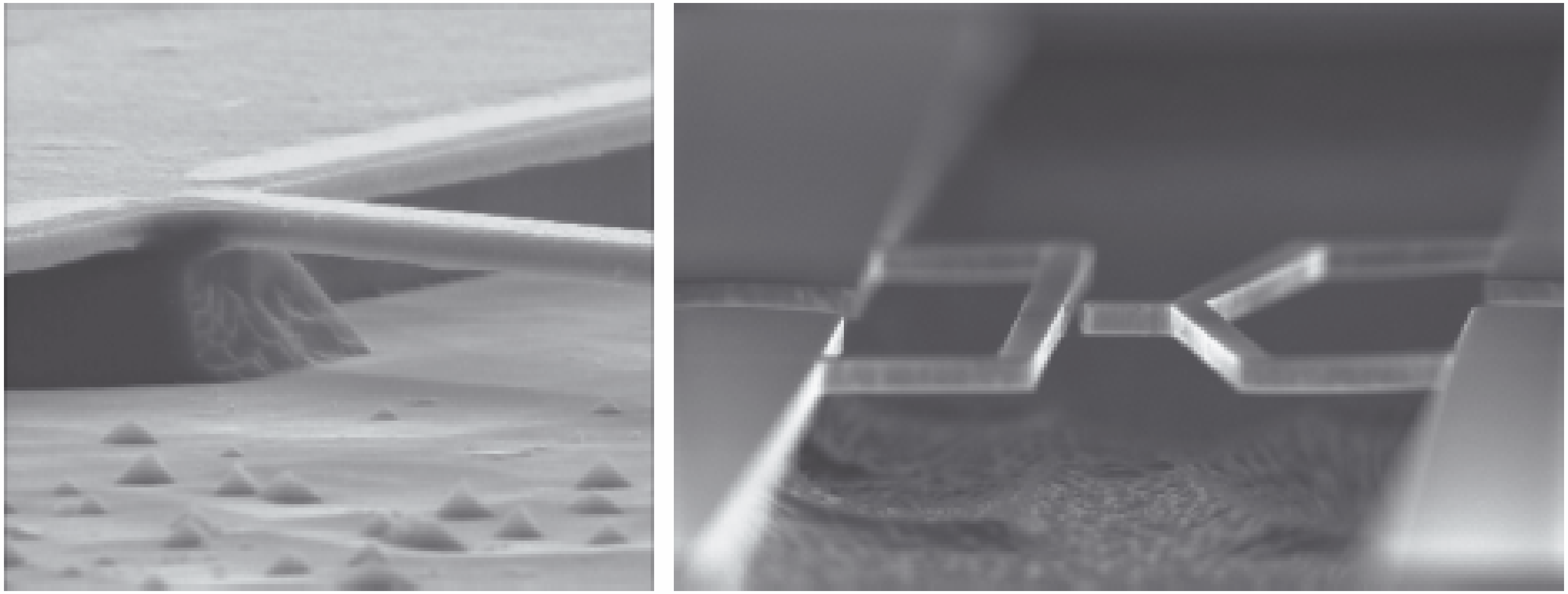

Figure 30.2 Microbridges by p^{++} etch stop and SOI. SEM micrographs courtesy Kestas Grigoras and Lauri Sainiemi, Aalto University

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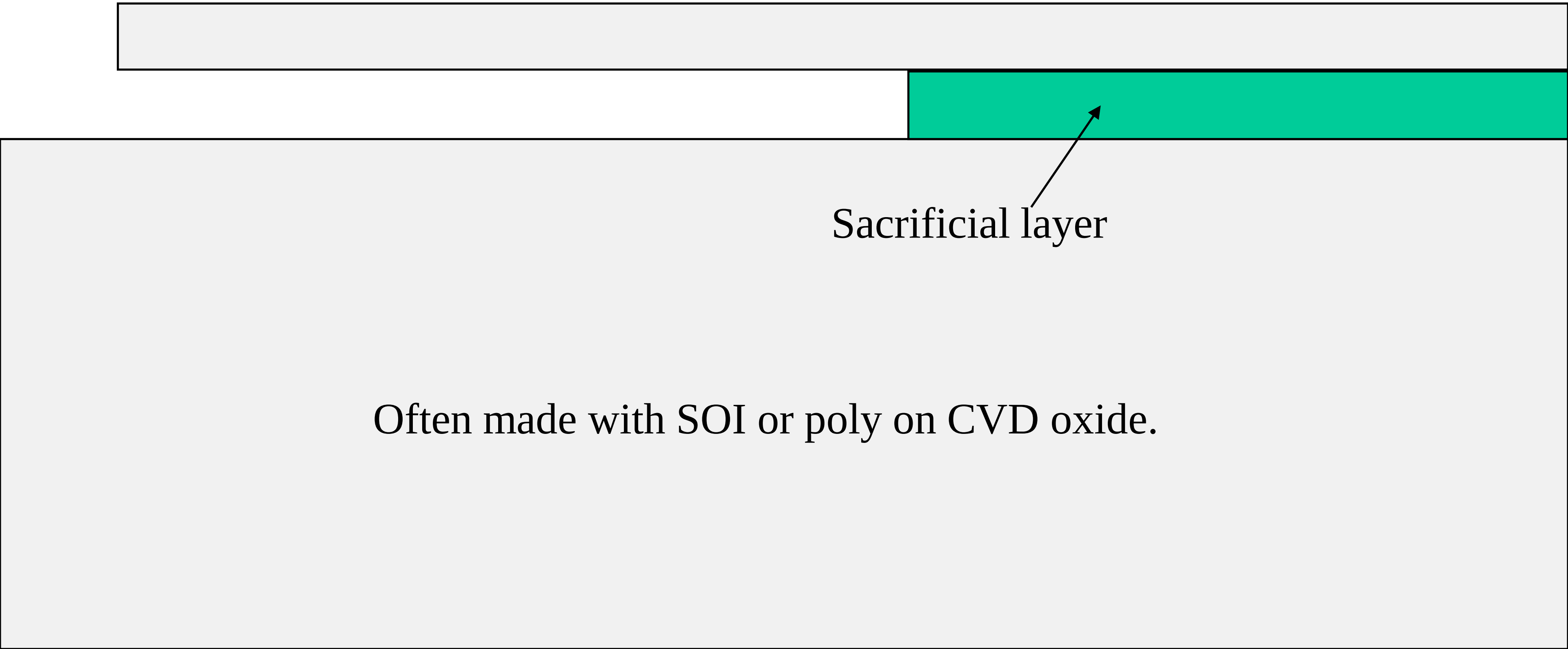
Etch selectivity between heavy and light boron doping.

Sacrificial layer

To make moving parts, components must be released from the substrate.

All lithographic steps should be complete before release, otherwise photoresist will get trapped.



Often made with SOI or poly on CVD oxide.

Cantilever fabrication

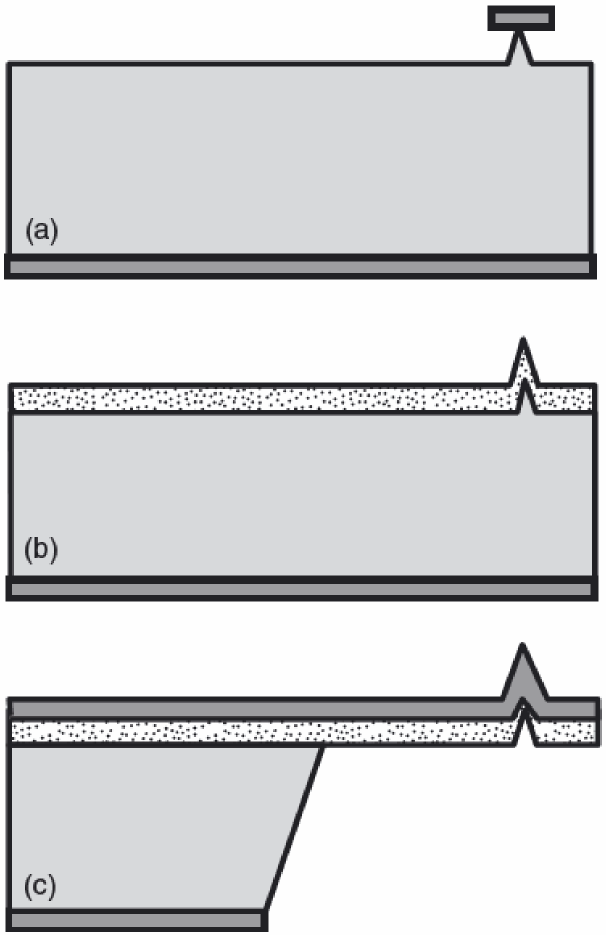


Figure 20.2 AFM cantilever and tip: (a) oxide-masked etching of tip; (b) p^{++} boron doping on front side; (c) Thermal oxidation and KOH etching from back side, stopping on p^{++} layer

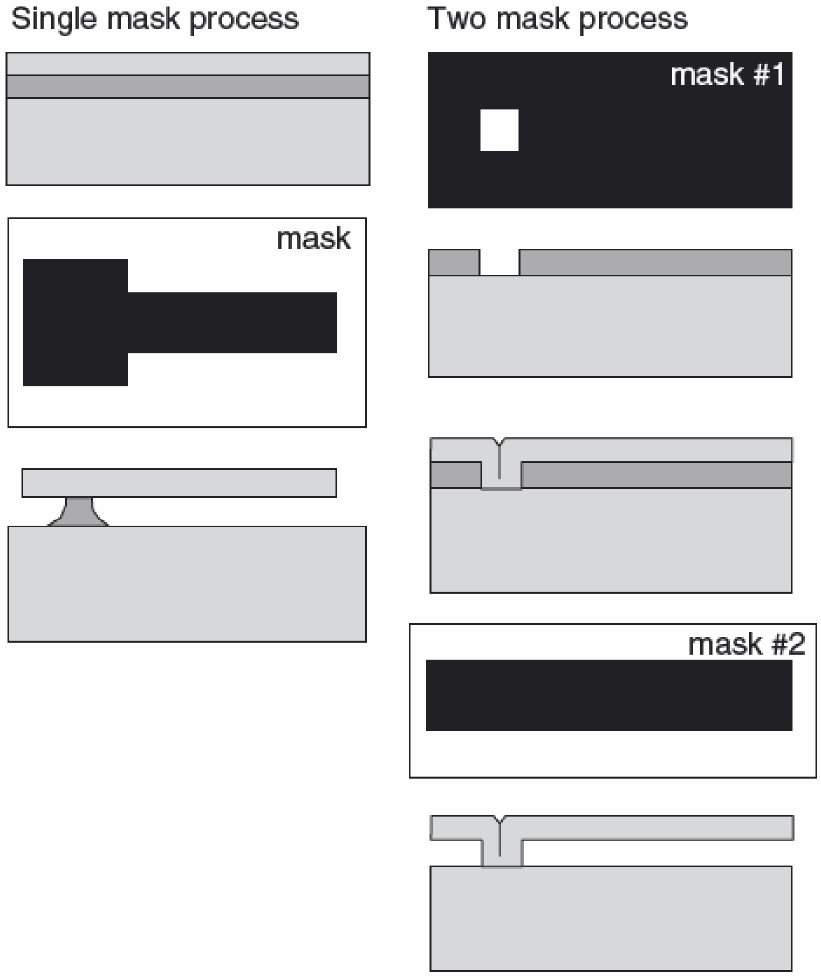
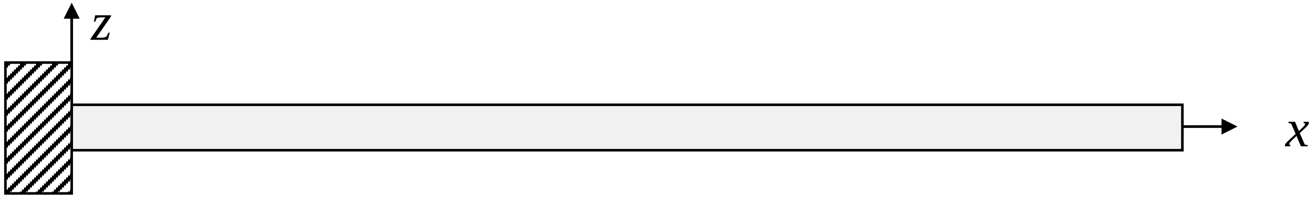


Figure 29.5 Polysilicon cantilevers with CVD oxide sacrificial layer: single mask process depends on timed etching while two-mask process is insensitive to oxide etch time

Beam vibrations

The Euler–Lagrange equation for a beam vibrating in the *x*-*z* plane is,



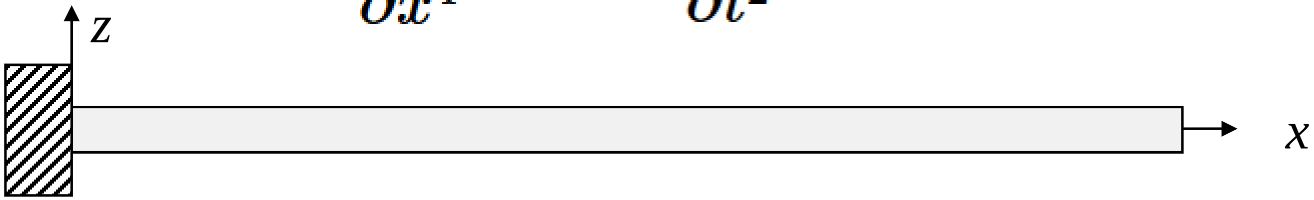
$$EI\frac{\partial^4 w}{\partial x^4} = -\mu\frac{\partial^2 w}{\partial t^2} + q(x)$$

w is the displacement of the beam in the *z* direction
E is the elastic modulus
μ is the mass per unit length
q is the load on the beam acting in the *z*-direction
I is the second moment of area of the beam's cross-section,

$$I = \int\int z^2 dydz.$$

Beam vibrations

$$EI\frac{\partial^4 w}{\partial x^4} = -\mu\frac{\partial^2 w}{\partial t^2} + q(x)$$

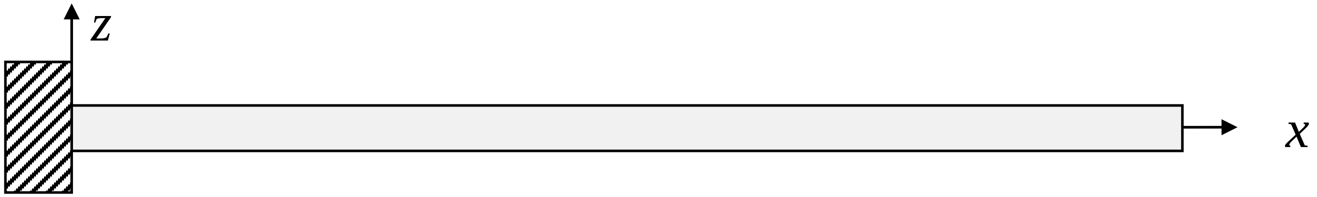


Normal mode solution:

$$w(x,t) = \left(A_1 \sin(kx) + A_2 \cos(kx) + A_3 \sinh(kx) + A_4 \cosh(kx)\right) e^{-i\omega t}$$

$$\omega = \sqrt{\frac{EI}{\mu}}\,k^2$$

Cantilever vibrations



Boundary conditions:

$$w = 0 \quad \text{and} \quad \frac{\partial w}{\partial x} = 0 \quad \text{at} \quad x = 0,$$

$$\frac{\partial^2 w}{\partial x^2} = 0 \quad \text{and} \quad \frac{\partial^3 w}{\partial x^3} = 0 \quad \text{at} \quad x = L_x$$

Solution:

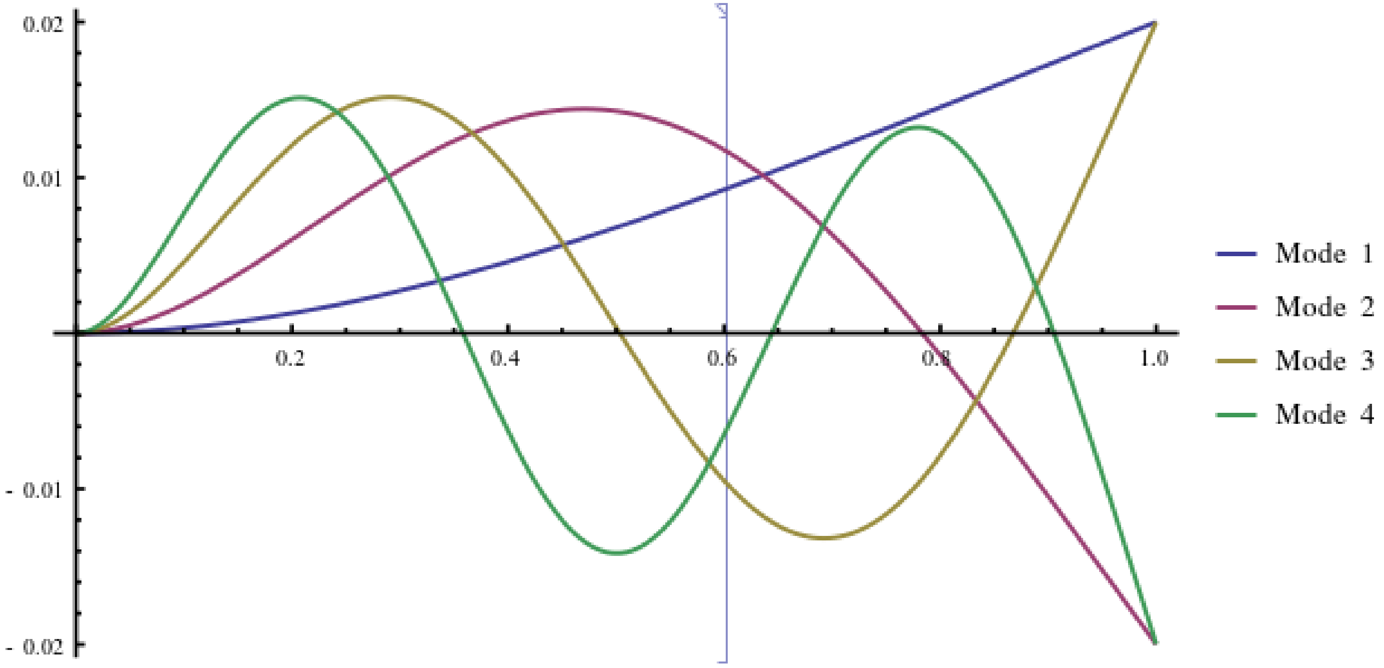
$$w_n(x,t) = A_n \left(\cosh(k_n x) - \cos(k_n x) + \frac{(\cos(k_n L_x) + \cosh(k_n L_x))(\sin(k_n x) - \sinh(k_n x))}{\sin(k_n L_x) + \sinh(k_n L_x)} \right)$$

$$\cosh(k_n L_x)\cos(k_n L_x) + 1 = 0$$

$$k_1 L_x = 1.875,\ k_2 L_x = 4.694,\ k_3 L_x = 7.855,\ k_4 L_x = 10.9955,\ \cdots$$

Cantilever vibrations

$$\omega_1 = \frac{3.516}{L_x^2}\sqrt{\frac{EI}{\mu}}, \quad \omega_2 = \frac{22.03}{L_x^2}\sqrt{\frac{EI}{\mu}}, \quad \omega_3 = \frac{61.70}{L_x^2}\sqrt{\frac{EI}{\mu}}, \quad \omega_4 = \frac{120.9}{L_x^2}\sqrt{\frac{EI}{\mu}}, \cdots$$



Mass evaporated onto the beam can be calculated from the frequency shift.

Boundary conditions

$$\omega = \sqrt{\frac{EI}{\mu}}\,k^2$$

fixed - free

$k_1L = 1.875$
$k_2L = 4.694$
$k_3L = 7.855$
$k_4L = 10.996$

fixed - fixed

$k_1L = 4.730$
$k_2L = 7.853$
$k_3L = 10.996$
$k_4L = 14.137$

pinned - pinned

$k_1L = \pi$
$k_2L = 2\pi$
$k_3L = 3\pi$
$k_4L = 4\pi$

Beam vibrations

Knowing *k*, and *w* at the boundaries, you can solve for *w*(*x*,*t*).

$$w(x,t) = \left(A_1 \sin(kx) + A_2 \cos(kx) + A_3 \sinh(kx) + A_4 \cosh(kx)\right) e^{-i\omega t}$$

fixed - fixed

$k_1L = 4.730$
$k_2L = 7.853$
$k_3L = 10.996$
$k_4L = 14.137$

pinned - pinned

$k_1L = \pi$
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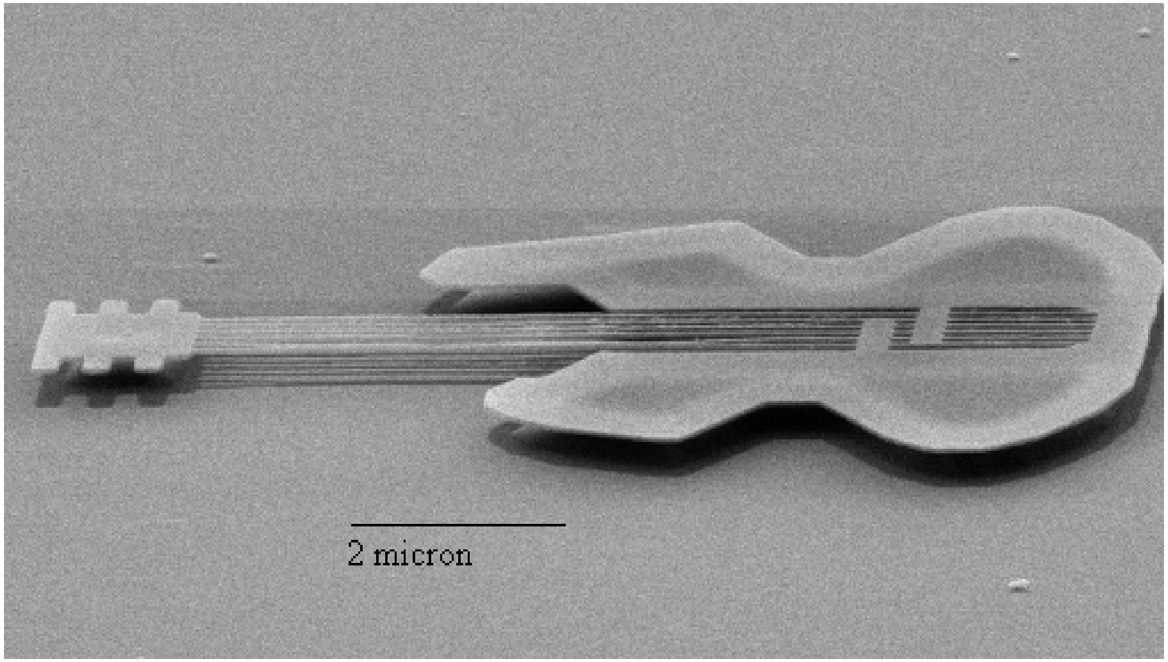
$k_4L = 4\pi$

Vibration frequencies



$k \sim 4.7/L \sim 8\text{E}5\ \text{m}^{-1}$

$$\omega = \sqrt{\frac{EI}{\mu}}k^2$$

E depends on the crystal orientation

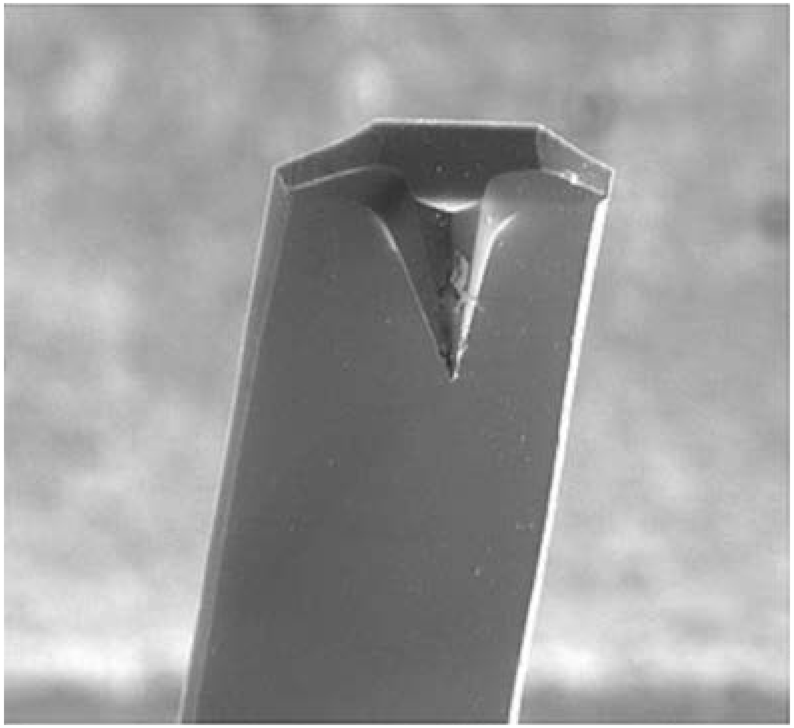
E(polysilicon) ~ 170 GPa

$f \sim 10$ MHz

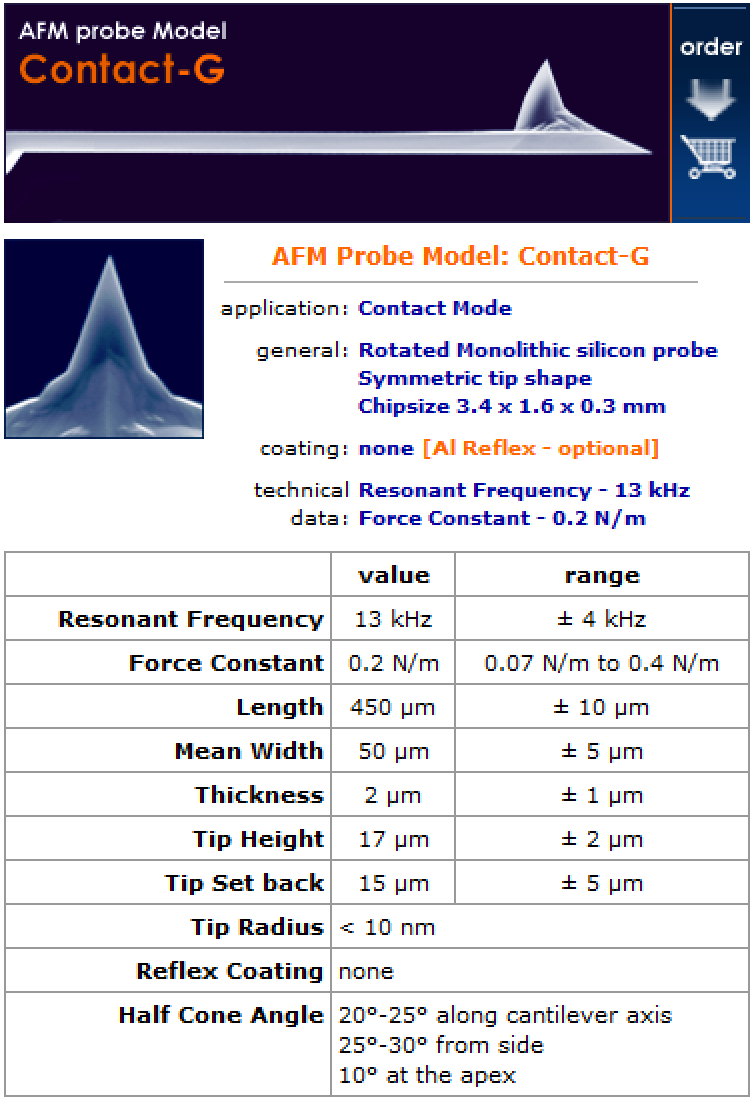
AFM

Contact model ~15 kHz
Noncontact mode ~200 kHz

Stiffer beams are used in nc-mode to avoid stiction.



http://ieeexplore.ieee.org/xpls/icp.jsp?arnumber=6817527



AFM Probe Model: Contact-G

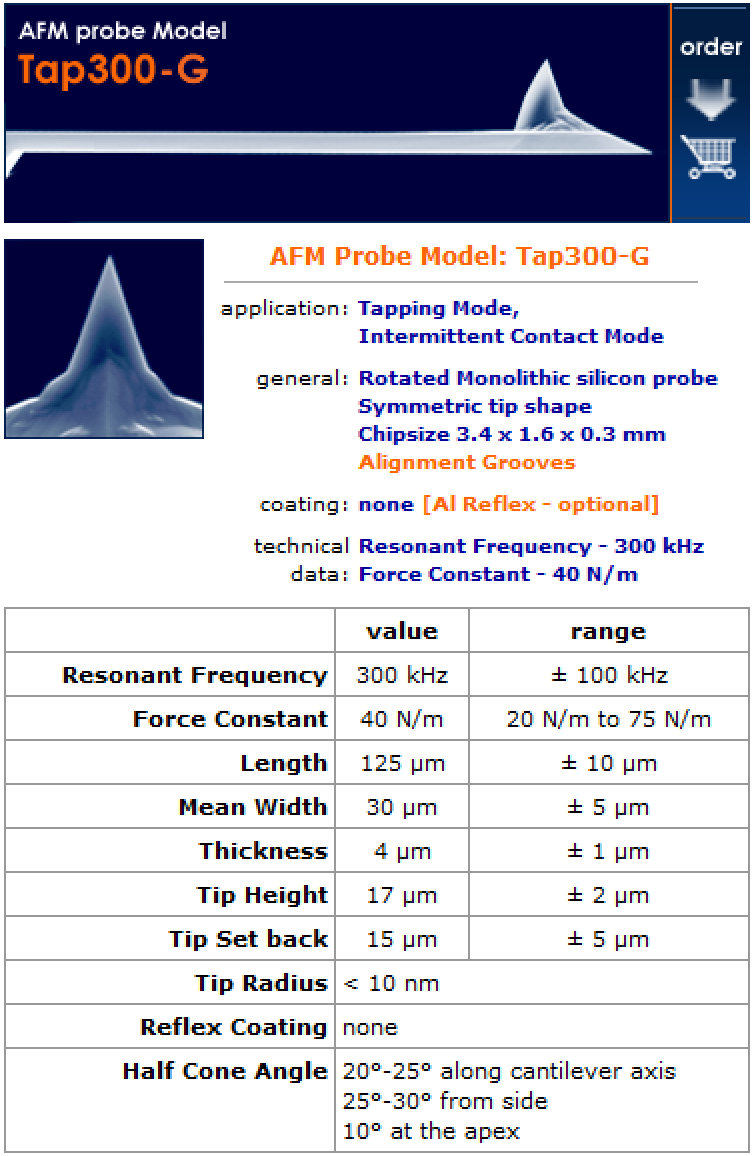
application: **Contact Mode**

general: **Rotated Monolithic silicon probe**
Symmetric tip shape
Chipsize 3.4 x 1.6 x 0.3 mm

coating: **none [Al Reflex - optional]**

technical data: **Resonant Frequency - 13 kHz**
Force Constant - 0.2 N/m

	value	range
Resonant Frequency	13 kHz	± 4 kHz
Force Constant	0.2 N/m	0.07 N/m to 0.4 N/m
Length	450 µm	± 10 µm
Mean Width	50 µm	± 5 µm
Thickness	2 µm	± 1 µm
Tip Height	17 µm	± 2 µm
Tip Set back	15 µm	± 5 µm
Tip Radius	< 10 nm	
Reflex Coating	none	
Half Cone Angle	20°-25° along cantilever axis 25°-30° from side 10° at the apex	



AFM Probe Model: Tap300-G

application: **Tapping Mode,**
Intermittent Contact Mode

general: **Rotated Monolithic silicon probe**
Symmetric tip shape
Chipsize 3.4 x 1.6 x 0.3 mm
Alignment Grooves

coating: **none [Al Reflex - optional]**

technical data: **Resonant Frequency - 300 kHz**
Force Constant - 40 N/m

	value	range
Resonant Frequency	300 kHz	± 100 kHz
Force Constant	40 N/m	20 N/m to 75 N/m
Length	125 µm	± 10 µm
Mean Width	30 µm	± 5 µm
Thickness	4 µm	± 1 µm
Tip Height	17 µm	± 2 µm
Tip Set back	15 µm	± 5 µm
Tip Radius	< 10 nm	
Reflex Coating	none	
Half Cone Angle	20°-25° along cantilever axis 25°-30° from side 10° at the apex	

$$K_{eff} = 3EI/L^3$$

http://www.budgetsensors.com/tapping_mode_afm_probes.html

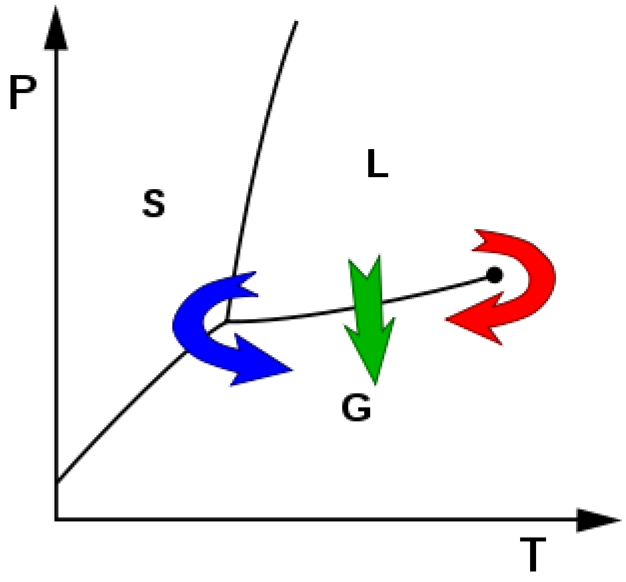
Stiction - Supercritical drying

Stiction is when two micromechanical parts touch and hold together due to Van der Waals forces or hydrogen bonds.

Capillary forces during drying can pull the components together.

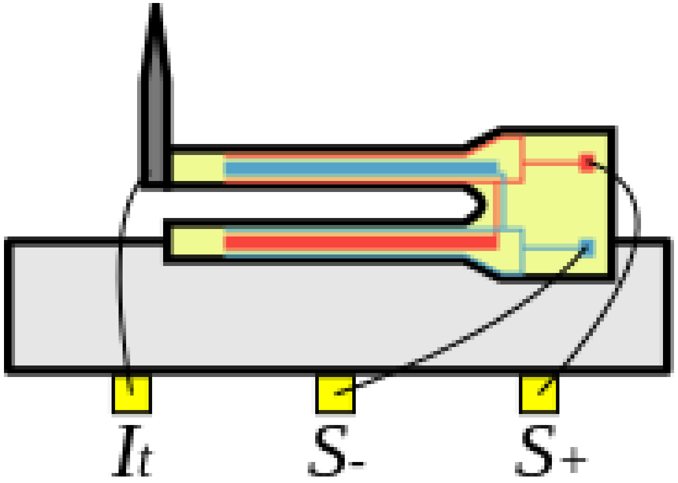
Supercritical drying (red arrow) in CO_2 is use avoid the capillary forces.

Water is washed away with acetone which is replaced by high pressure CO_2.



https://en.wikipedia.org/wiki/Supercritical_drying

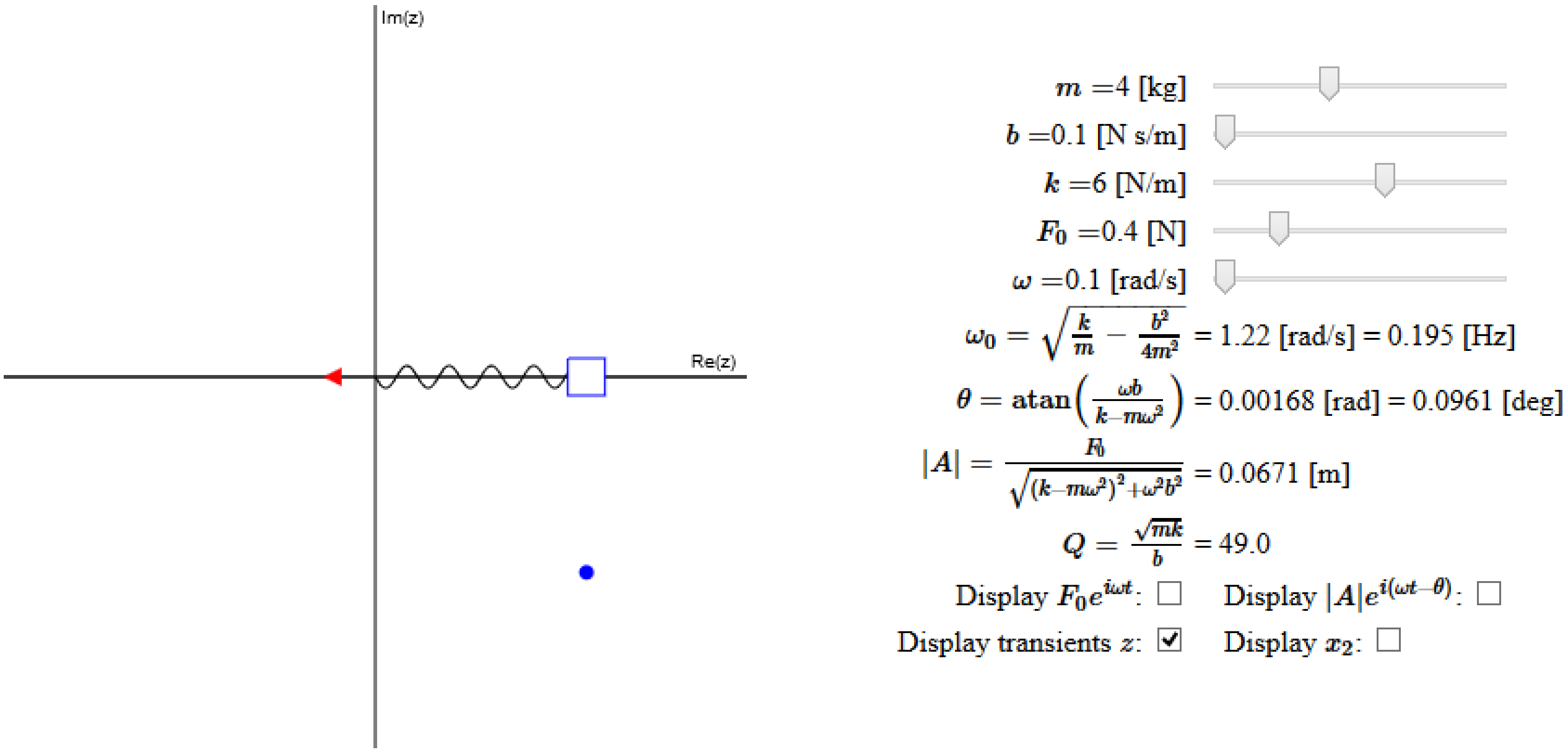
Tuning fork AFM



Compact, can be used in UHV
Use a phase-locked loop to detect frequency shift.

https://en.wikipedia.org/wiki/Non-contact_atomic_force_microscopy

Resonance of a damped driven harmonic oscillator



m =4 [kg]

b =0.1 [N s/m]

k =6 [N/m]

F_0 =0.4 [N]

ω =0.1 [rad/s]

$\omega_0 = \sqrt{\frac{k}{m} - \frac{b^2}{4m^2}}$ = 1.22 [rad/s] = 0.195 [Hz]

$\theta = \text{atan}\left(\frac{\omega b}{k - m\omega^2}\right)$ = 0.00168 [rad] = 0.0961 [deg]

$|A| = \frac{F_0}{\sqrt{(k - m\omega^2)^2 + \omega^2 b^2}}$ = 0.0671 [m]

$Q = \frac{\sqrt{mk}}{b}$ = 49.0

Display $F_0 e^{i\omega t}$: ☐ Display $|A|e^{i(\omega t - \theta)}$: ☐

Display transients z: ☑ Display x_2: ☐

Accelerometers

Measures acceleration
Phones
Free fall detectors
Game controllers
Airbag sensors
Tire pressure sensors
Machine vibrations
Seismic activity
Pedometers
Inertial navigation systems

(integrate the acceleration to determine where you are)

Piezoresistive accelerometer

Top resistor compressed
Bottom resistor stretched
under acceleration

Release holes to undercut
the proof mass.

SOI: Silicon On Insulator
DRIE: Deep Reactive
Ion Etching

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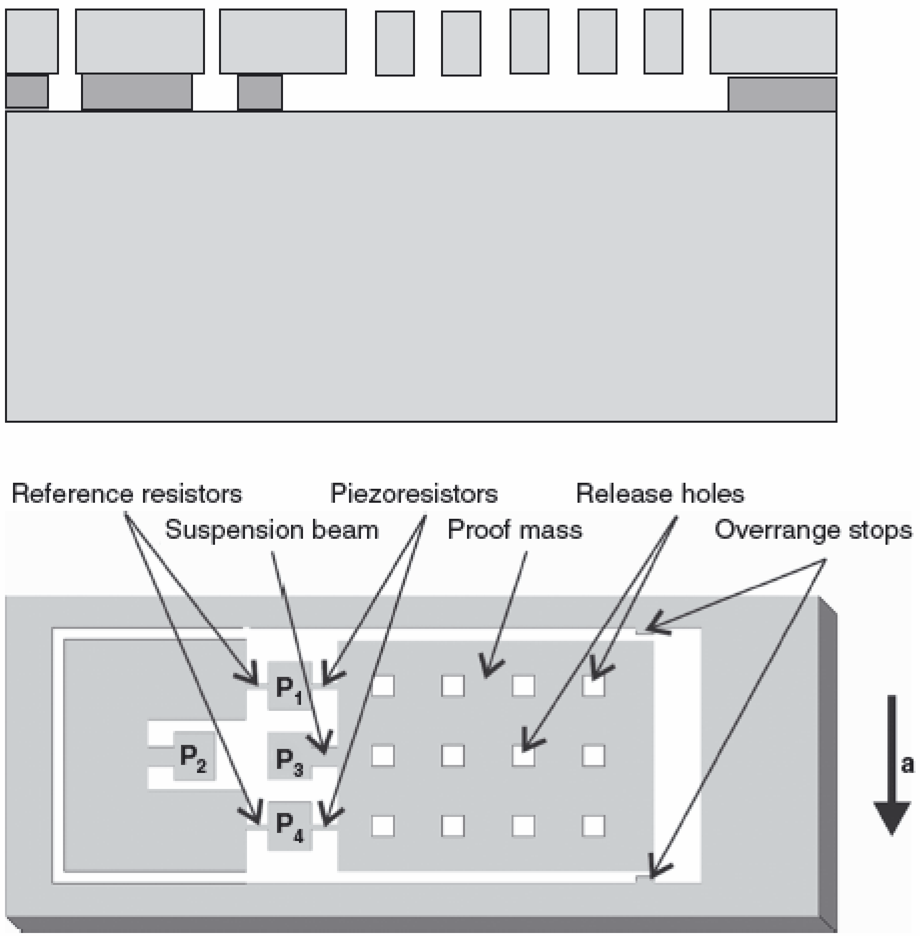
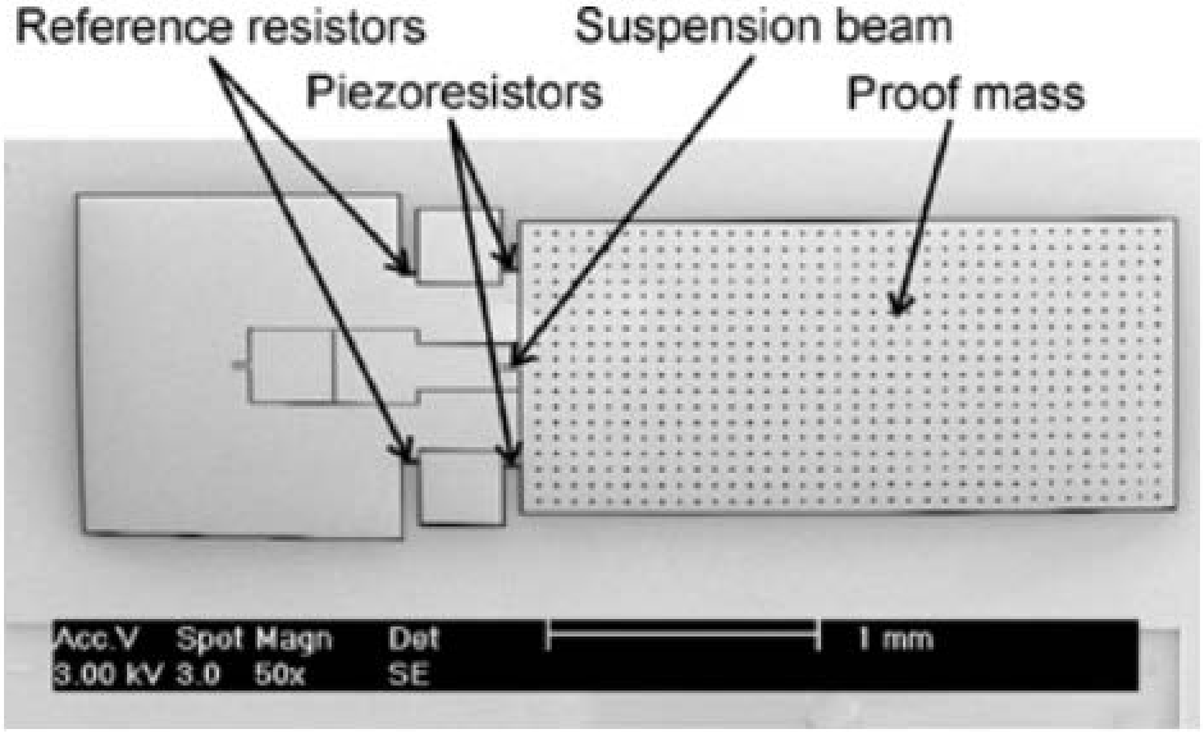


Figure 29.1 Piezoresistive accelerometer: cross sectional and top views of DRIE etched SOI device. Buried oxide etching for release. Reproduced from Eklund and Shkel (2007) by permission of IOP

Piezoresistive accelerometer

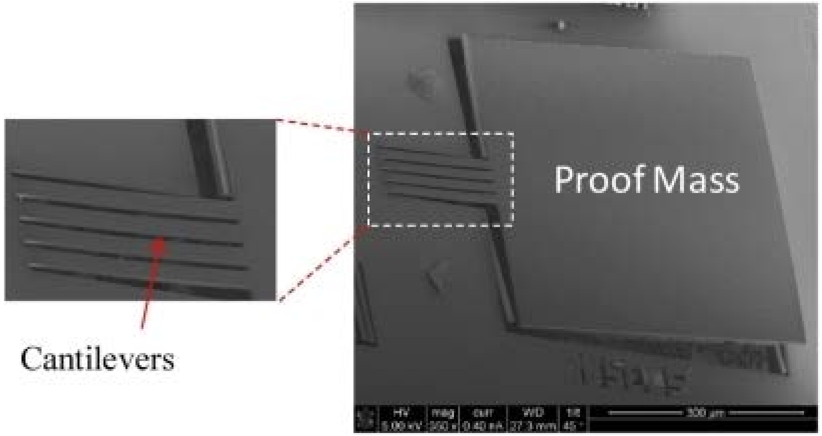


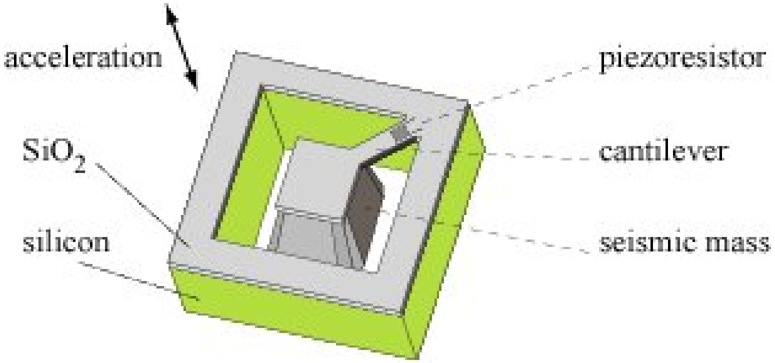
Scanning electron micrograph of an SOI-based piezoresistive accelerometer, fabricated in a single fabrication step.

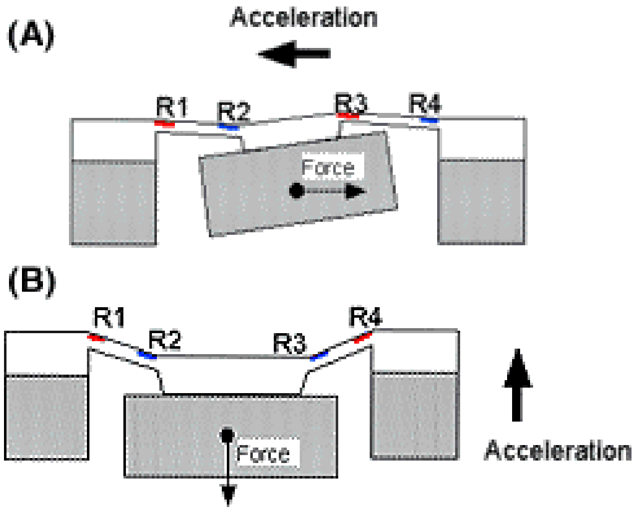
Scale bar is 1 mm

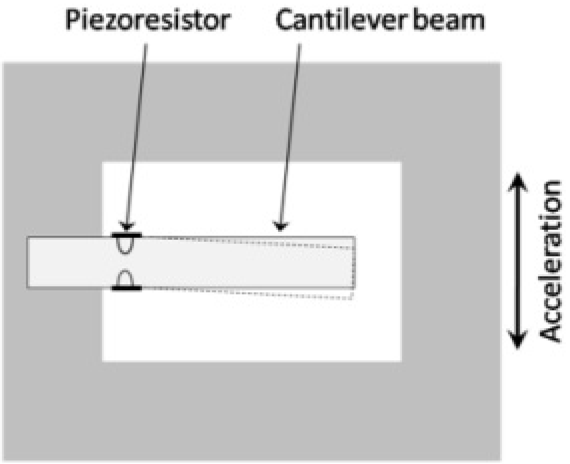
http://www.eng.uci.edu/news/2008/8/eecs-paper-showcased-journal-micromechanics-and-microengineering-highlights

Piezoresistive accelerometer designs







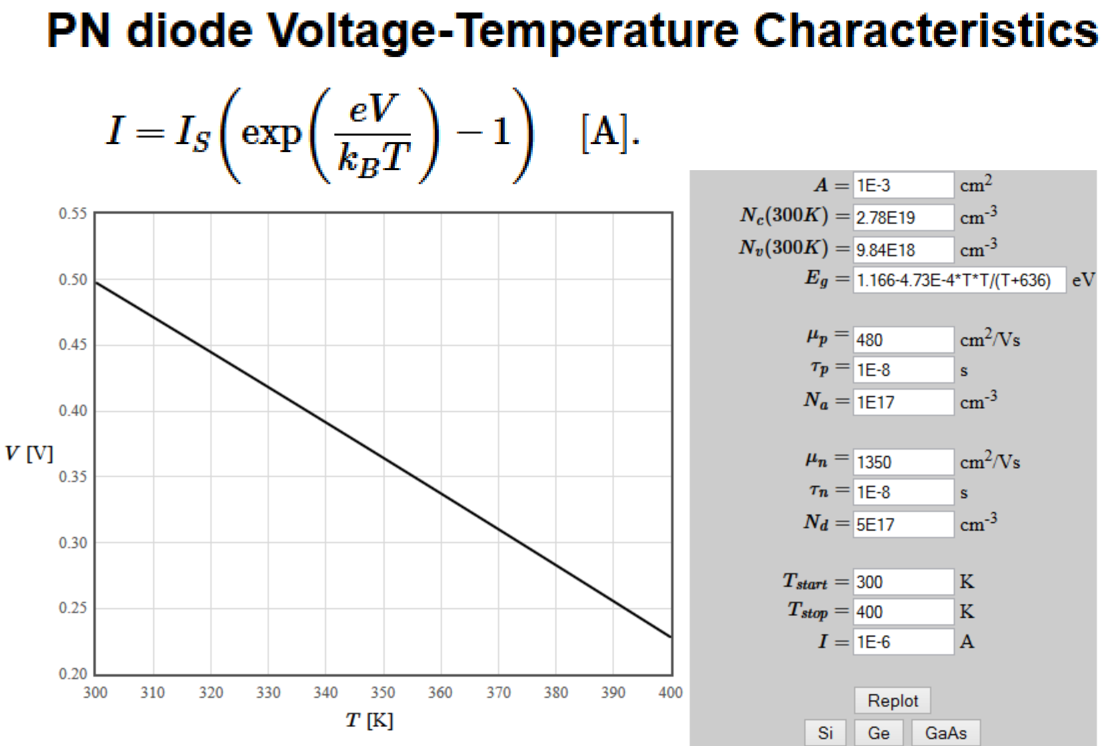


Piezoresistive elements

$\Delta R/R \sim (3 \times 10^{-10}\ \mathrm{Pa}^{-1})\ \Delta\sigma$

$\Delta R/R \sim (1.5 \times 10^{-3}\ \mathrm{C}^{-1})\ \Delta \mathrm{T}$

Temperature changes in resistivity are much bigger.
Use a diode as a thermometer.



PN diode Voltage-Temperature Characteristics

$$I = I_S\left(\exp\left(\frac{eV}{k_BT}\right) - 1\right) \quad [\mathrm{A}].$$

$A =$ 1E-3 cm^2
$N_c(300K) =$ 2.78E19 cm^{-3}
$N_v(300K) =$ 9.84E18 cm^{-3}
$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV

$\mu_p =$ 480 $\mathrm{cm}^2/\mathrm{Vs}$
$\tau_p =$ 1E-8 s
$N_a =$ 1E17 cm^{-3}

$\mu_n =$ 1350 $\mathrm{cm}^2/\mathrm{Vs}$
$\tau_n =$ 1E-8 s
$N_d =$ 5E17 cm^{-3}

$T_{start} =$ 300 K
$T_{stop} =$ 400 K
$I =$ 1E-6 A

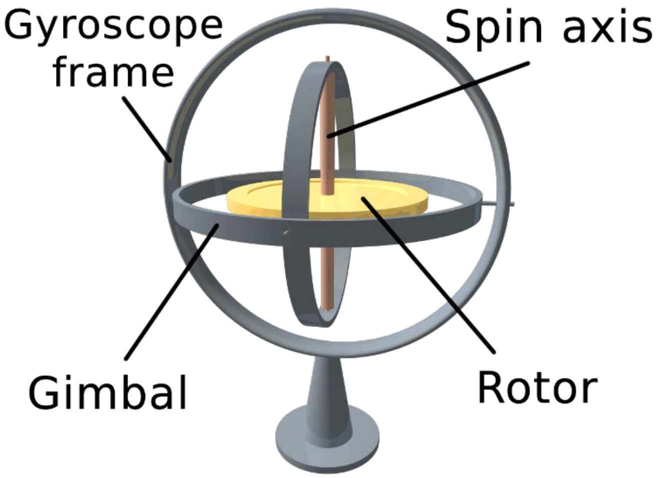
http://lamp.tu-graz.ac.at/~hadley/psd/L6/VT_I.php

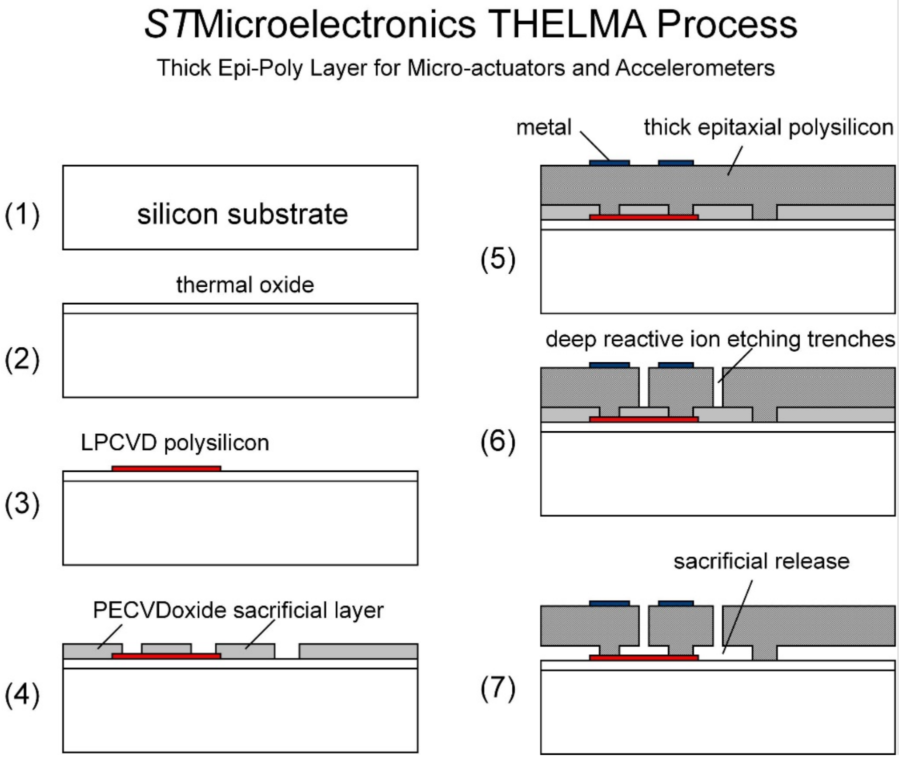
MEMs gyroscopes

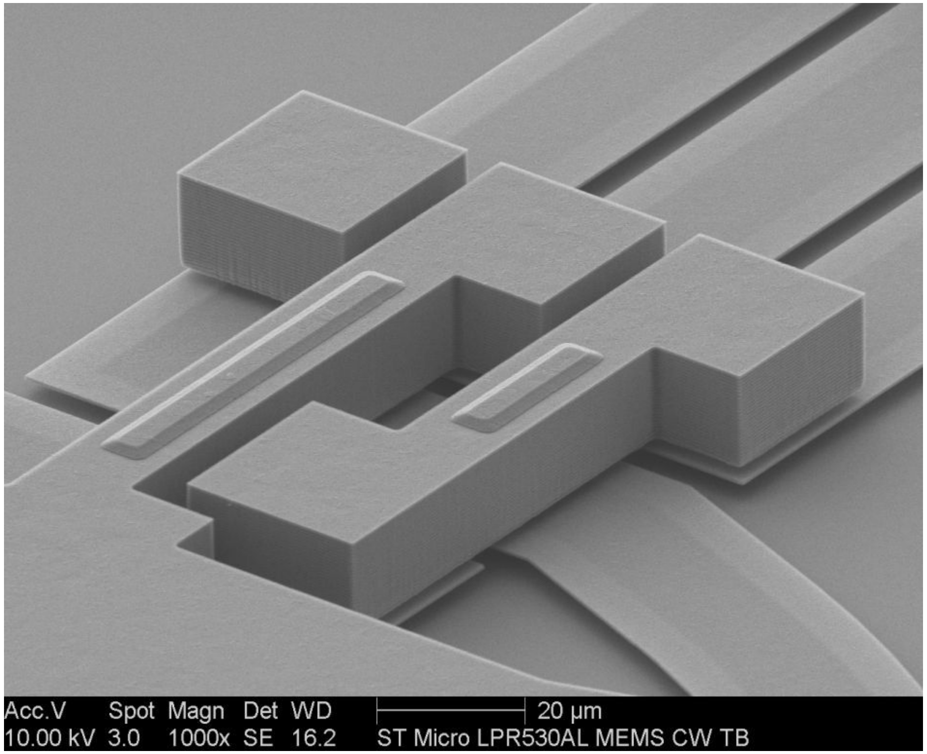
Measuring and maintaining orientation

Octocopters, Segway, game controllers

Vibrating structure gyroscope = Coriolis vibratory gyroscope (CVG)



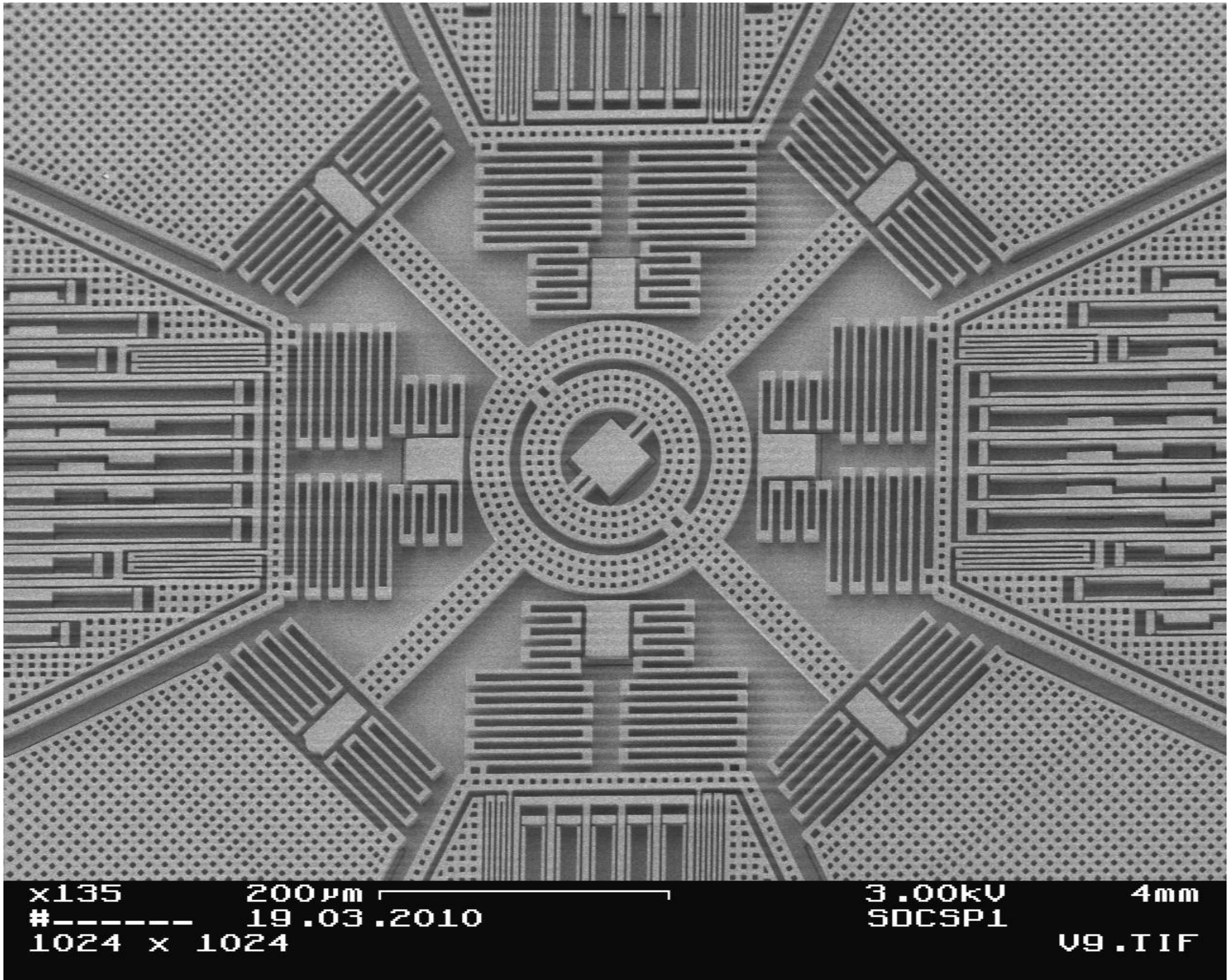




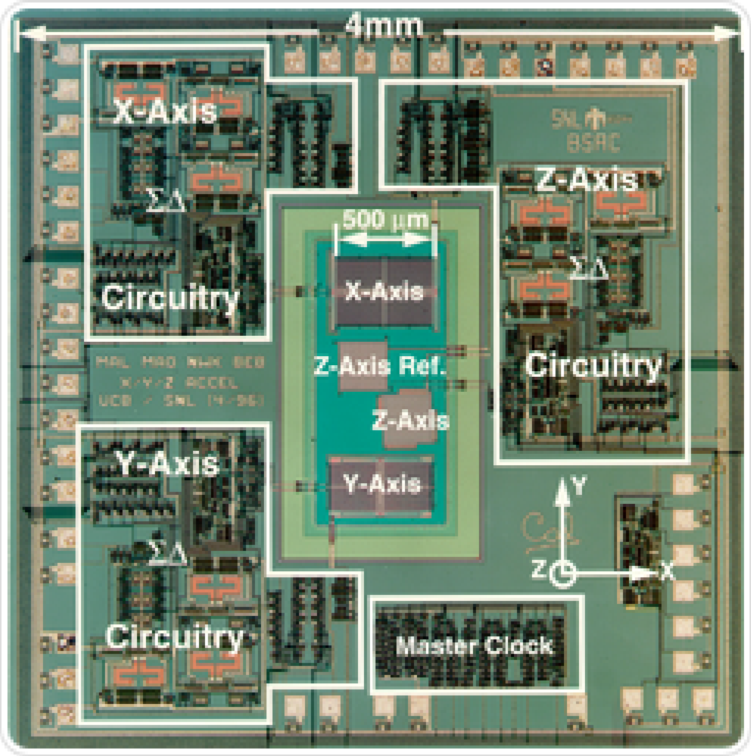
THELMA (*Th*ick *E*pi-Poly *L*ayer for *M*icro Actuators and *A*ccelerometers)
2.5 μm thick thermal oxide is grown
LPCVD polysilicon is grown to form electrical conduction layers
1.6- μm thick layer of sacrificial oxide, low temperature PECVD
Epitaxial polysilicon layer
Chemical mechanical polishing
Metal conductors are deposited and patterned on top of the epi-poly layer.
Dry etching (deep reactive ion etching) of Epi-poly layer.
Sacrificial layer is removed using vapor or liquid phase hydrofluoric etch.

http://memscentral.com/Secondlayer/mems_motion_sensor_perspectives-5.htm

MEMs gyroscopes



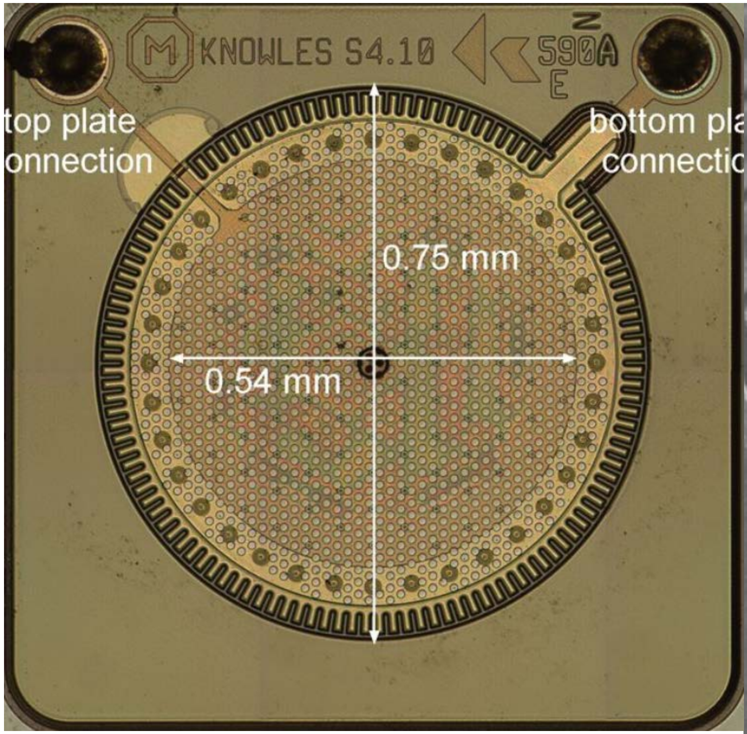
– MEMS Inertial and Pressure Sensors

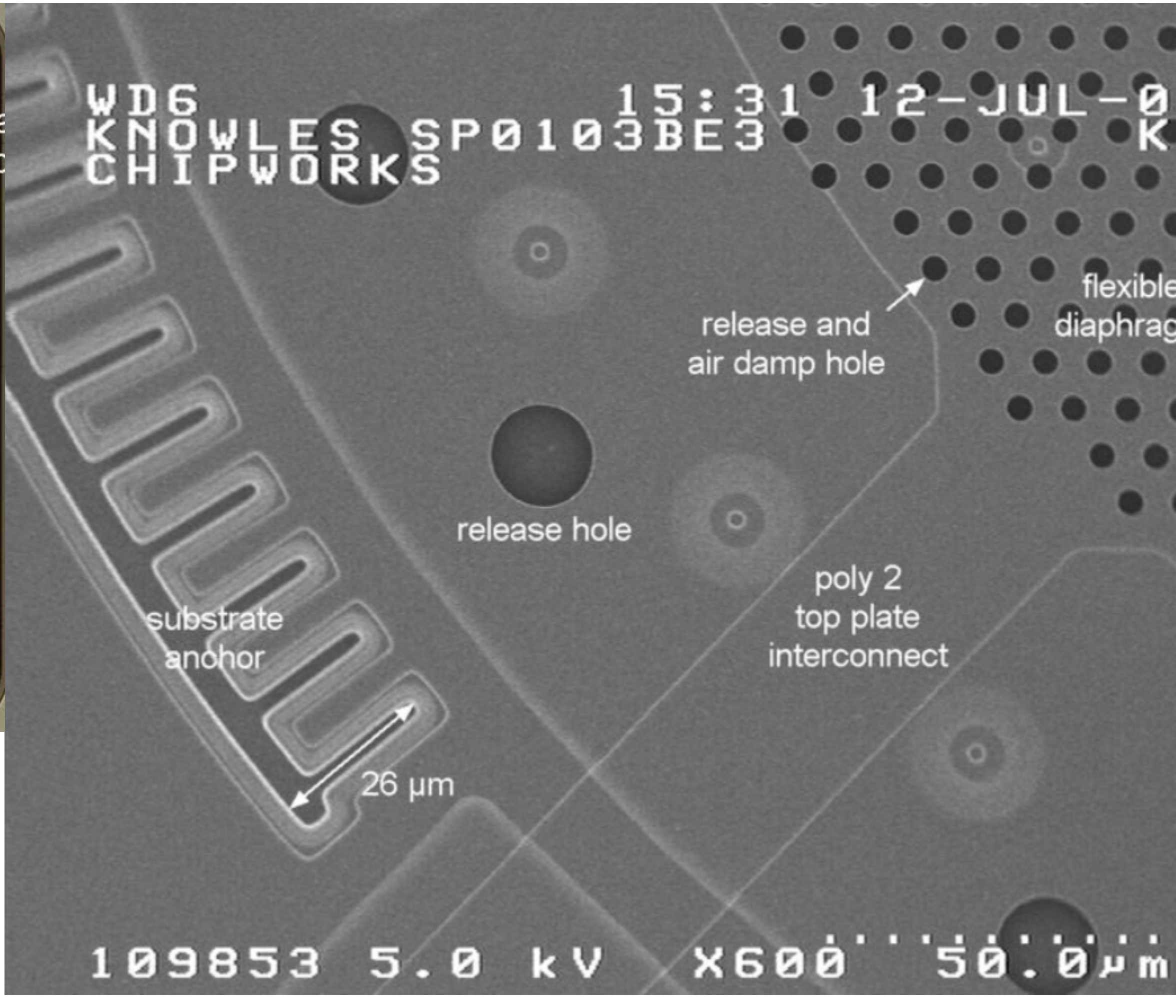


Microelectromechanical system (MEMS) sensors, including accelerometers, gyroscopes, pressure sensors, and microphones, have become a multi-billion dollar market in consumer electronics, automobile, and industrial applications. Sandia helped lay the foundation for these sensors in the 1990s, when the labs fabricated early exploratory designs for accelerometers and gyroscopes from the University of California, Berkeley. Sandia also demonstrated a MEMS-first fabrication process for integrating MEMS with supporting complementary metal–oxide–semiconductor (CMOS) electronics on the same chip. Today, Sandia fills niches in national security, where commercial devices are not available because the technology is too immature or the market is too small.

http://www.sandia.gov/mstc/mems_info/movie_gallery.html

MEMs microphones

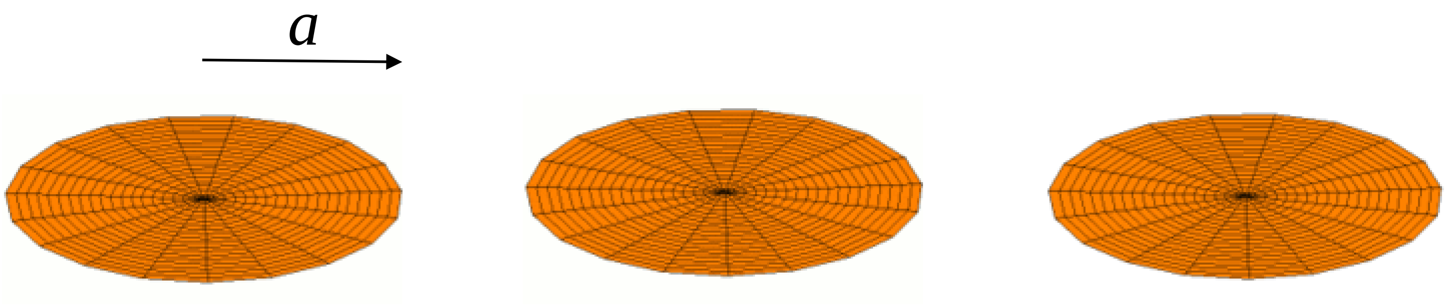




Hearing aids
Phones, Tablets
Machine health
Noise cancellation

http://www.memsjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html

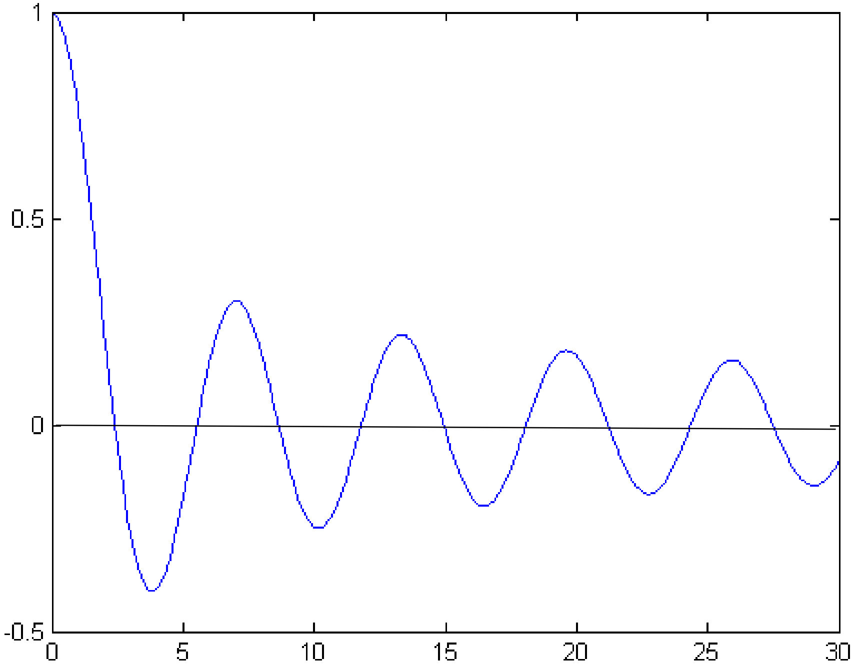
Vibrations of a membrane



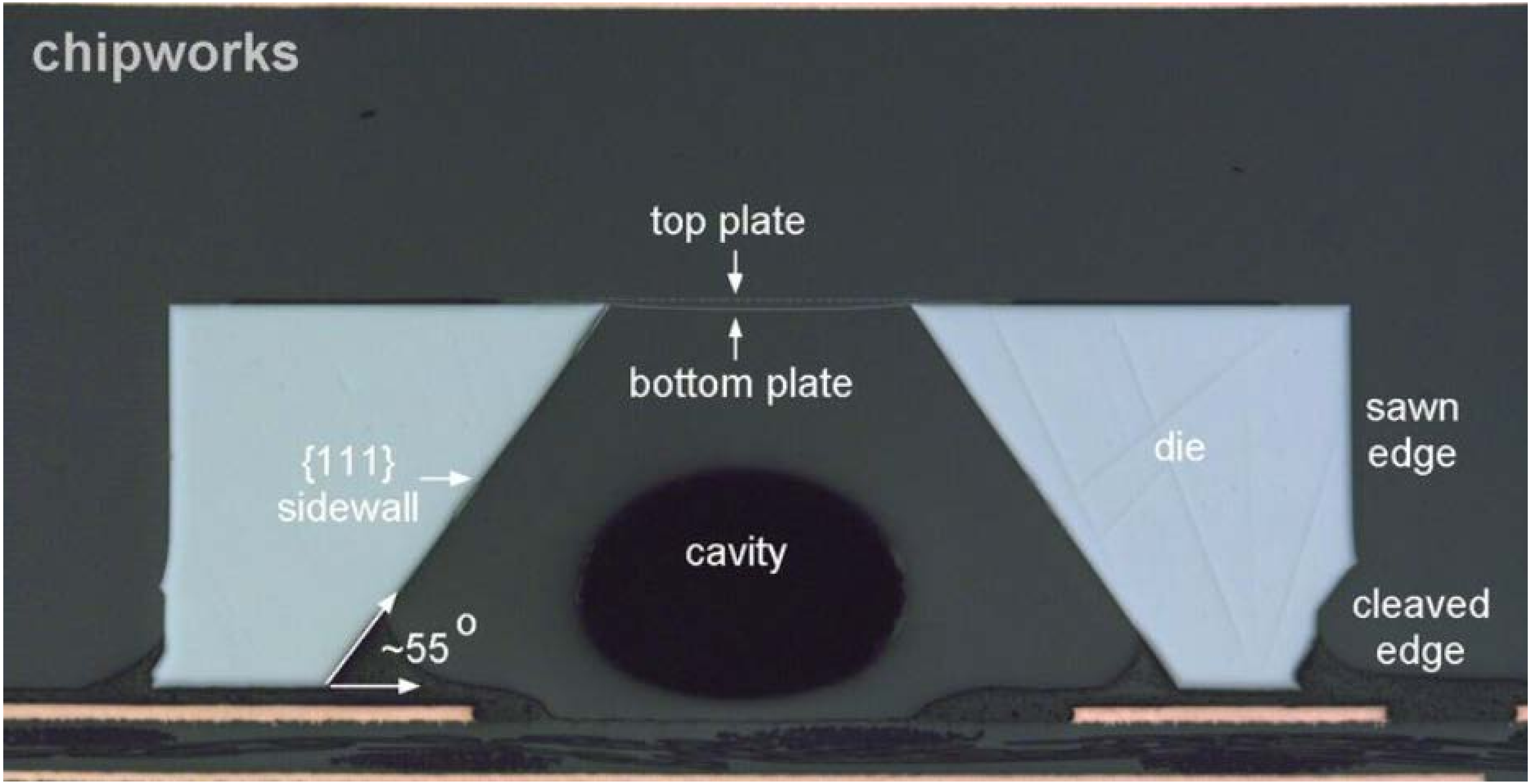
https://en.wikipedia.org/wiki/Vibrations_of_a_circular_membrane

$$u(r) = J_0\left(x_n \frac{r}{a}\right)$$

$x_1 = 2.404825558$
$x_2 = 5.520078110$
$x_3 = 8.653727913$



MEMs microphones

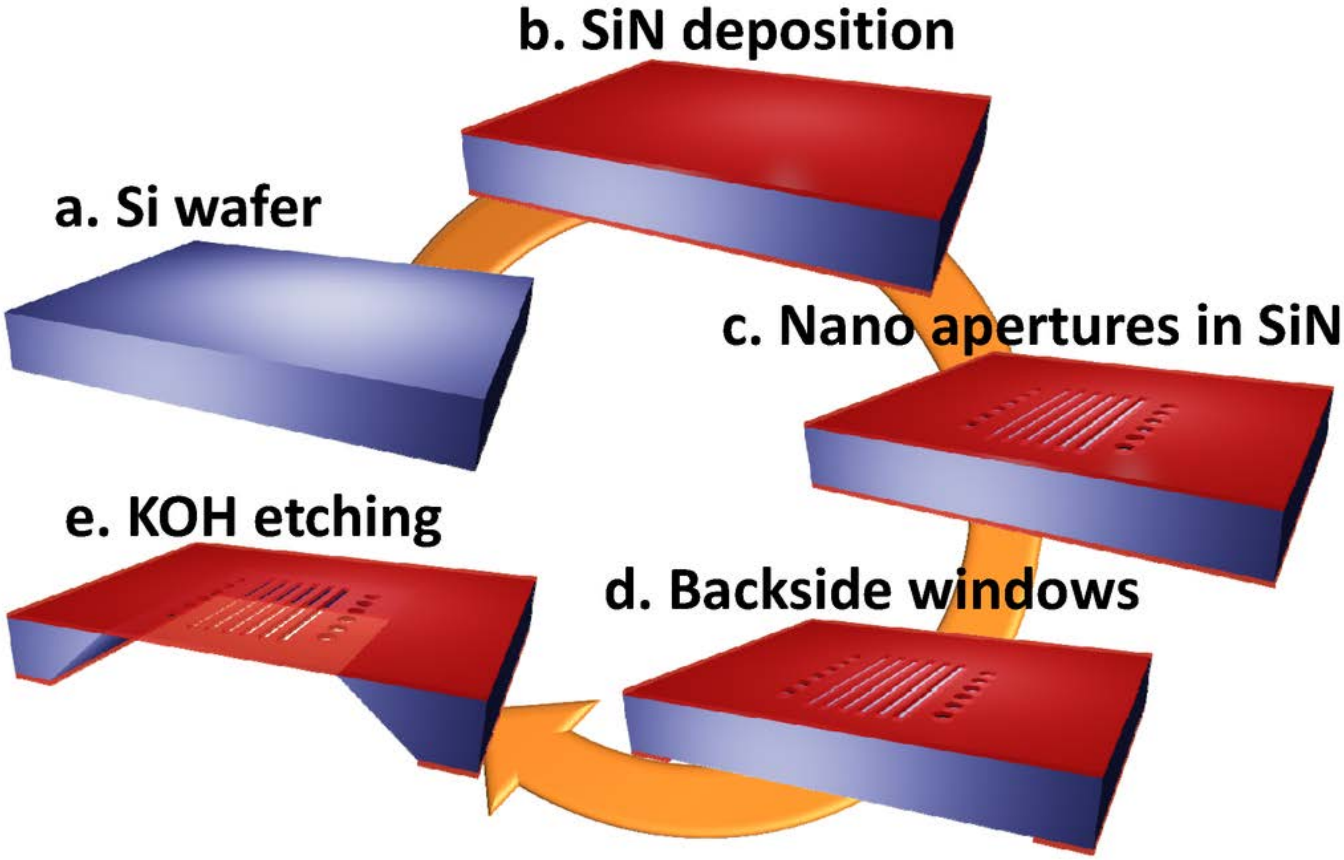


"It is most probable that the back side cavity etch was performed before this final step, probably by using a KOH wet etch."

http://www.memsjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html

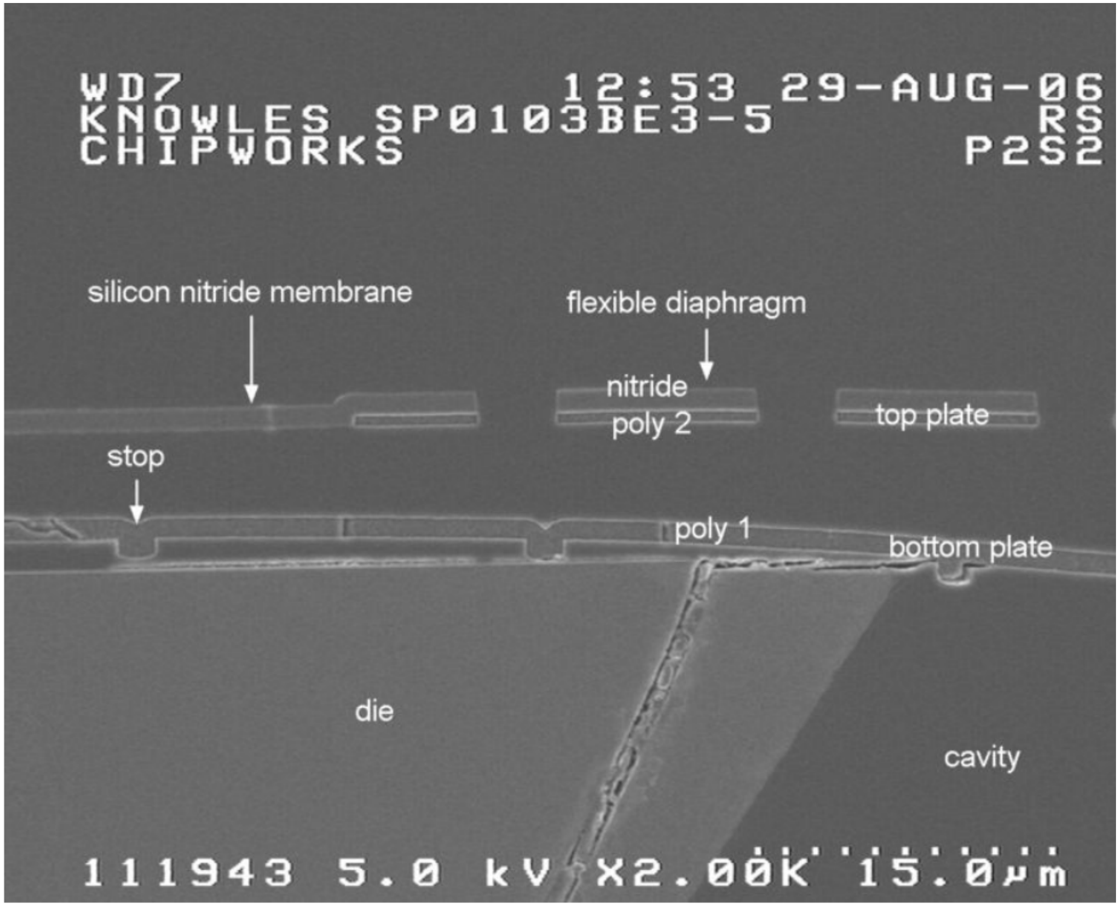
Pressure sensor

https://www.youtube.com/watch?v=juf4d3sgOJw&list=PLV_Nzprr4V67UgN7plihCXLrVniS-8FIC



http://www.mdpi.com/2072-666X/4/4/370/htm

MEMs microphones



"The fabrication of the two membranes, separated by an air gap, would have depended on the spacer layer, likely silicon dioxide, which would have been removed during the release step through the holes in the top plate, likely with anhydrous HF."

http://www.memsjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html