Capacitive sensors and their readout electronics

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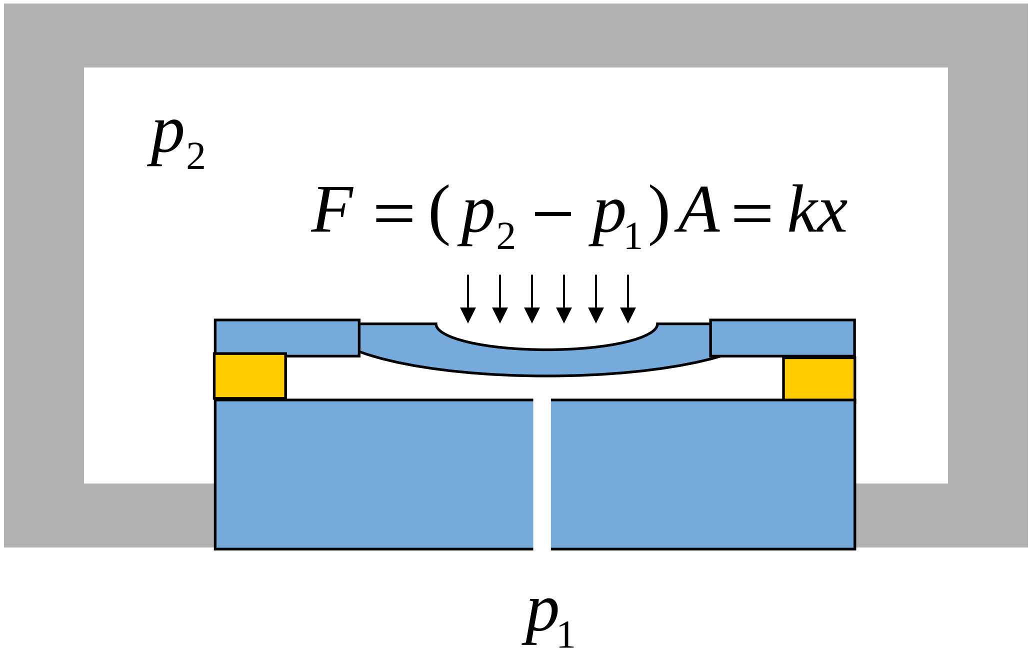
Motivation for capacitive sensors

- Low power consumption
- High resolution
- Small temperature coefficient (e.g., in capacitive MEMS sensors)
- Possibility for high-volume manufacturing (e.g., by using MEMS technology)
- Potential for low cost
- Potential for monolithic integration with readout electronics
- Possibility to reuse of IP blocks (i.e., designs) both in IC and MEMS parts
- In capacitive MEMS sensors, the dynamic range can be tailored in a wide range by scaling the dimensions of the MEMS structure

Example: Capacitive pressure sensor



$$x = \frac{3\left(1-\nu^2\right)}{16}\frac{\Delta p R^4}{E t^3}$$

$$x < t$$

$$\Delta p_{\mathrm{max}} = \frac{16}{3\left(1-\nu^2\right)}\frac{E t^3 d}{R^4}$$

“Convenient” measuring range (*dynamic range*) for a Si sensor with the area 1 mm^2 is p = 0.01 bar … 100 bar

Dynamic range limited by nonlinearity and eventually the membrane touching the bottom wafer (=> advantage: tolerance against pressure shocks)

Readout of a capacitive sensor

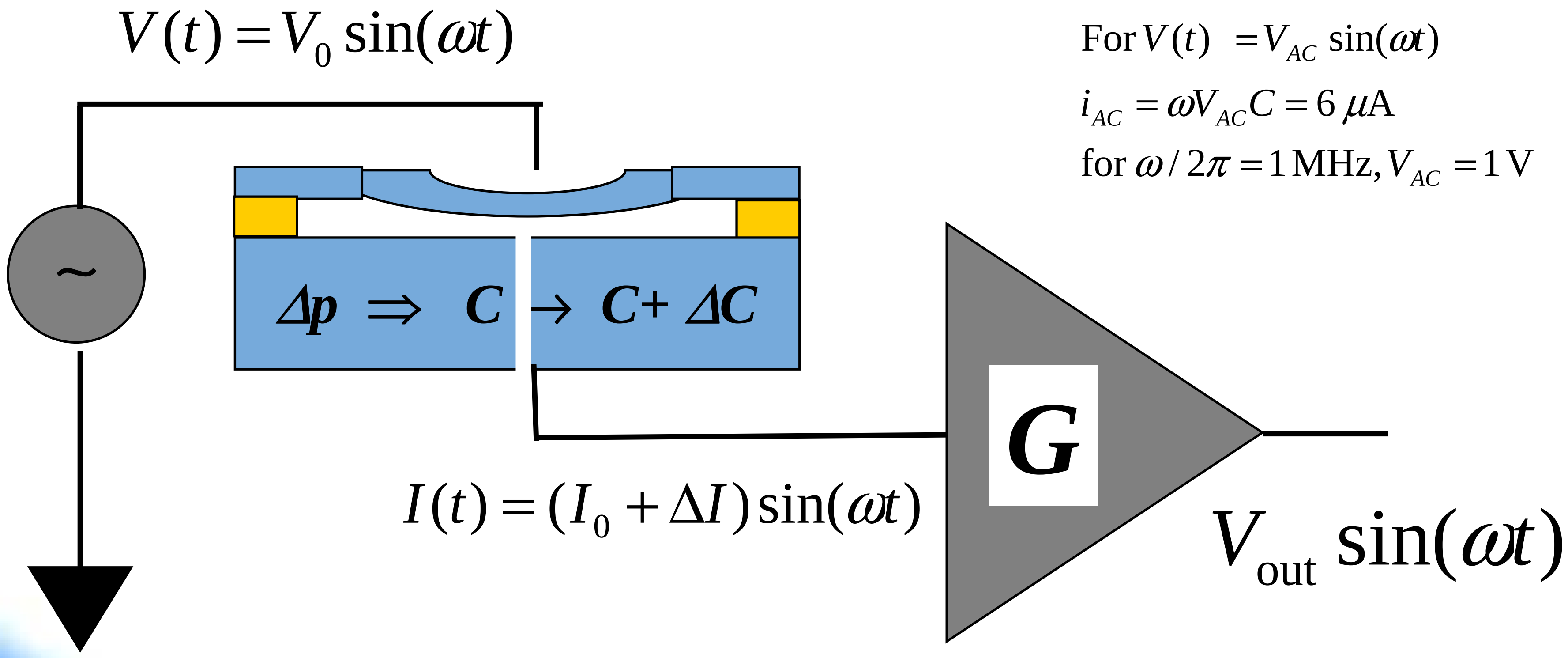
1. AC readout (i.e., displacement measurement)

Typically $C = 1\,\text{pF}$

For $V(t) = V_{AC}\sin(\omega t)$

$i_{AC} = \omega V_{AC} C = 6\,\mu\text{A}$

for $\omega / 2\pi = 1\,\text{MHz}, V_{AC} = 1\,\text{V}$



$$V(t) = V_0 \sin(\omega t)$$

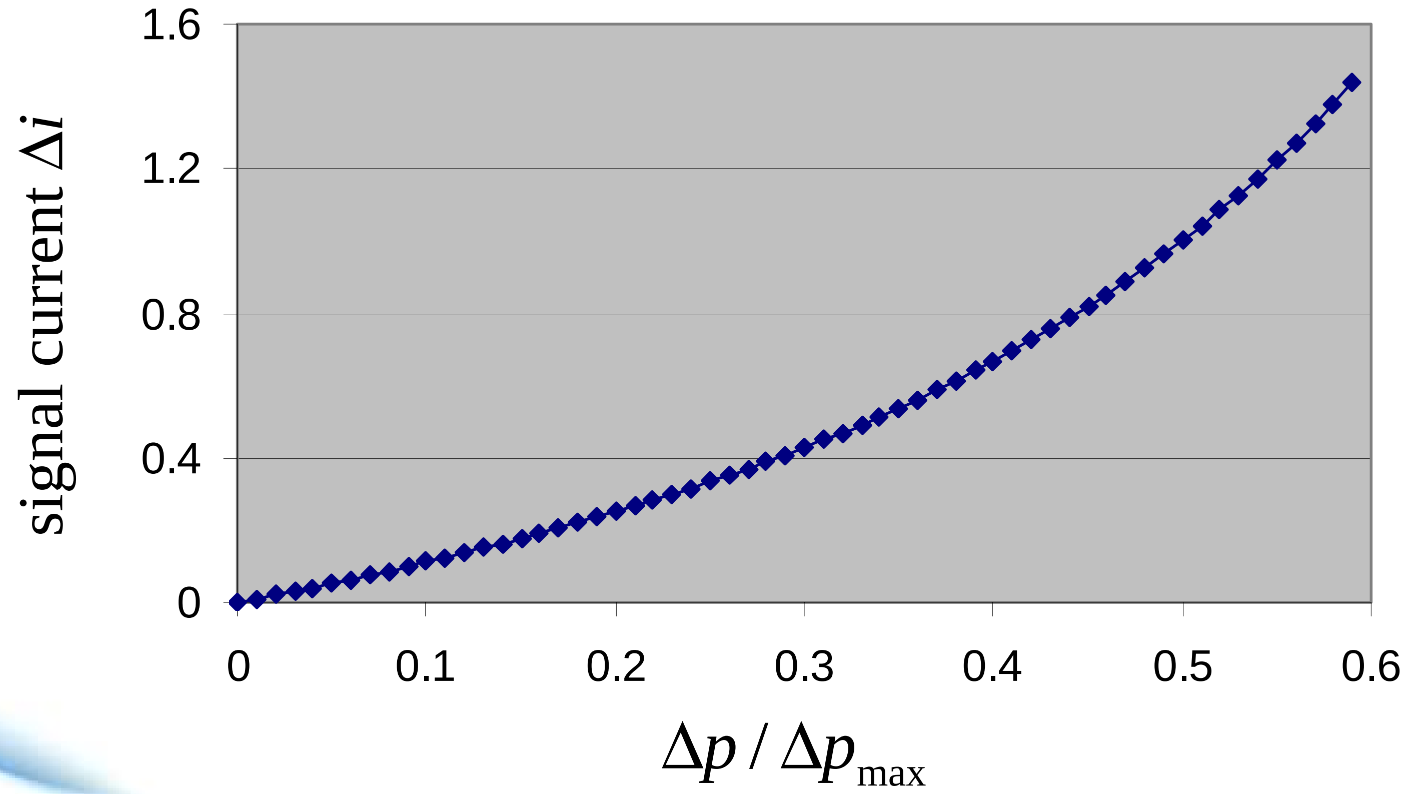
$$I(t) = (I_0 + \Delta I)\sin(\omega t)$$

$$V_{\text{out}} \sin(\omega t)$$

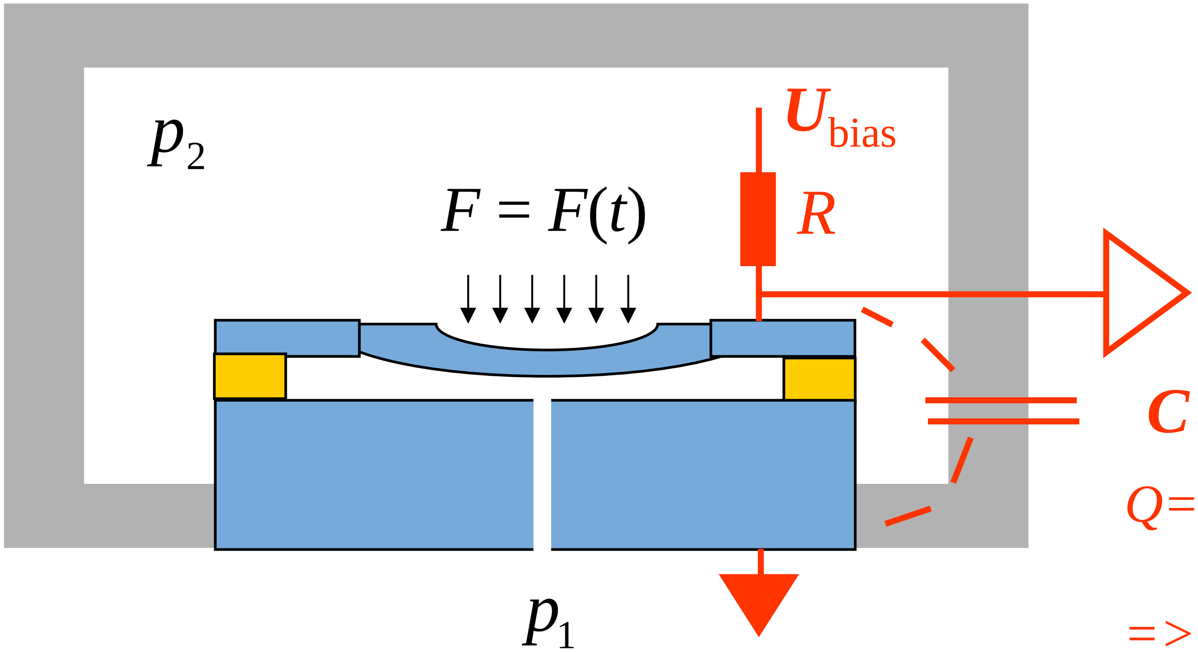
Transfer function of the capacitive pressure sensor

$$\Delta i = \omega \Delta C U_{AC}$$

$$C \approx \frac{C_0}{1 - x/d}$$



2. DC readout (velocity measurement)



$C = C(t)$

$Q = CV = \text{constant}$

over $\tau = RC$

$\Rightarrow \Delta V = -U_{bias} \Delta C / C$

Bias the membrane by “constant” charge and measure voltage changes induced by the motion of the membrane

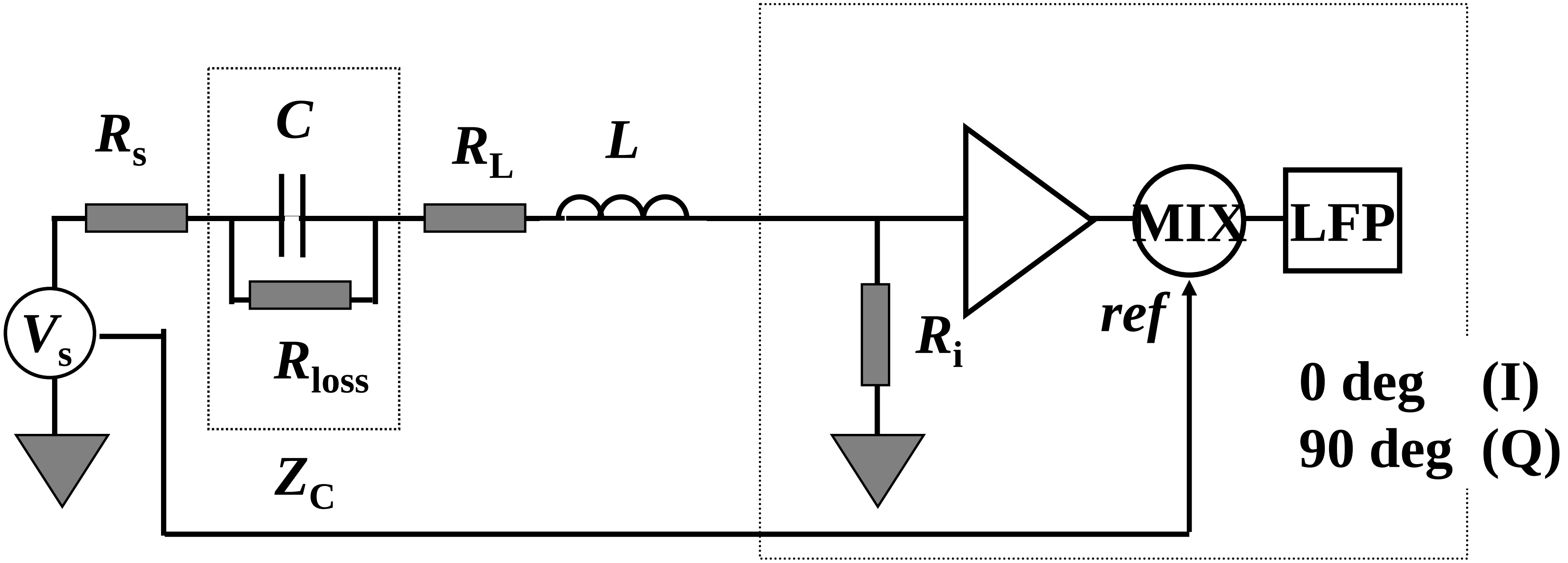
Velocity of the diaphragh is measured, NOT position

Motional current (calculate typical example)

Examples: microphone, dynamical pressure, vibration, resonators

3. Readout using a tuned circuit

IMPROVED RESOLUTION BY TUNING!



Q-factor enhancement to the 90 deg signal => high resolution

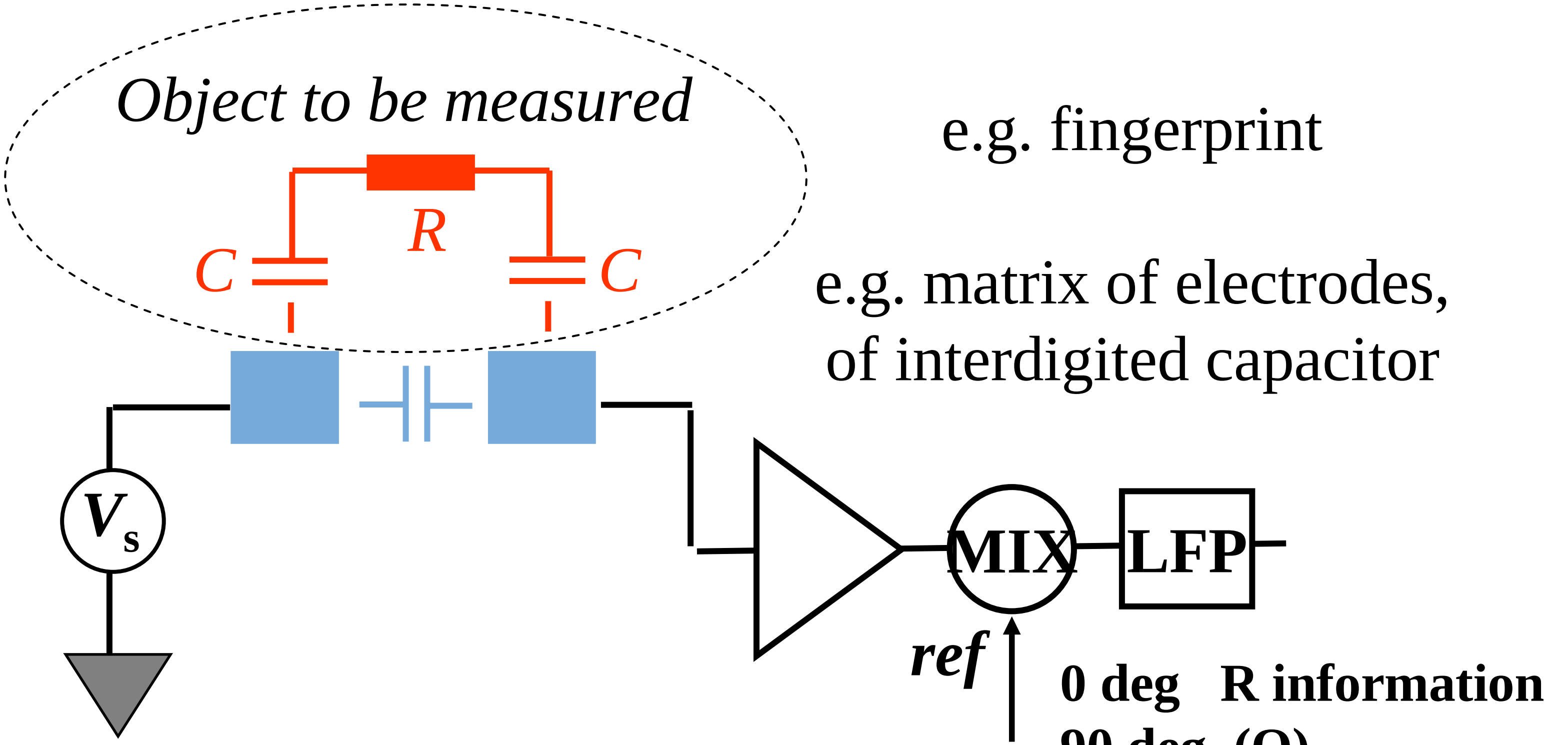
Sqrt(*Q*) enhancement of the noise at the resonance frequency

Long term stability of the tuned circuit problematic (e.g., T coeff of the inductor)

0 deg signal is a measure of the loss factors

Suited particularly for dynamic measurements: dynamic pressure, microphone, vibration, ..

4. Capacitive sensors based on the loss factor measurement



e.g. fingerprint

e.g. matrix of electrodes,
of interdigited capacitor

0 deg R information
90 deg (Q)

5. **Resonating capacitive sensors**

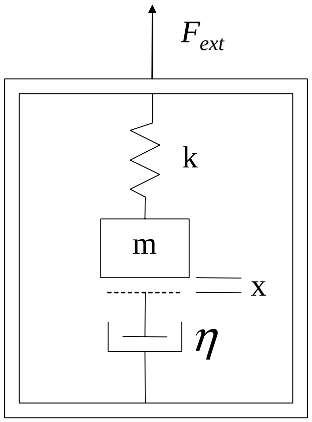
Advantages over static capacitive sensors

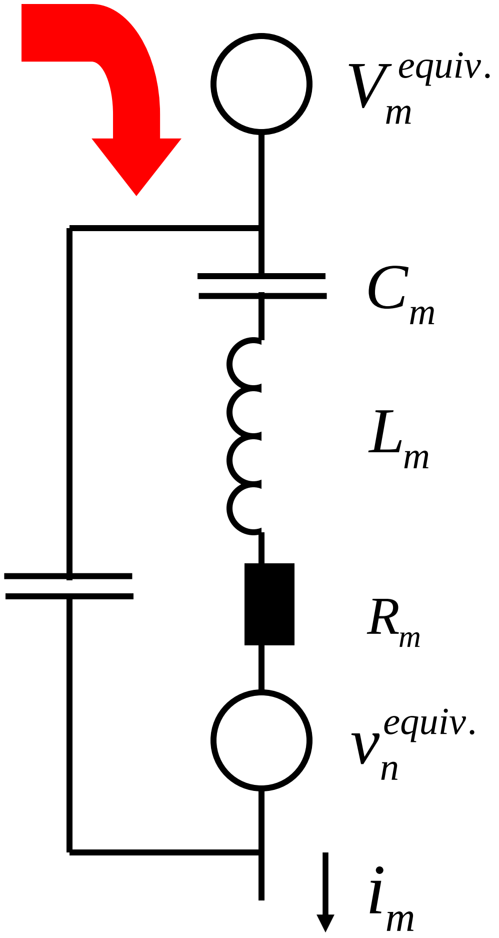
- Improved resolution (at least sometimes)
- Easier to make a readout electronics which does not limit the resolution
- Output can be coded in the *frequency* of the output voltage. This may be an advantage.
- Several measurements can be measured transformed into a mechanical resonance measurement (strain, force, pressure, acceleration, temperature, mass depostion, ..)
- Additional information can be obtained from the dissipation (Q value of the mechanical resonance)

Equation for the mechanical resonance

$$m\frac{d^2x}{dt^2}+\eta\frac{dx}{dt}+kx=F_{ext}$$

$$F_{ext} = Mechanical\ force + Electrical\ force$$





Static capacitance

Transfer function at operation point:

$$|G(\omega)|=\frac{1}{\sqrt{(\omega_0^2-\omega^2)^2+\frac{\omega_0^2\omega^2}{Q^2}}}$$

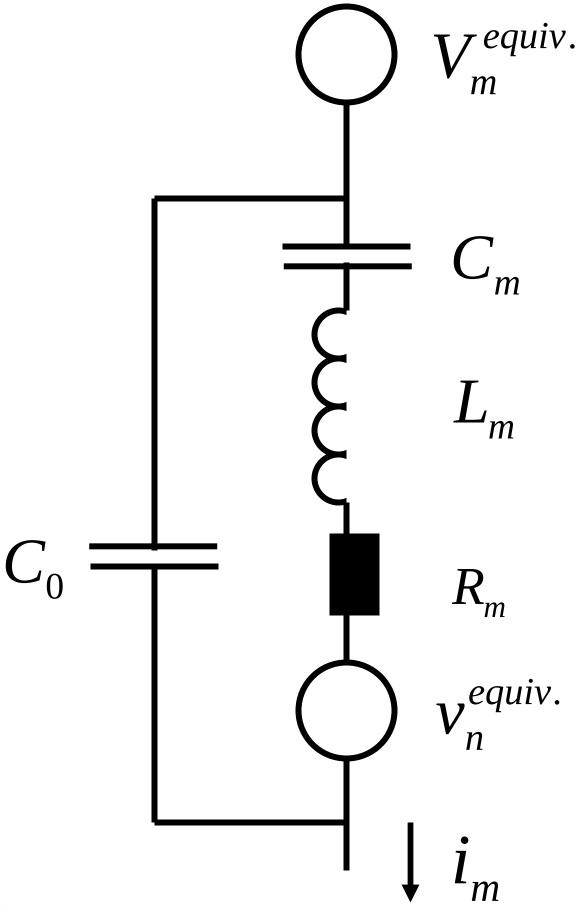
$$\omega_0 = 2\pi f_0$$

$$Q=\omega_0 m/\eta$$

Motional quantities (“m”)

$$v_n^{equiv.}=\sqrt{4k_BTR_m}$$

Mechanical resonator as a sensor



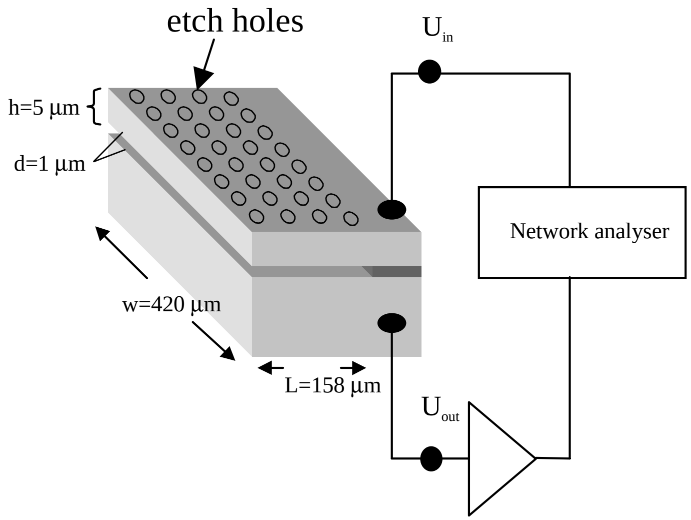
Spring term: strain, force, pressure, acceleration, ..

Mass term: mass change, pressure, ..

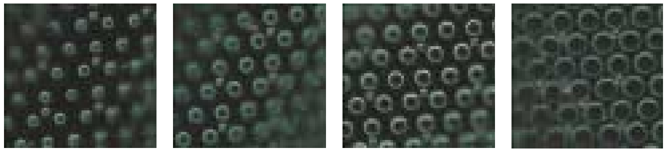
Loss term: pressure from flow loss, viscous surface effects, rapid mass fluctuations, ...

Example: resonating pressure sensor (Tomi Mattila et al, 2000)

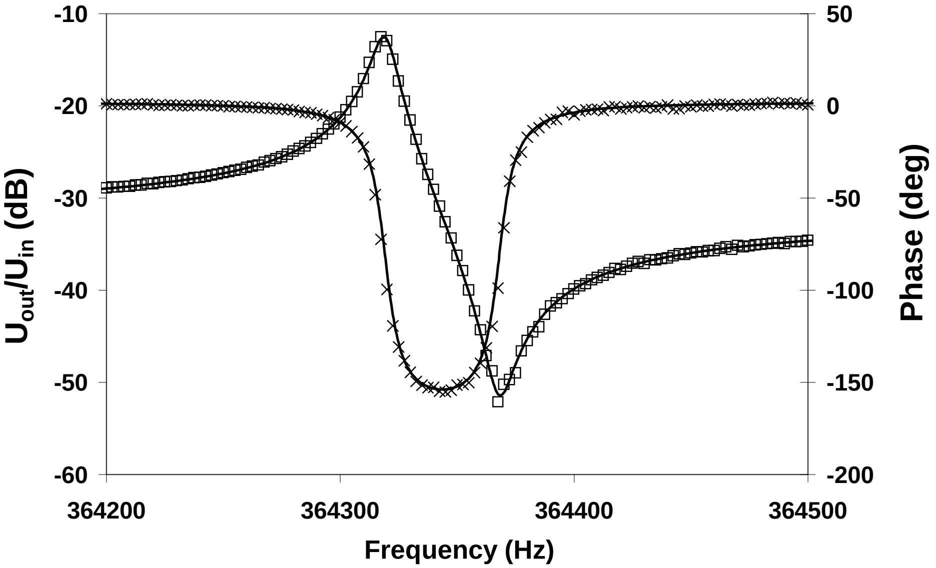
(a)



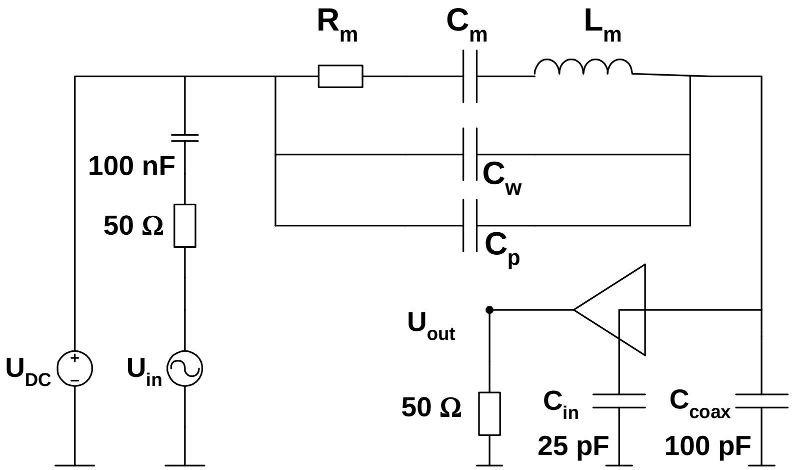
(b)

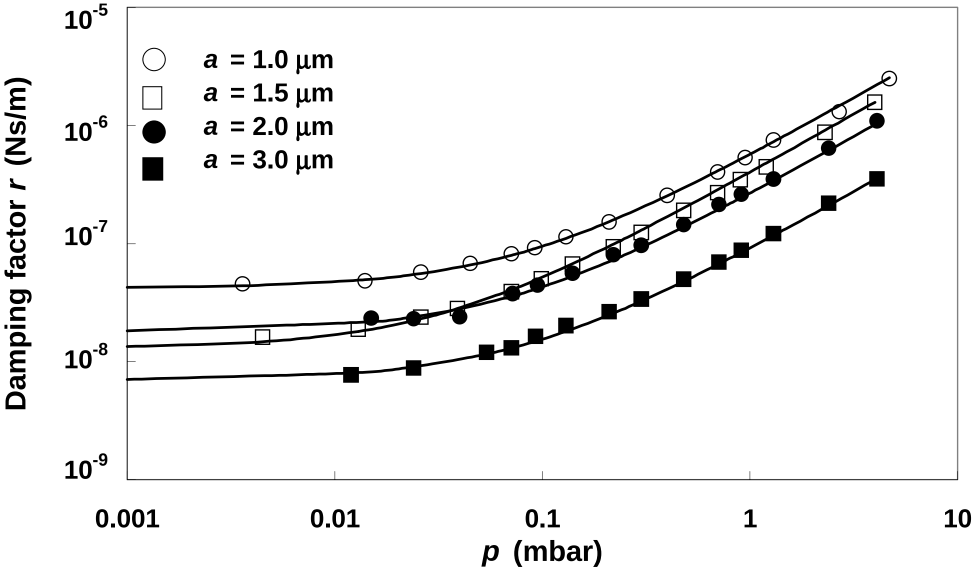


r(µm)	1.0	1.5	2.0	3.0



Example: resonating pressure sensor (2)



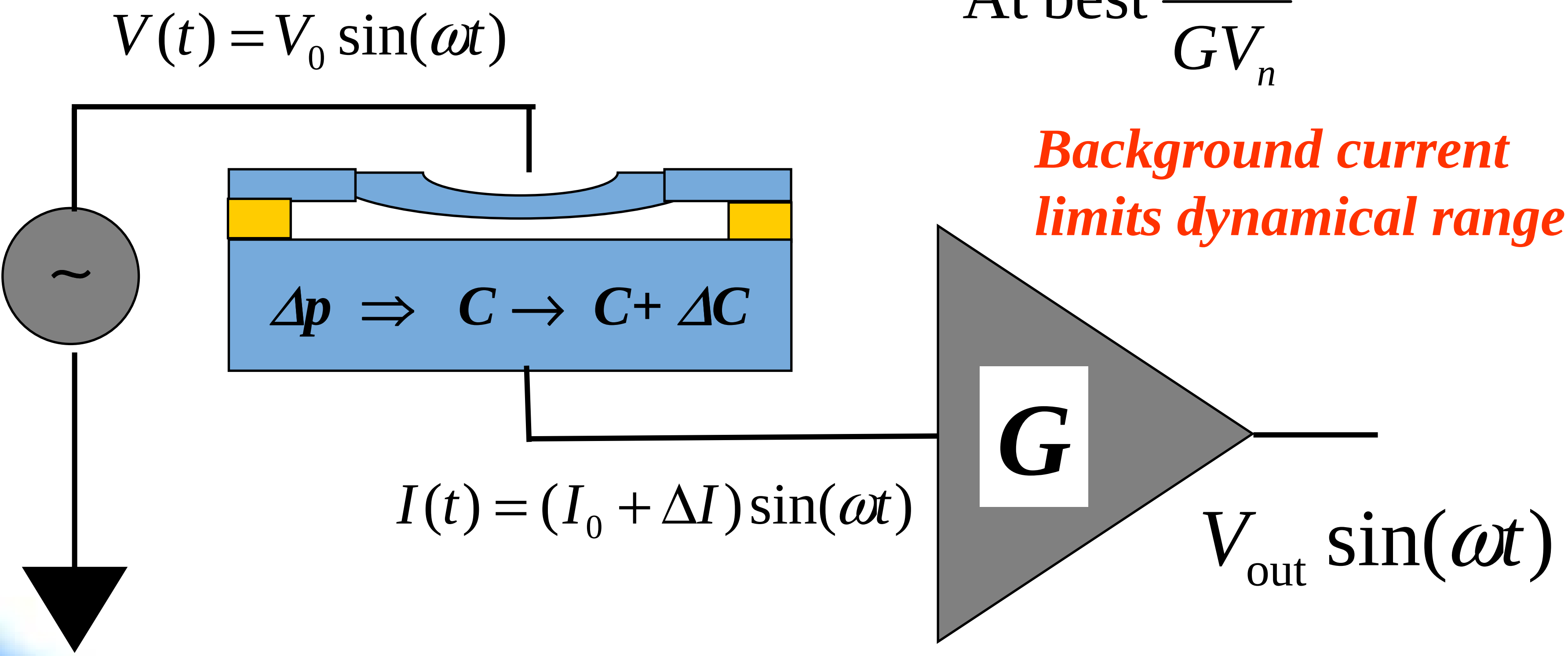


Measurement techniques related to capacitive sensors

Dynamical range of AC readout

$$\text{At best } \frac{V_{out}^{\max}}{G V_n}$$

Background current limits dynamical range



$$V(t) = V_0 \sin(\omega t)$$

$$\Delta p \Rightarrow C \rightarrow C + \Delta C$$

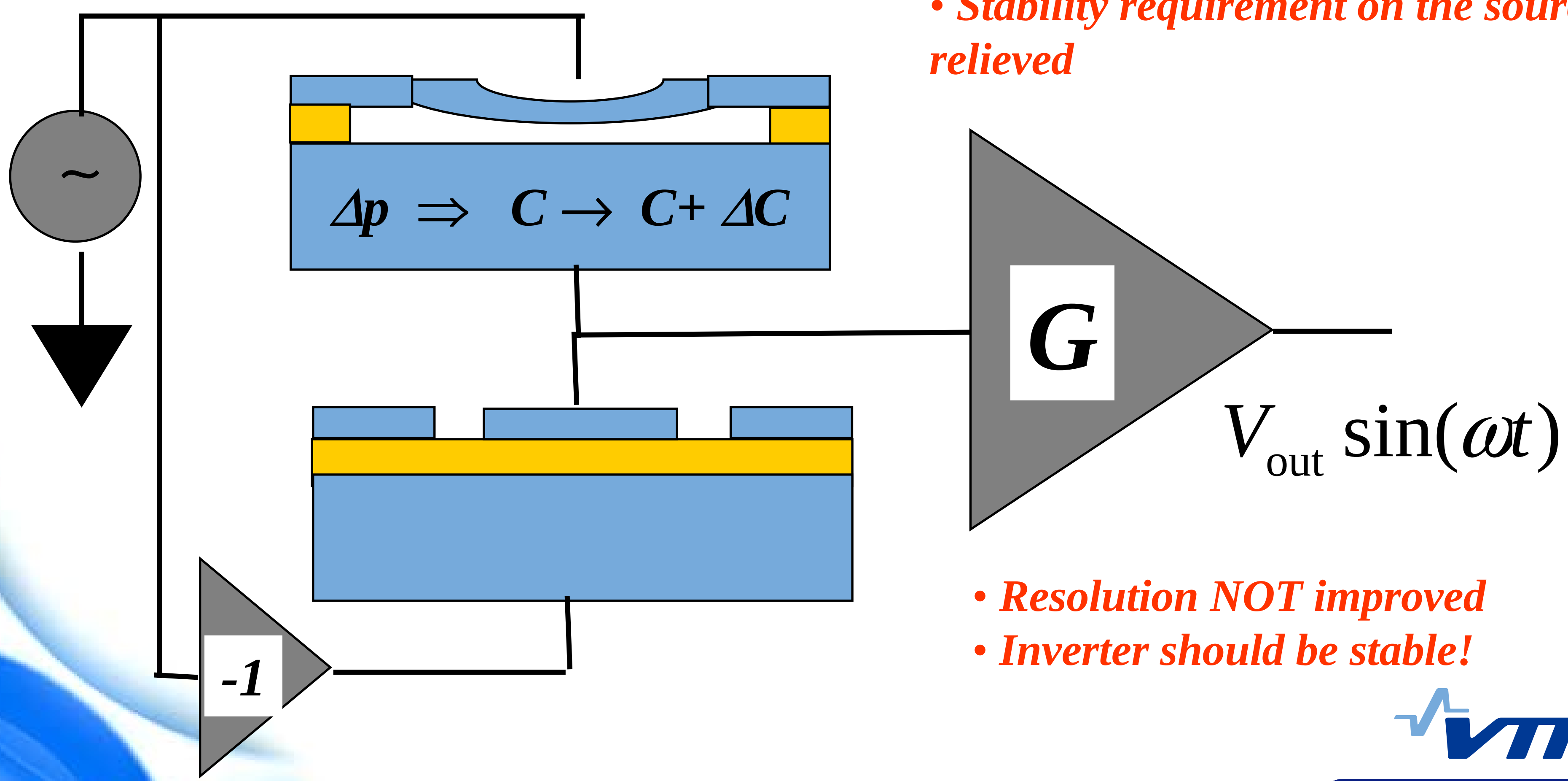
$$I(t) = (I_0 + \Delta I)\sin(\omega t)$$

$$V_{\text{out}} \sin(\omega t)$$

Bridge measurement

- ***Zero background signal***
- ***Improved dynamical range***
- ***Reference C on the same chip!***
- ***Stability requirement on the source relieved***

$$V(t) = V_0 \sin(\omega t)$$



$$V_{out} \sin(\omega t)$$

- ***Resolution NOT improved***
- ***Inverter should be stable!***

Guarding of parasitic capacitances

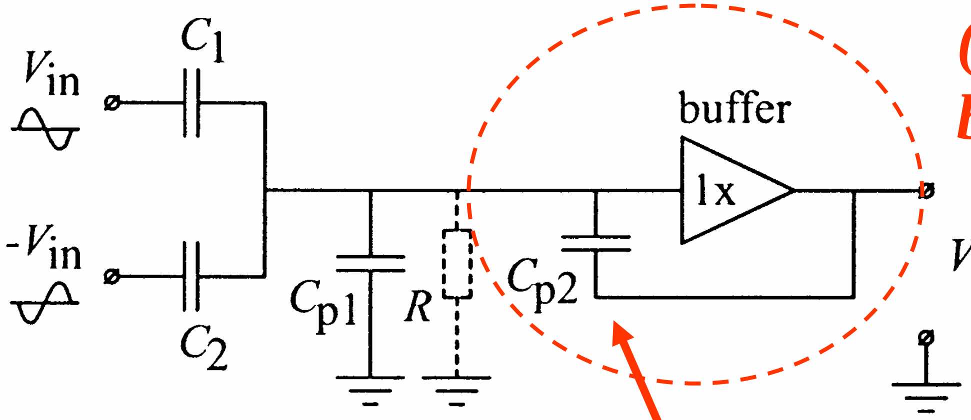


Fig. 10.14. Elimination of parasitic capacitor C_{p2} by bootstrapping

(active) guarding bootstrapping

Intrinsic parasitic C (cannot be bootstrapped) (f.ex. anchor area of released MEMS)

Parasitics from cables, f.ex. (CAN be guarded)

Guarding of parasitic capacitances (2)

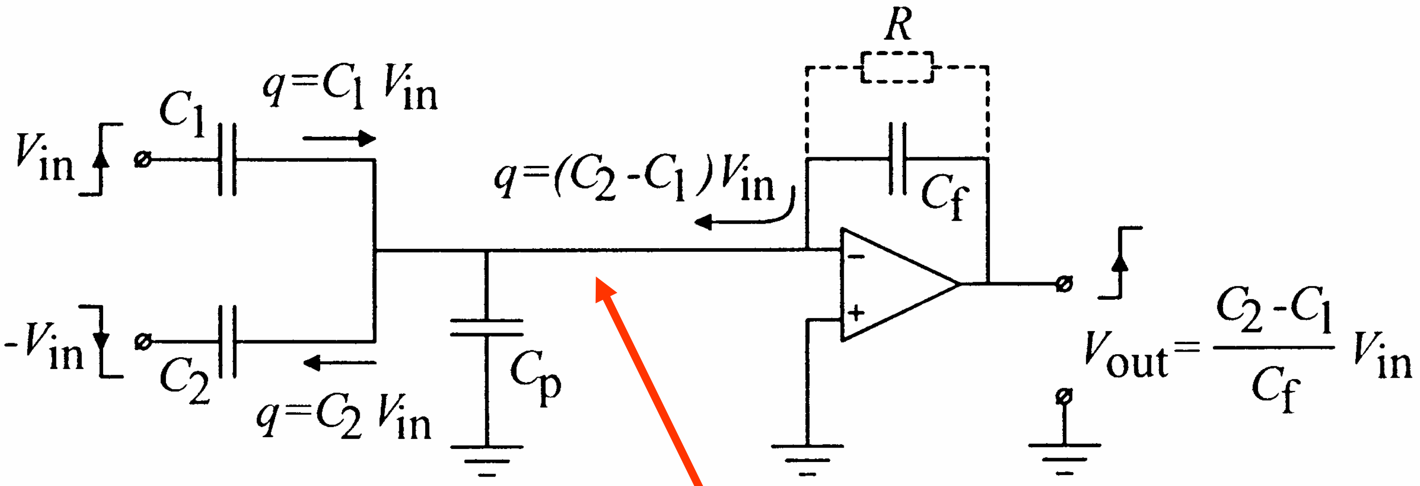
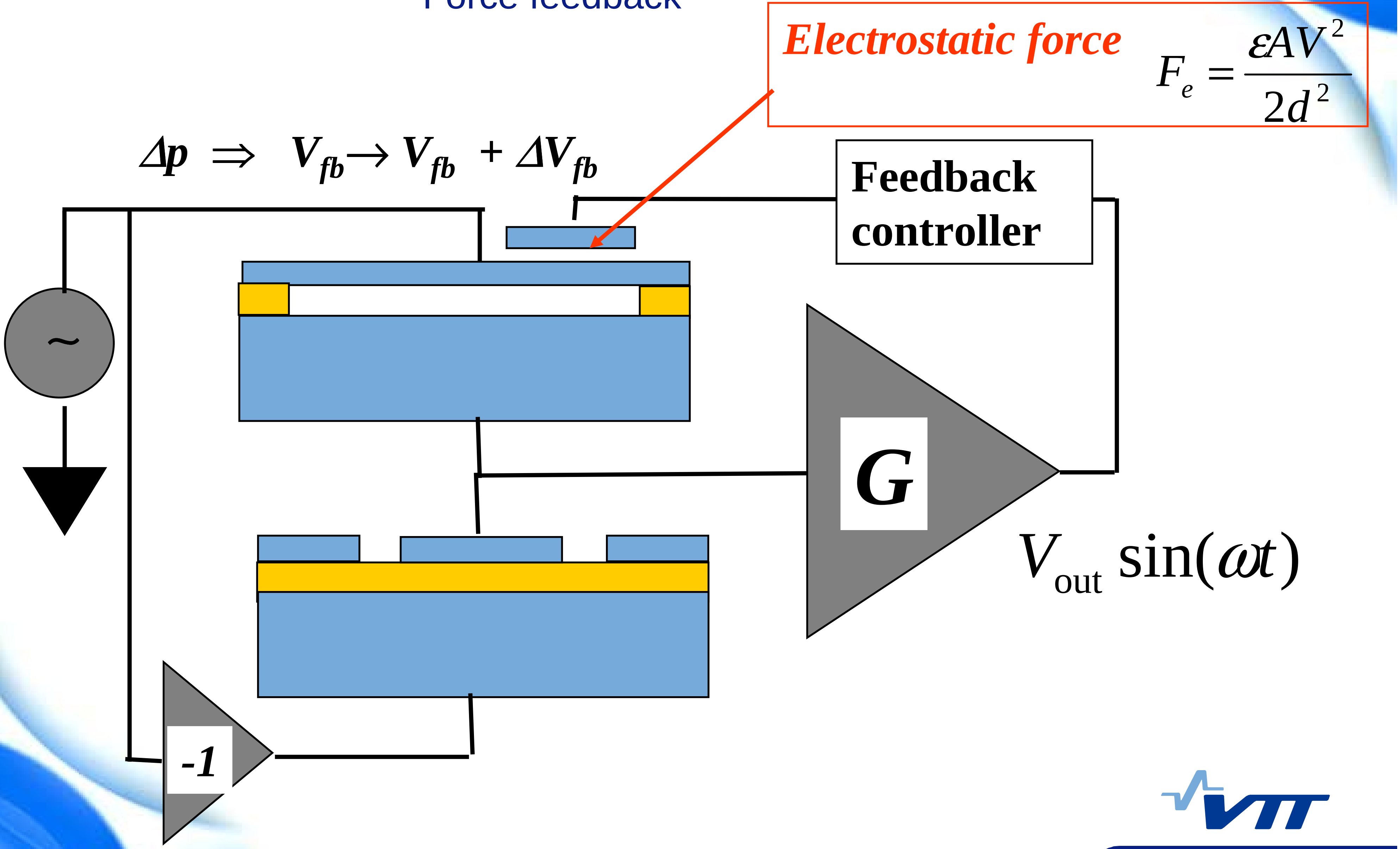


Fig. 10.15. Principle of charge sensing

The potential of the signal line is kept at virtual ground => no current flows across Cp

Force feedback



Electrostatic force $F_e = \frac{\varepsilon A V^2}{2d^2}$

$\Delta p \Rightarrow V_{fb} \rightarrow V_{fb} + \Delta V_{fb}$

Feedback controller

$V_{out} \sin(\omega t)$

Features of force feedback

Nonlinearity of the spring does not matter since the membrane is not moving

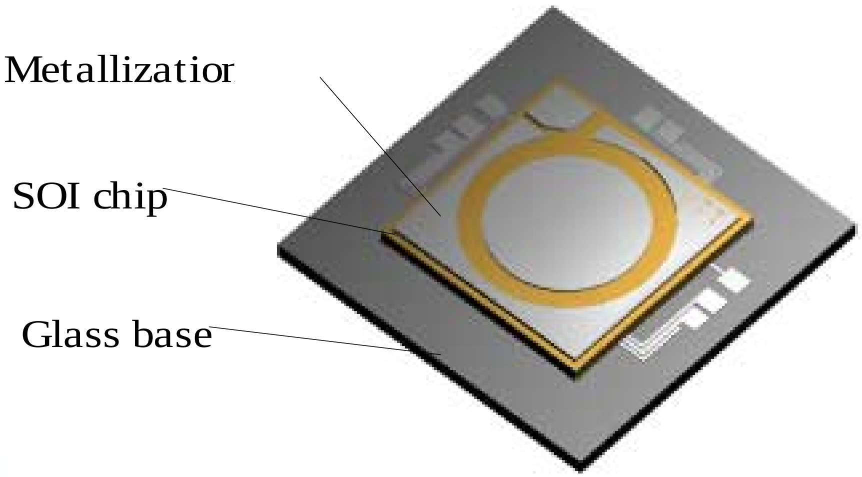
Linearity requirement now concerns the feedback circuitry, not the transducer

Obtaining linearity requires special solutions since electrostatic force is proportional to the voltage squared

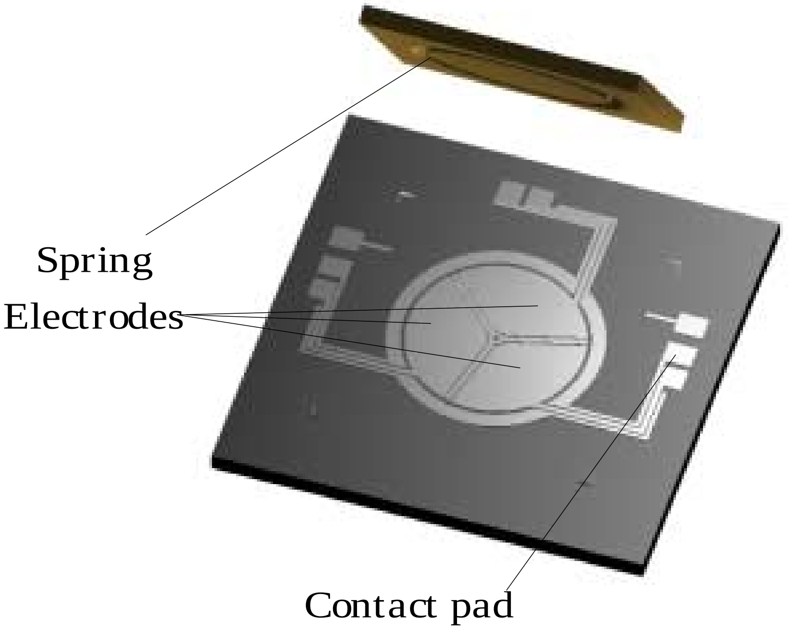
Transfer function is modified by the feedback

Micromechanical silicon precision scale

Top view

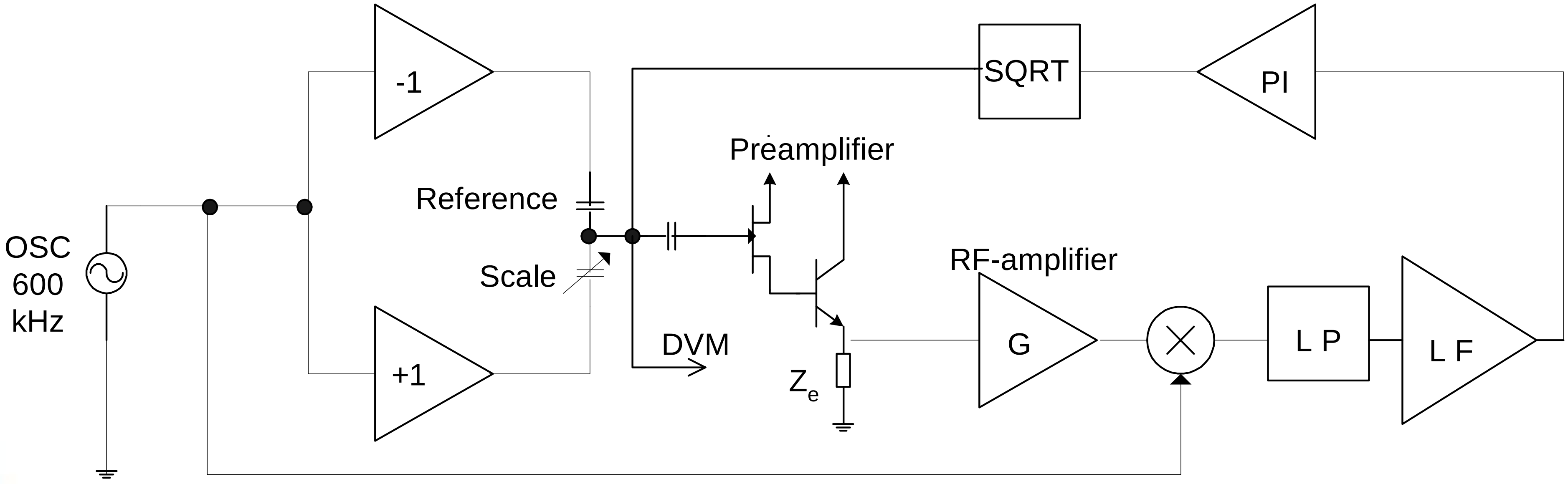


Exploded view



VTT Automation, VTT Electronics, MIKES

(First) prototype electronics for the precision scale



Brownian Noise of Capacitive Sensors

DYNAMICS OF MEMS CAPACITOR

$$m\frac{d^2x}{dt^2}+\eta\frac{dx}{dt}+kx=\frac{\varepsilon A}{2(d-x)^2}(V+V_n)^2+F_{mech}+F_n$$

F_{mech} is a mechanical force (f.ex., gravity)

V_n is the voltage noise $\langle V_n(t)V_n(t+\tau)\rangle = 2k_BTR\delta(\tau)$

F_n is the force noise $\langle F_n(t)F_n(t+\tau)\rangle = 2k_BT\eta\delta(\tau)$

- Nonlinear dynamics (=> mixing effects)
- Coupling between electrical and mechanical noise

From friction to noise

Linearized system: $x_\omega = G(\omega) f_\omega$

Transfer function $G(\omega) = \dfrac{\omega_0^2 / k}{\omega_0^2 - \omega^2 + i\omega_0\omega/Q}$,

$$\omega_0 = \sqrt{\frac{k}{m}}$$

Thermal noise

$$\frac{1}{2}k_B T = \frac{1}{2}k\overline{x_n^2}$$

Brownin liike

$$\overline{x_n^2} = \frac{\overline{f_n^{\,2}}}{k^2}\int_0^\infty \frac{\omega_0^4}{\left(\omega_0^2 - \omega^2\right)^2 + \left(\omega_{0^2}\omega/Q\right)^2}\frac{d\omega}{2\pi} = \overline{f_n^{\,2}}\,\frac{\omega_0^4 Q}{4k^2} = \frac{k_B T}{k}$$

$$\overline{f_n^{\,2}} = \sqrt{4k_B T\eta}$$

(White force noise assumed)

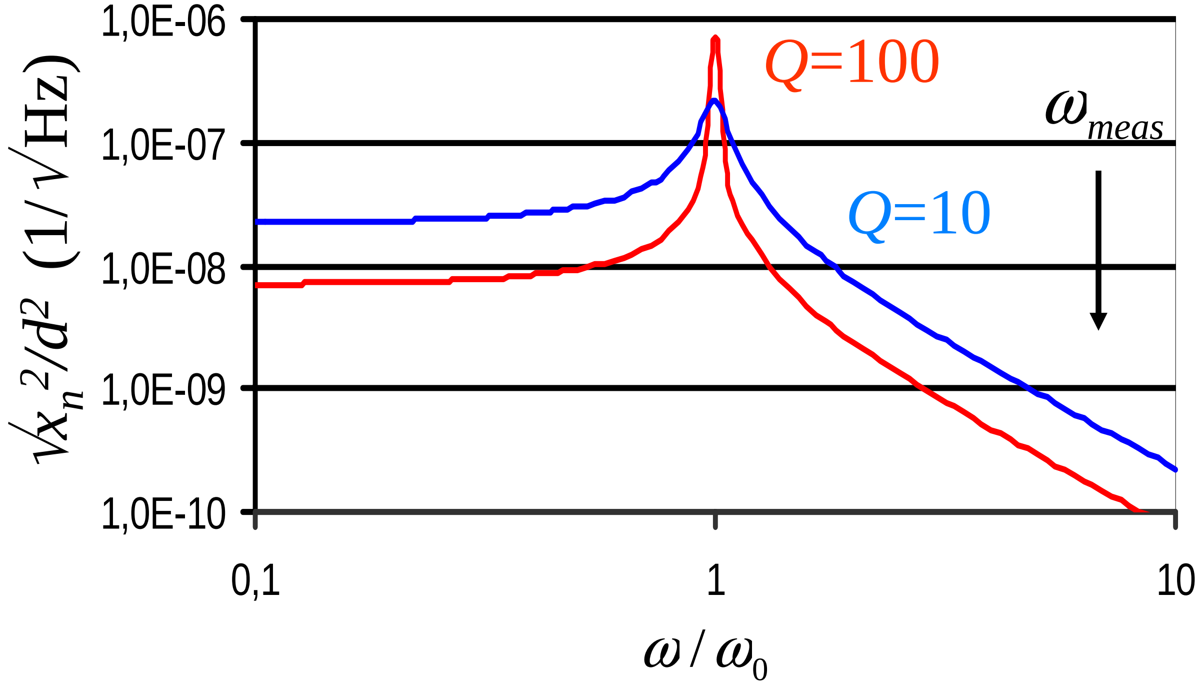
η on kitkakerroin, $\eta = \dfrac{k}{Q\omega_0}$, Q on mekaaninen hyvyysluku

Mechanical noise

$$\frac{x_n^2/d^2}{\Delta f} = \frac{4Qk_BT}{\omega_0 kd^2} \quad \text{at } \omega=\omega_m$$

$$= \frac{4k_BT}{Q\omega_0 kd^2} \quad \text{at } \omega=0$$

Displacement noise



Low-freq noise decreases by increasing *Q* (= decreasing friction) (vacuum encapsulation)

Signal-to-noise

Intrinsic only!

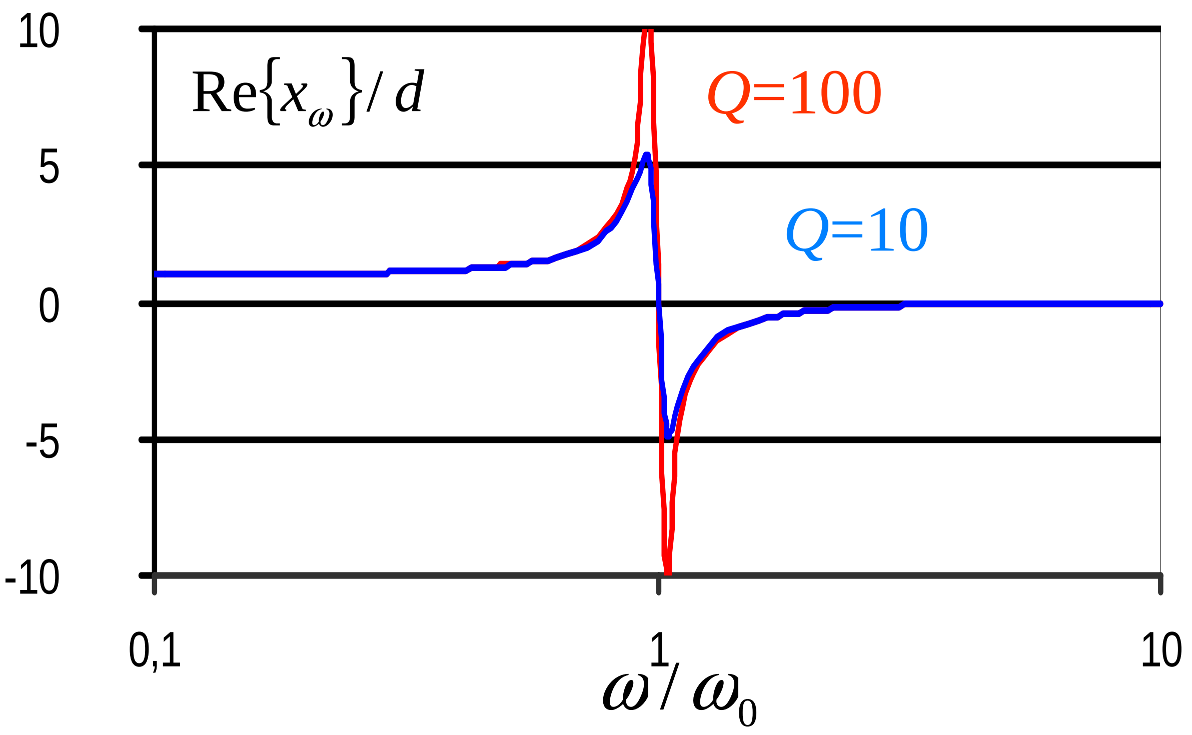
$$\frac{\mathrm{Re}\{x_\omega\}}{d} = \frac{1-\omega^2/\omega_0^2}{\left(1-\omega^2/\omega_0^2\right)^2+\left(\omega/\omega_0 Q\right)^2}\,\frac{\mathrm{Re}\{f_\omega\}}{kd}$$

$$\frac{S}{N} = \frac{x/d}{\sqrt{x_n^2/d^2}}$$

$$= \frac{\sqrt{\frac{Q\omega_0}{k}F}}{\sqrt{4k_B T\Delta f}}$$

at low frequencies

Other noise sources!



Signal-to-noise is the important quantity
Not signal itself (i.e. sensitivity)

Capacitive sensor has an internal noise mechanism which arises from internal energy dissipation.

It is temperature dependent.

It can be quantitatively predicted !

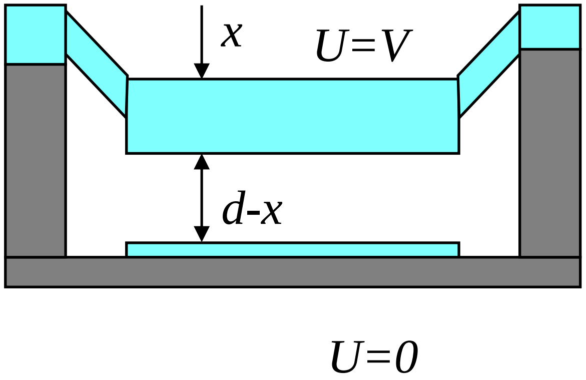
Magnitude of the noise can be calculated from the equipartion theorem $\frac{1}{2} kx^2 = \frac{1}{2} k_B T$ *and the equation of motion for the released membrane of the capacitive sensor.*

The latter determines how noise is shaped with frequency.

Electrostatic actuation (the concept of transducer)

Actuation (i.e. movement) of the released electrode by using electrostatic force

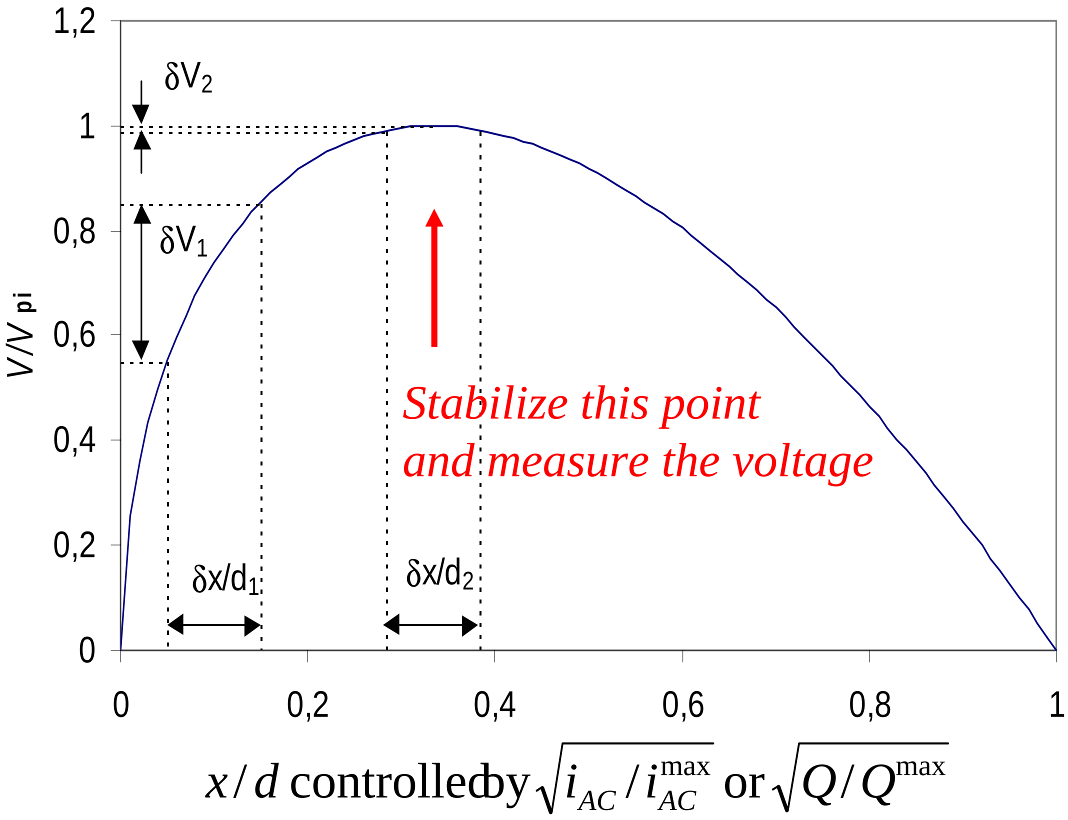
$$F_{el} = F_{spring} \quad \Leftrightarrow \quad \frac{\varepsilon_0 A V^2}{2(d-x)^2} = kx$$



Pull in at $V_{pi} = \sqrt{\frac{8kd^2}{27C_0}}$

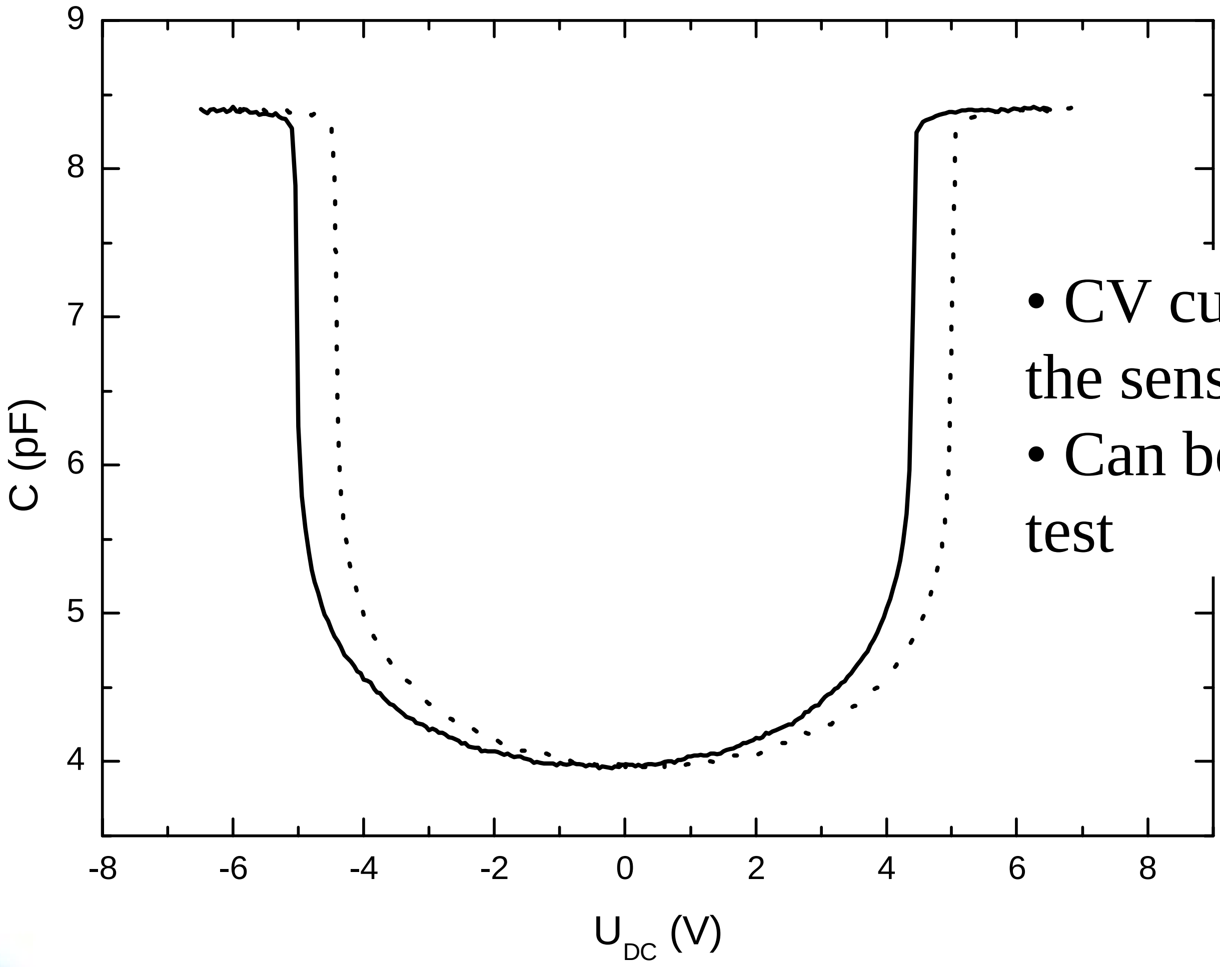
The electrodes are snapped together due to the nonlinearity of the electrostatic force

“Eigencurve” of a moving parallel plate capacitor



Stabilize this point
and measure the voltage

CV curve of a moving plate capacitor



- CV curve shows that the sensor is working
- Can be used for self test

Miscellaneous

Literature

1. **Stanfordin tämään kevään “Introduction to Sensors” kurssi http://design.stanford.edu/Courses/me220/me220.html**
2. **M. Elwenspoek, R. Wiegerink: “Mechanical Microsensors” , Springer 2001 *(contains no S/N analysis!!!)***
3. **Universal capacitive readout (= general purpose ultra-low noise CMOS ASIC, contact info@microsensors.com)**
4. **Y. Netzer, “The Design of Low-Noise Amplifiers”, Proc. IEEE Vol. 69, No. 6, p. 728 – 741 (1981).**

http://design.stanford.edu/Courses/me220/list.html#notes

Lecture 1: Human/Animal Sensors
Lecture 2: Sensor Performance Characteristics
Lecture 3: Strain Gauges
Lecture 4: Capacitive Sensors and Accelerometer Fundamentals
Lecture 5: ADXL50 Micromachine Accelerometer Demonstration
Lecture 6: Piezoelectric Sensors
Lecture 7: Pressure Sensors
Lecture 8: Thermometers
Lecture 9: Flow Sensors
Lecture 10: Radiation Sensors
Lecture 11: IR Sensors Demo: IR Motion
Lecture 12: Inductive and Magnetic Sensors
Lecture 13: Active Sounding Measurement Techniques Examples
Lecture 14: DC Motor Demonstration
Lecture 15: Micromachine Sensor Design and Fabrication
Lecture 16: Chemical Sensors

Lecture 17: Gyroscopes

Other (RF) MEMS coursess

- Prof. Antti Räisäsen RF-MEMS kurssi
- International master's program on RFMEMS through the AMICOM Network of Excellence (Advanced MEMS for communications)
- VTT is a partner is this network
- Contact persons: jussi.tuovinen@vtt.fi, aarne.oja@vtt.fi