



Lecture 8

Humidity sensors

Capacitive Sensors



Humidity = amount of water vapor in a gas

“Moisture” = amount of water absorbed or adsorbed by a liquid or a solid

Absolute humidity (g/m^3) = water vapor mass contained in a given gas volume

Relative humidity (RH) = water vapor partial pressure, expressed as percentage of pressure needed to make saturated the gas mixture at the same temperature

$$RH = 100 \frac{P_W}{P_S}$$

P_W = water vapor partial pressure
 P_S = saturated water vapor pressure at a given temperature



The majority of electrical insulators show a significant decrease of resistivity with increasing contained water.

If a hygroscopic mean (e.g. lithium chloride, LiCl) is added, the decrease of resistivity is even greater.

Therefore, by measuring the changes of electrical resistance as a function of humidity variations allows to have a “resistive hygrometer” (or “humistor”).

Types of resistive hygrometers:

- Salts (LiCl , BaF_2 , P_2O_5)
- Conductive polymers (which ionize when water permeates)
- Treated surfaces

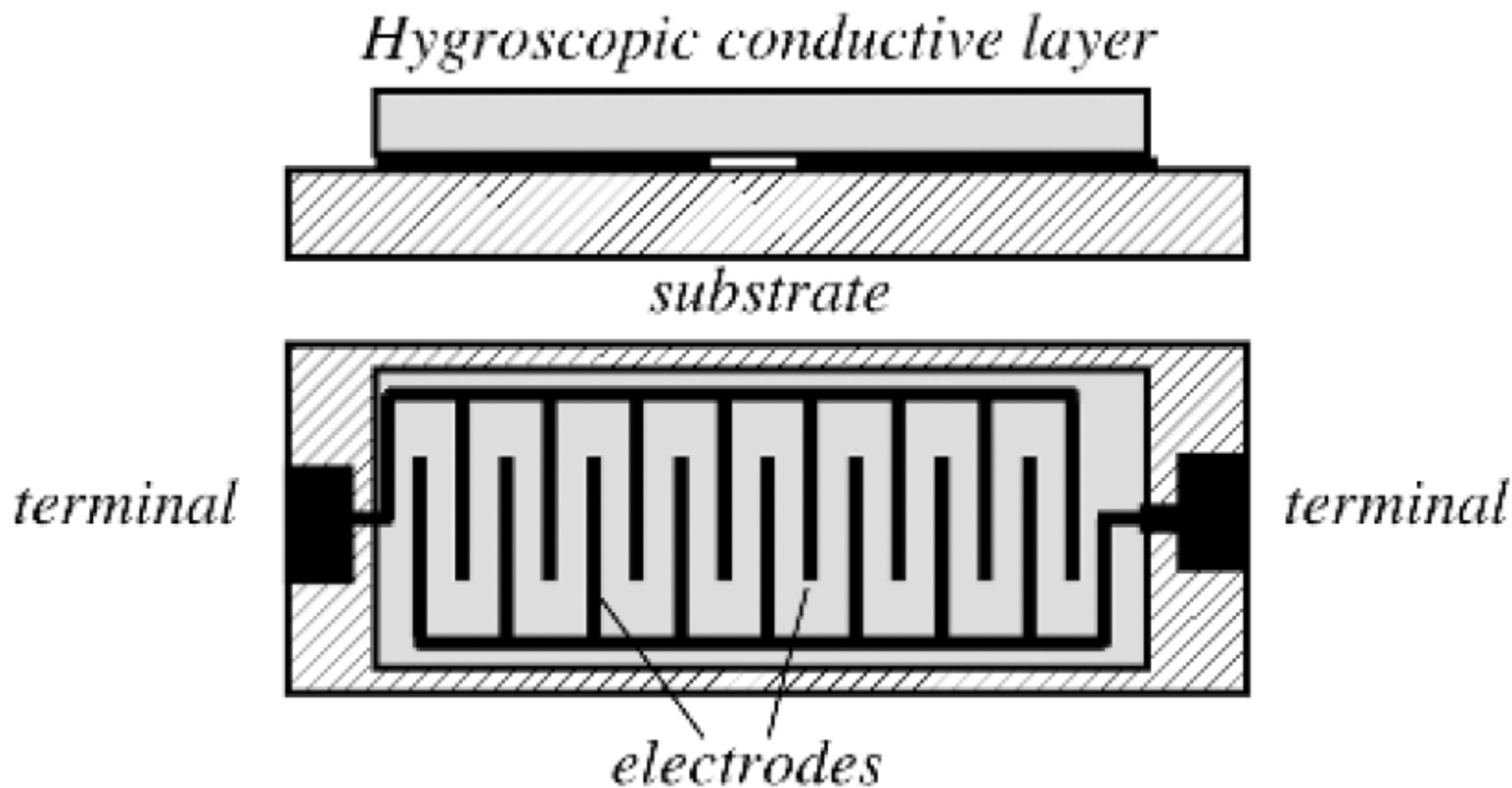


Fig. 13.6. Composition of a conductive humidity sensor.

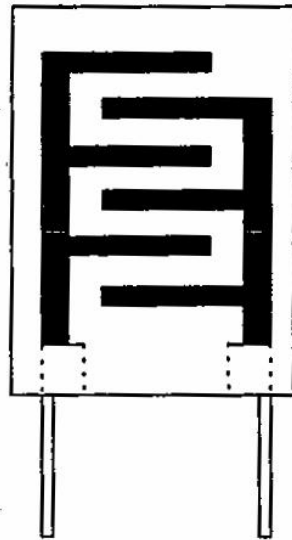


Sensors based on conductive polymers resist to surface contamination (agents do not penetrate into the polymer); they are more accurate at high levels of humidity, less at lower values ($<15\%$), because of the low levels of ionization.

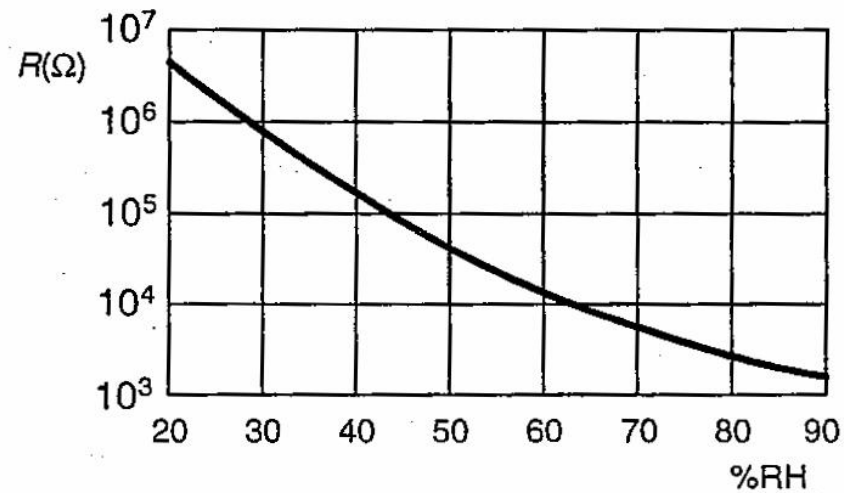
Sensors based on treated surfaces are quicker, however, they resist less to surface contamination.

Compared to capacitive hygrometers, resistive hygrometers are more accurate for $RH > 95\%$ (they do not saturate), but are slower and less accurate for $RH < 15\%$, are accurate at high levels of humidity.

Response times are slow (water molecules must permeate most of the material before determining changes in resistivity).



(a)



(b)

Figure 2.30 Resistive humidity sensor based on a bulk polymer and its resistance–humidity characteristic (from Ohmic Instruments).



TABLE 2.8 Specifications of Bulk Polymer Resistive Hygrometers

Parameter	EMD-2000	UPS-500
RH range	0% to 100%	15% to 95%
Accuracy	$\pm 1\%$ RH	$\pm 2\%$ RH
Hysteresis	$\pm 1\%$ RH at 25°C	$<0.2\%$ RH
Temperature coefficient	-0.3% RH/°C	-0.27% RH/°C
Long-term drift	—	$<2\%$ RH/5 years
Response time	10 s ^a	5 s ^b
Operating temperature	-40°C to 100°C	-30°C to 70°C
Excitation frequency	1 kHz to 10 kHz	33 Hz to 1 kHz
Excitation voltage	1 V (peak to peak)	1 V to 6 V (peak to peak)

^a Time to reach 90% or better of equilibrium rate for a step change from 11% RH to 93% RH.

^b 63% step change.



The “dew point” is the temperature to which air must be cooled in order to have the water vapor condensating into water (at constant pressure). The dew point is a saturation point.

The dew point is associated to relative humidity (RH): high RH means that the dew point is close to air temperature. RH=100% means that the dew point is equal to air temperature and air is water vapor saturated.



⇒ At a given pressure, independently on temperature, the dew point indicates the **molar fraction** of water vapor in the air.

If $P_{atm} \uparrow$ (without changing the molar fraction), the dew point \uparrow and water condensates at a higher temperature. If the molar fraction of water vapor is decreased (i.e., the air is made more dry), the dew point is returned to its initial value.

⇒ At a given temperature, independently on pressure, the dew point indicates **absolute humidity** of air.

If temperature \uparrow (without changing absolute humidity), the dew point increases and water condensates at a higher pressure. If absolute humidity is decreased, the dew point is returned to its initial value.



- The sensor most commonly used for dew-point measurement has a reflective surface which is cooled by solid state (semiconductor) Peltier heat pump.
- The temperature of the reflective surface is detected by a resistive thermometer embedded in the same material.
- Light generated by a LED (light emitting diode) is directed toward the mirror surface and the reflected light is detected by a light sensor.
- As temperature decreases, when it reaches the dew point condensate begins to form on the mirror surface, light scattering is generated and detected by the photosensor. The system is therefore so able to detect the dew point

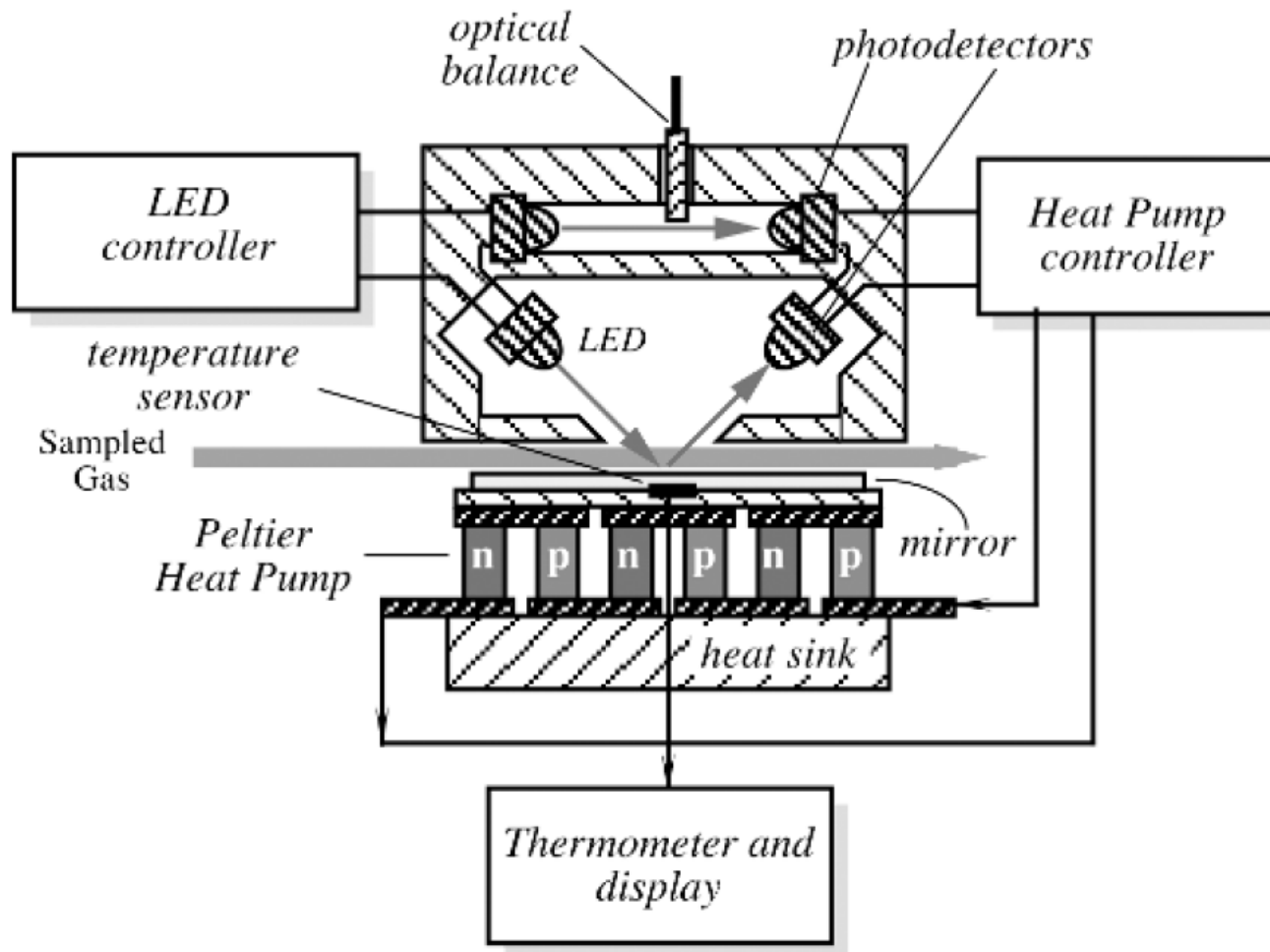


Fig. 13.9. Chilled-mirror dew-point sensor with an optical bridge.

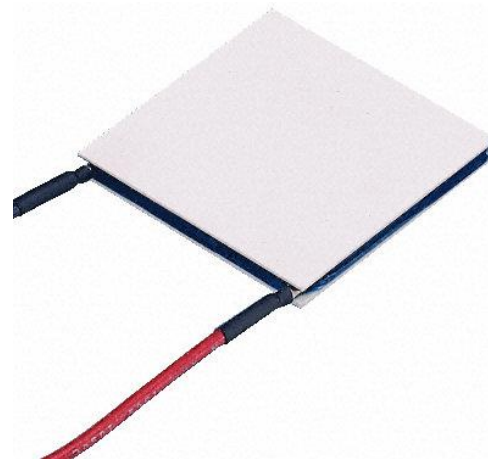
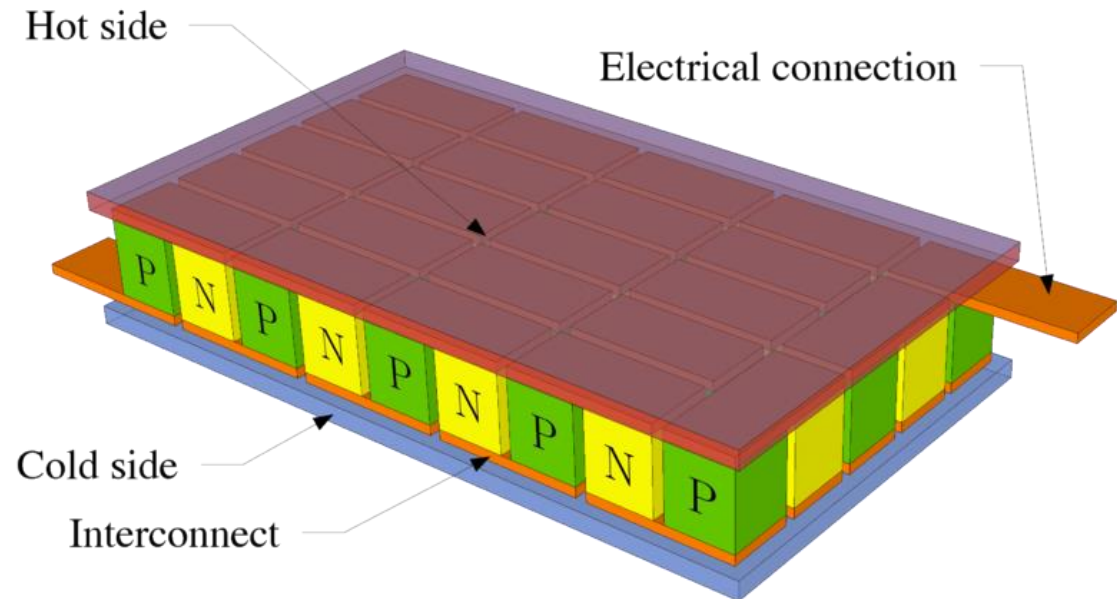


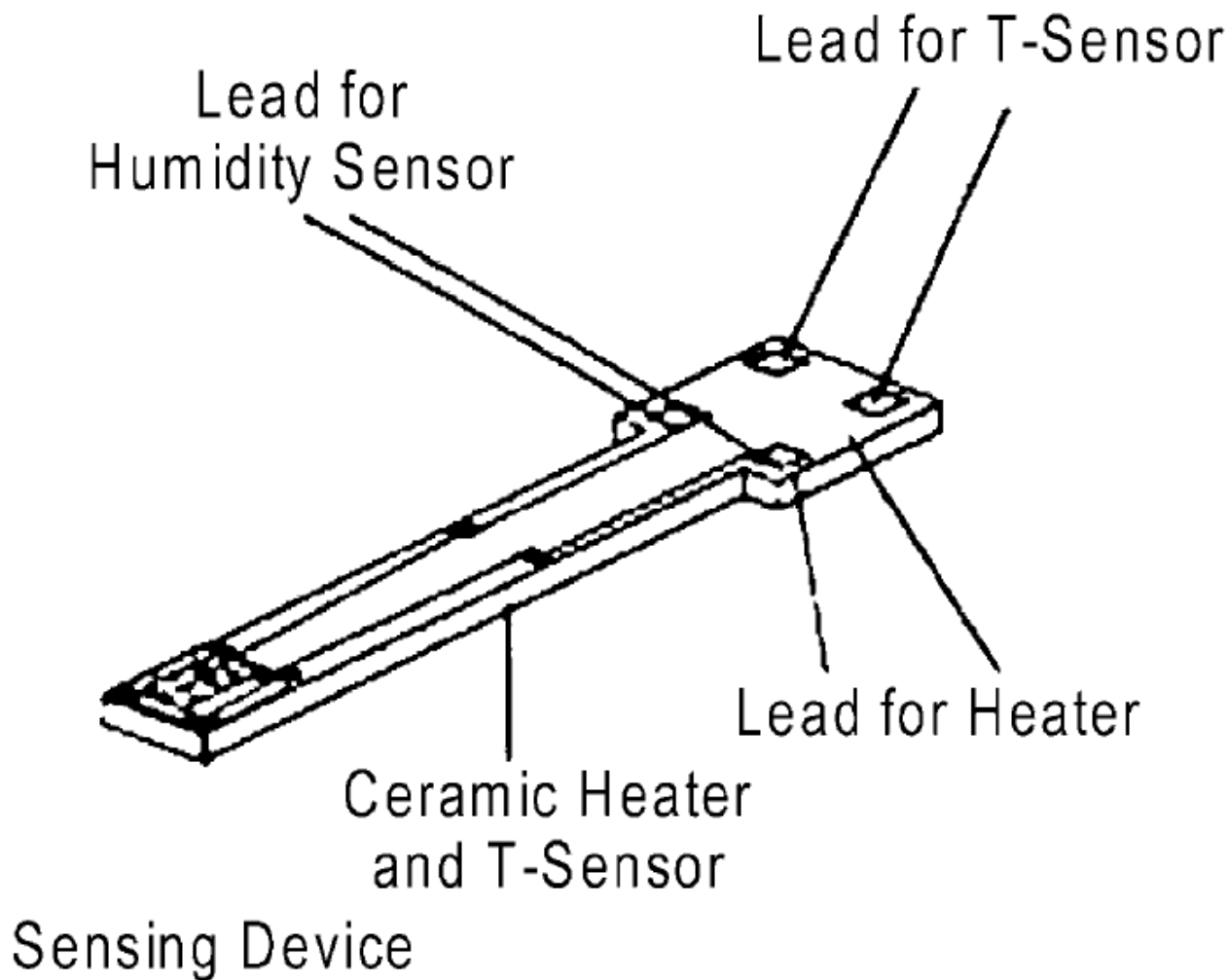
Peltier heat pump (solid state refrigerator, thermo-electric cooler, TEC)

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A Peltier cooler is a solid-state active heat pump which transfers heat from one side of the device to the other, with consumption of electrical energy, depending on the direction of the current.

Thermoelectric cooling is based on the Peltier effect to create a heat flux between the junction of two different types of materials.





A miniaturised LiCl dew point sensor, by Sakai et al.



A capacitor consists of two electric conductors separated by a dielectric (solid, liquid, or gas) or a vacuum.

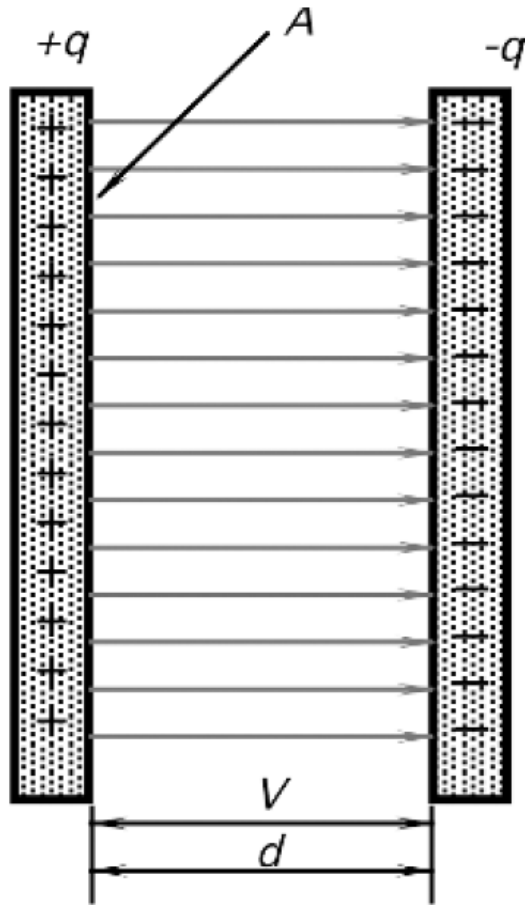
The relationship between the charge Q and the difference in voltage V between them is described by means of its capacitance, $C = Q/V$

This capacitance depends on:

- the geometrical arrangement of the conductors
- the dielectric material between them

$$C = C(\varepsilon, G)$$

(G : 'geometry' or 'shape' factor)



capacity

$$C = \frac{q}{V}$$

impedance $Z = \frac{V}{i} = -\frac{j}{\omega C} = \frac{1}{j\omega C}$

$$\Rightarrow C = \frac{\epsilon_0 \epsilon_r A}{d} = \epsilon_0 \epsilon_r G$$

Shape factor:

$$G = \frac{A}{d}$$

In a capacitor formed by n equal parallel plane plates having an area A , with a distance d between each pair, and an interposed material with a relative dielectric constant ϵ_r , the capacitance is

$$C \approx \frac{\epsilon_0 \epsilon_r A}{d} (n - 1)$$

where $\epsilon_0 = 8.85 \text{ pF/m}$ is the dielectric constant for vacuum. Therefore, any **measurand producing a variation in ϵ_r , A , or d** will result in a change in the capacitance C and can be in principle sensed by that device.

The condenser microphone described by E. C. Wente in 1917 is perhaps the earliest capacitive sensor.

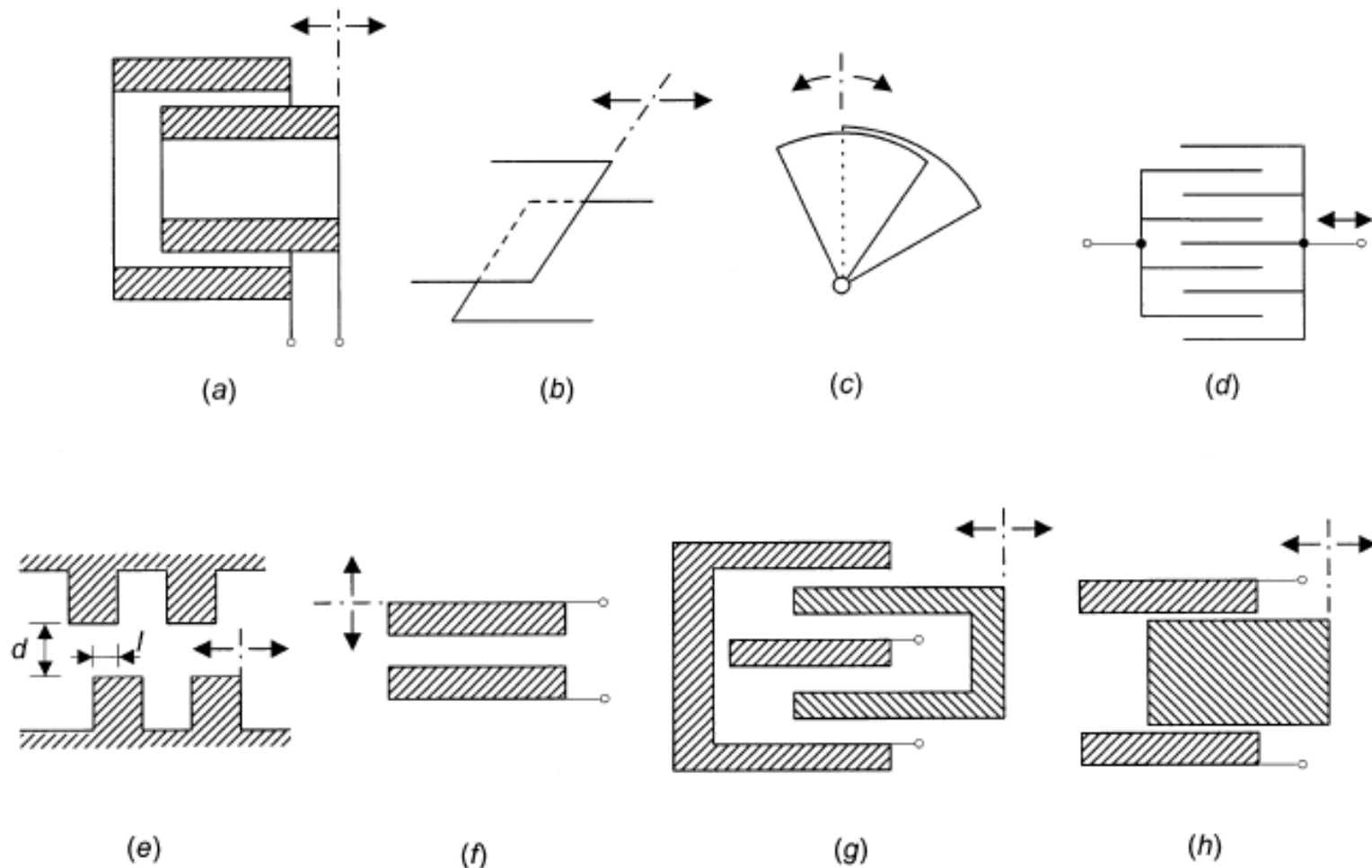


Figure 4.3 Different arrangements for capacitive sensors based on (a–e) a variation of area, (f) plate separation, and (g, h) dielectric.

For many of these configurations, there are models consisting of multiple plates, whose capacitance is given by

$$C \approx \frac{\varepsilon_0 \varepsilon_r A}{d} (n-1)$$

if they are parallel plates.

It is important to note that for multiple plate sensors, if for example the variable parameter is A , the sensitivity increases because we have

$$\frac{dC}{dA} = \frac{\varepsilon}{d} (n-1)$$

but the relative sensitivity remains the same, $dC/C = dA/A$. Thus they provide a larger capacitance but the same percent change. C usually ranges from 1 pF to 500 pF and the supply frequency is normally selected higher than 10 kHz in order to reduce the sensor output impedance.

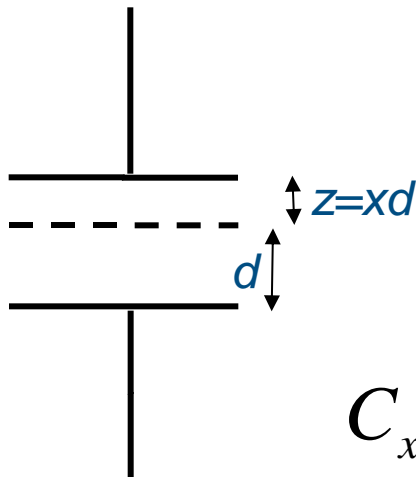


Table A.5. Dielectric Constants of Some Materials at Room Temperature (25°C)

Material	κ	Frequency (Hz)	Material	κ	Frequency (Hz)
Air	1.00054	0	Paraffin	2.0–2.5	10^6
Alumina ceramic	8–10	10^4	Plexiglas	3.12	10^3
Acrylics	2.5–2.9	10^4	Polyether sulfone	3.5	10^4
ABS/polysulfone	3.1	10^4	Polyesters	3.22–4.3	10^3
Asphalt	2.68	10^6	Polyethylene	2.26	10^3 – 10^8
Beeswax	2.9	10^6	Polypropylenes	2–3.2	10^4
Benzene	2.28	0	Polyvinyl chloride	4.55	10^3
Carbon tetrachloride	2.23	0	Porcelain	6.5	0
Cellulose nitrate	8.4	10^3	Pyrex glass (7070)	4.0	10^6
Ceramic (titanium dioxide)	14–110	10^6	Pyrex glass (7760)	4.5	0
Cordierite	4–6.23	10^4	Rubber (neoprene)	6.6	10^3
Compound for thick-film capacitors	300–5000	0	Rubber (silicone)	3.2	10^3
Diamond	5.5	10^8	Rutile \perp optic axis	86	10^8
Epoxy resins	2.8–5.2	10^4	Rutile \parallel optic axis	170	10^8
Ferrous oxide	14.2	10^8	Silicone resins	3.4–4.3	10^4
Flesh (skin, blood, muscles)	97	40×10^6	Tallium chloride	46.9	10^8
Flesh (fat, bones)	15	40×10^6	Teflon	2.04	10^3 – 10^8
Lead nitrate	37.7	6×10^7	Transformer oil	4.5	0
Methanol	32.63	0	Vacuum	1	—
Nylon	3.5–5.4	10^3	Water	78.5	0
Paper	3.5	0			



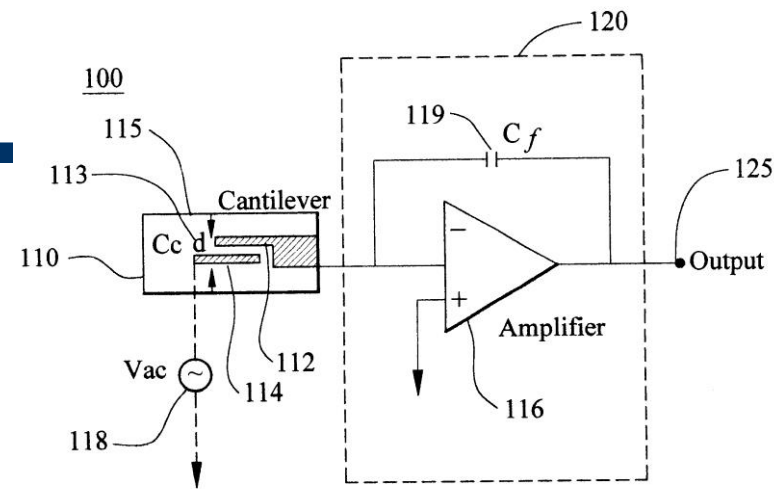
Variable capacity (plate distance)



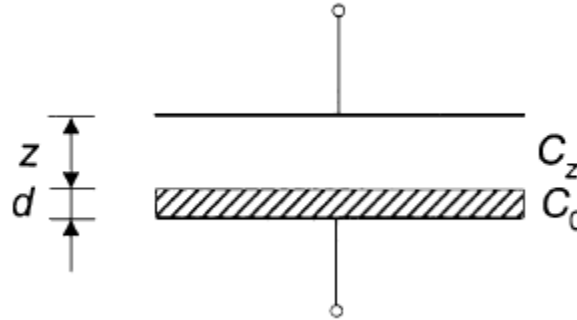
$$C_x = \epsilon \frac{A}{d + z} = \epsilon \frac{A}{d + xd} = \epsilon \frac{A}{d(1 + x)}$$

$$\frac{dC}{dz} = \frac{-\epsilon A}{d^2(1 + x)^2} = \frac{-C_0}{d(1 + x)^2} \approx -\frac{C_0}{d}(1 - 2x + 3x^2 - 4x^3 + \dots)$$

→ the sensor is nonlinear because the sensitivity instead of being constant depends on z and increases when d and z are small. This might suggest capacitors with a very small d, but there is a minimal separation determined by dielectric breakdown, which is 30 kV/cm for air.



For a sensor of the kind $C = \epsilon A/z$, the sensitivity is $-\epsilon A/z^2$, also nonlinear.



Adding a dielectric, yields for each part of the capacitor, $C_z = \epsilon_0 A/z$ and $C_0 = \epsilon_r \epsilon_0 A/d$.

The total capacitance will be the series combination of both parts:

$$C = \frac{C_0 C_z}{C_0 + C_z} = \epsilon_r \epsilon_0 \frac{A}{d + \epsilon_r z} \quad (1)$$

The sensitivity is now:

$$\begin{aligned}\frac{dC}{dz} &= -\frac{\epsilon_r \epsilon_0 A \epsilon_r}{(d + \epsilon_r z)^2} = -\frac{\epsilon_r^2 \epsilon_0 A}{d^2} \frac{1}{\left(1 + \frac{\epsilon_r z}{d}\right)^2} \\ &\approx -\frac{C_0}{d} \epsilon_r [1 - 2\epsilon_r x + 3(\epsilon_r x)^2 - \dots]\end{aligned}$$

which is more linear than $\epsilon A/z^2$.

Equation (1) also shows the effect of a dielectric covering an electrode plate for example, for electrical insulation.



- **Flow** - Many types of flow meters convert flow to pressure or displacement, using an orifice for volume flow or Coriolis effect force for mass flow. Capacitive sensors can then measure the displacement.
- **Pressure** - A diaphragm with stable deflection properties can measure pressure with a spacing-sensitive detector.
- **Liquid level** - Capacitive liquid level detectors sense the liquid level in a reservoir by measuring changes in capacitance between conducting plates which are immersed in the liquid, or applied to the outside of a non-conducting tank.
- **Spacing** - If a metal object is near a capacitor electrode, the mutual capacitance is a very sensitive measure of spacing.
- **Scanned multiplate sensor** - The single-plate spacing measurement can be extended to contour measurement by using many plates, each separately addressed. Both conductive and dielectric surfaces can be measured.
- **Thickness measurement** - Two plates in contact with an insulator will measure the insulator thickness if its dielectric constant is known, or the dielectric constant if the thickness is known.



- **Ice detector** - Airplane wing icing can be detected using insulated metal strips in wing leading edges.
- **Shaft angle or linear position** - Capacitive sensors can measure angle or position with a multiplate scheme giving high accuracy and digital output, or with an analog output with less absolute accuracy but faster response and simpler circuitry.
- **Lamp dimmer switch** - The common metal-plate soft-touch lamp dimmer uses 60 Hz excitation and senses the capacitance to a human body.
- **Keyswitch** - Capacitive keyswitches use the shielding effect of a nearby finger or a moving conductive plunger to interrupt the coupling between two small plates.
- **Limit switch** - Limit switches can detect the proximity of a metal machine component as an increase in capacitance, or the proximity of a plastic component by virtue of its increased dielectric constant over air.
- **X-Y tablet** - Capacitive graphic input tablets of different sizes can replace the computer mouse as an x-y coordinate input device. Finger-touch-sensitive, z-axis-sensitive and stylus-activated devices are available.
- **Accelerometers** - Analog Devices has introduced integrated accelerometer lcs with a sensitivity of 1.5g. With this sensitivity, the device can be used as a tiltmeter.



Capacitive sensors: examples of biomedical applications

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Minimally invasive therapy (small vessels catheters with diameter of 2mm)
Capacitive devices are mainly competing with fiber optic pressure sensors and strain gauges

cateter with either
capacity, fiber or
piezo resistive

Long-term monitoring of blood pressure (for abdominal aortas aneurism and CHF by implantable pressure monitoring systems. In such applications, power consumption becomes an important issue and capacitive devices offer a clear advantage over piezoresistive ones. [capacity sensors: LOW POWER APP!! this is very important, they absorbe less than the others, thus it's important for long term monitoring](#)

Intraocular **pressure monitoring** (for glaucoma), Intracranial pressure monitoring, clinical assessment of prosthetic socket fit and pressure distribution in artificial joints

important, it's used when miniaturization is needed.
they can be embedded in devices with both
conditioning circuit and the sensor

also if we want a "net" of sensors

Monitoring of physical activity by **accelerometers**, used for measuring inclination of body segments and activity of daily living, with application in patient rehabilitation, but also to register the kind of movements that occur in healthy persons during normal standing. [for monitoring physical activity, like step, but also the motion of the segments](#)



Capacitive sensors: examples of biomedical applications

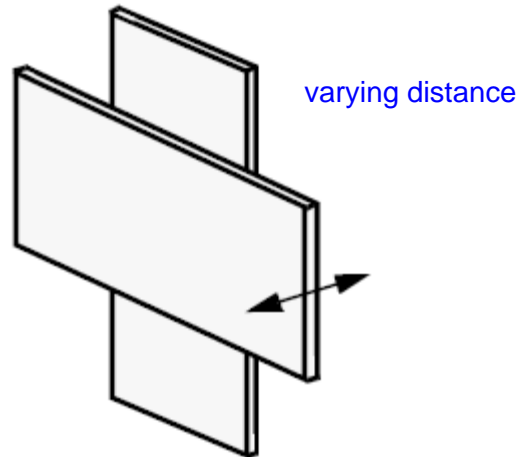
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generally piezo-electric (not resistive) but right now also cap.
because they can be miniaturized and batched. they are also
bi directional

Ultrasound imaging technology with capacitive devices that can be batch fabricated to form a transducer array with array elements that can be as small as 50 μm diameter.

Miniature capacitive transducers, known in low frequency applications as condenser microphones, are used in hearing. Low noise capacitive microphone with higher sensitivity and broader bandwidth than those used in traditional **hearing aids**.

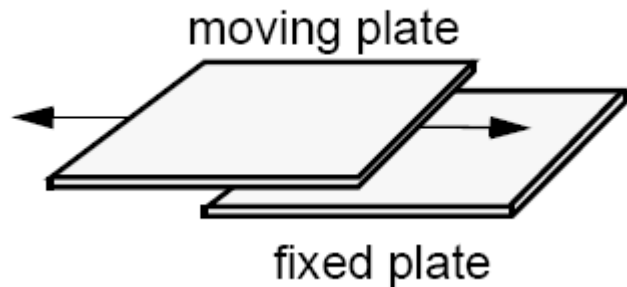
Humidity sensors for the diagnosis of pulmonary diseases



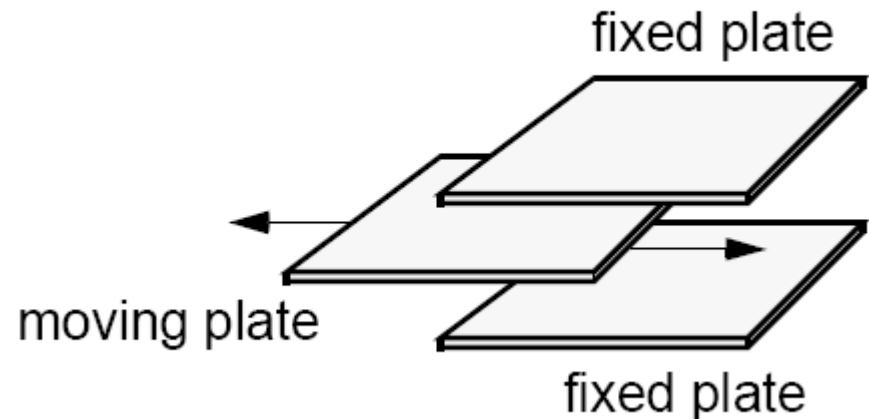
We can also combine the 3 (see next slide)

varying area (the overlapping b/w the two plates)

overlap/underlap



here it changes the dielectric

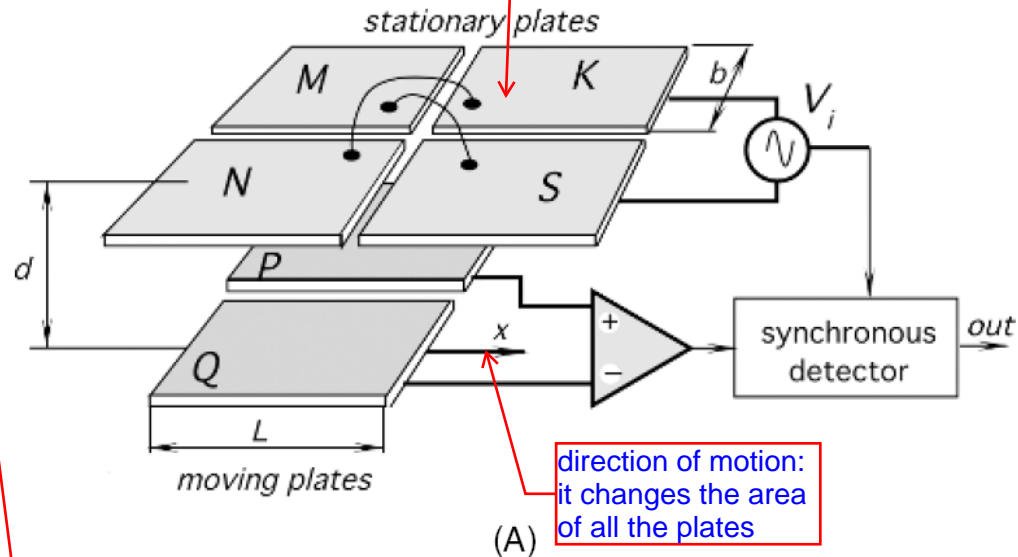




Bridge capacitive motion sensor

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ofc the other is equal but with a "-"

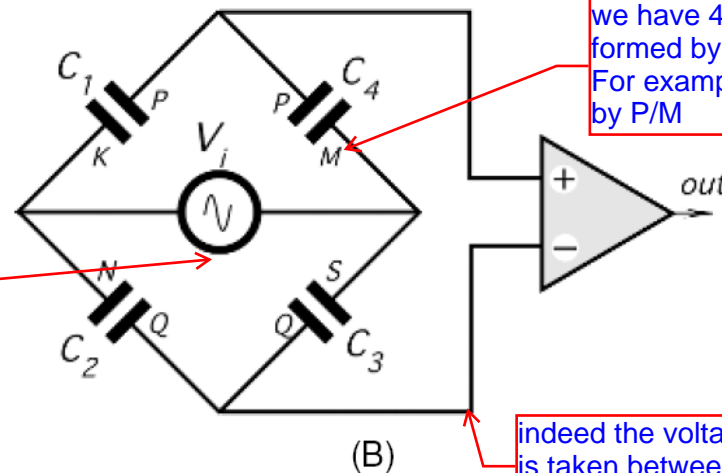


direction of motion:
it changes the area
of all the plates

$$C_1 = \frac{\epsilon_0 b}{d} \left(\frac{L}{2} + x \right)$$

in equilibrium the two plates are centered, and the area is given by $b \cdot L/2$. $C_1=C_3$ and $C_4=C_2$

excitation:
alternating voltage



we have 4 capacitor,
formed by the couples.
For example in this case
by P/M

Spoiler, sono posizionati
come per un ponte di
wheatstone

indeed the voltage
is taken between
plate P and Q

output is linear
because we use a full
bridge configuration

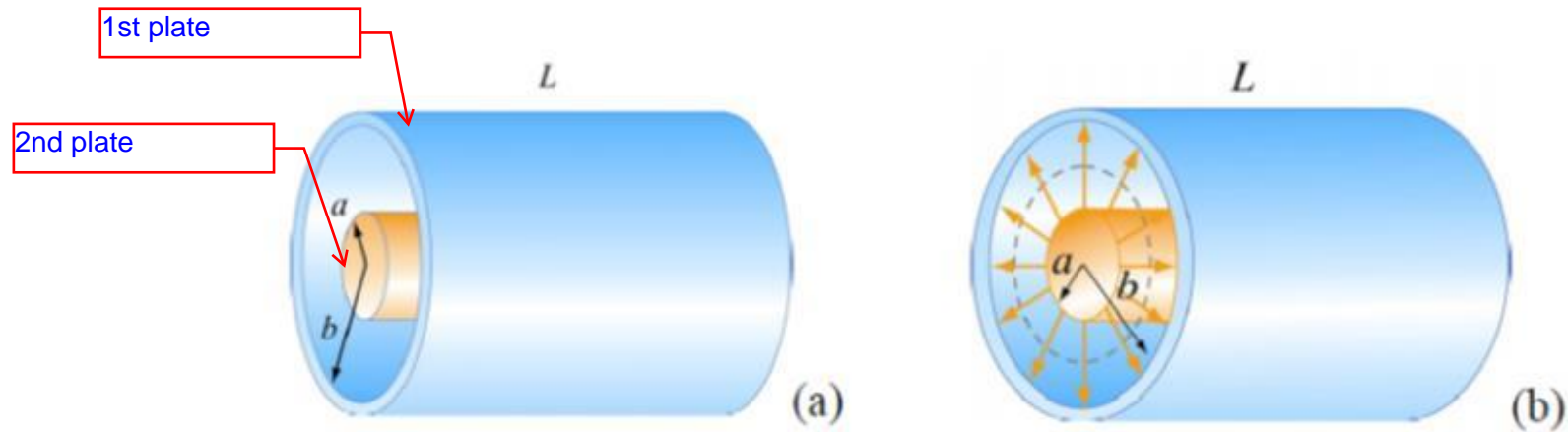


Figure 5.2.4 (a) A cylindrical capacitor. (b) End view of the capacitor. The electric field is non-vanishing only in the region $a < r < b$.

The shape factor changes! It's no more A/d ! Before we had only considered a plane flat capacitor.



To calculate the capacitance, we first compute the electric field everywhere. Due to the cylindrical symmetry of the system, we choose our Gaussian surface to be a coaxial cylinder with length $\ell < L$ and radius r where $a < r < b$. Using Gauss's law, we have

$$\oiint_S \vec{E} \cdot d\vec{A} = EA = E(2\pi r\ell) = \frac{\lambda\ell}{\epsilon_0} \Rightarrow E = \frac{\lambda}{2\pi\epsilon_0 r} \quad (5.2.5)$$

where $\lambda = Q/L$ is the charge per unit length. Notice that the electric field is non-vanishing only in the region $a < r < b$. For $r < a$, the enclosed charge is $q_{\text{enc}} = 0$ since any net charge in a conductor must reside on its surface. Similarly, for $r > b$, the enclosed charge is $q_{\text{enc}} = \lambda\ell - \lambda\ell = 0$ since the Gaussian surface encloses equal but opposite charges from both conductors.

The potential difference is given by

$$\Delta V = V_b - V_a = -\int_a^b E_r dr = -\frac{\lambda}{2\pi\epsilon_0} \int_a^b \frac{dr}{r} = -\frac{\lambda}{2\pi\epsilon_0} \ln\left(\frac{b}{a}\right) \quad (5.2.6)$$

where we have chosen the integration path to be along the direction of the electric field lines. As expected, the outer conductor with negative charge has a lower potential. This gives

RESULT:

$$C = \frac{Q}{|\Delta V|} = \frac{\lambda L}{\lambda \ln(b/a) / 2\pi\epsilon_0} = \frac{2\pi\epsilon_0 L}{\ln(b/a)} \quad (5.2.7)$$

the shape factor is this just without the dielectric

Once again, we see that the capacitance C depends only on the geometrical factors, L , a and b .

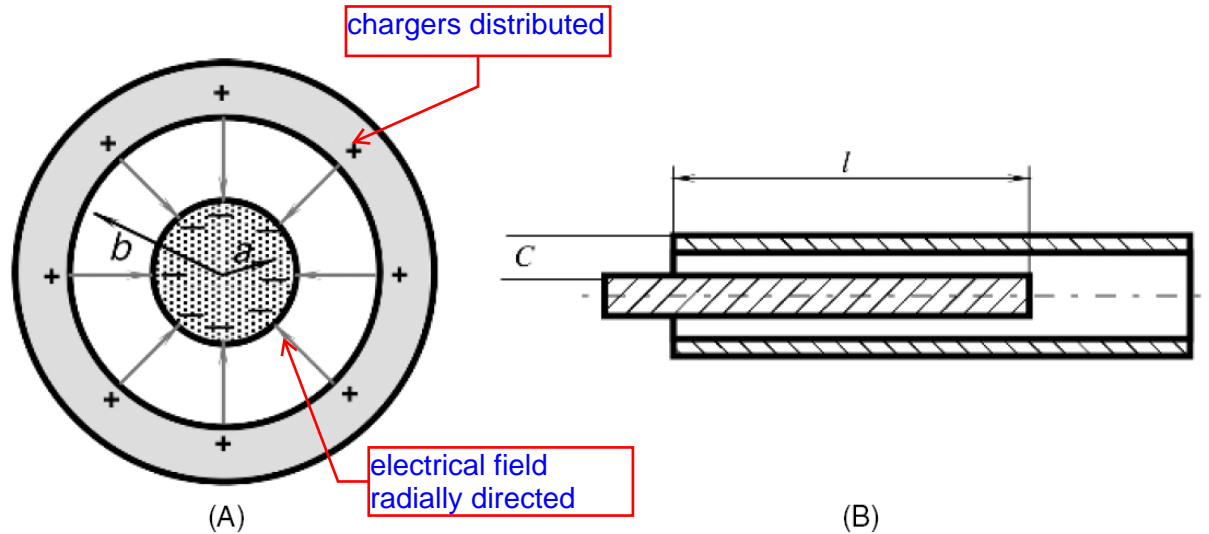


Fig. 3.5. Cylindrical capacitor (A); capacitive displacement sensor (B).

$$\text{if } l \gg b \quad G = \frac{2\pi\ell}{\ln(b/a)}$$

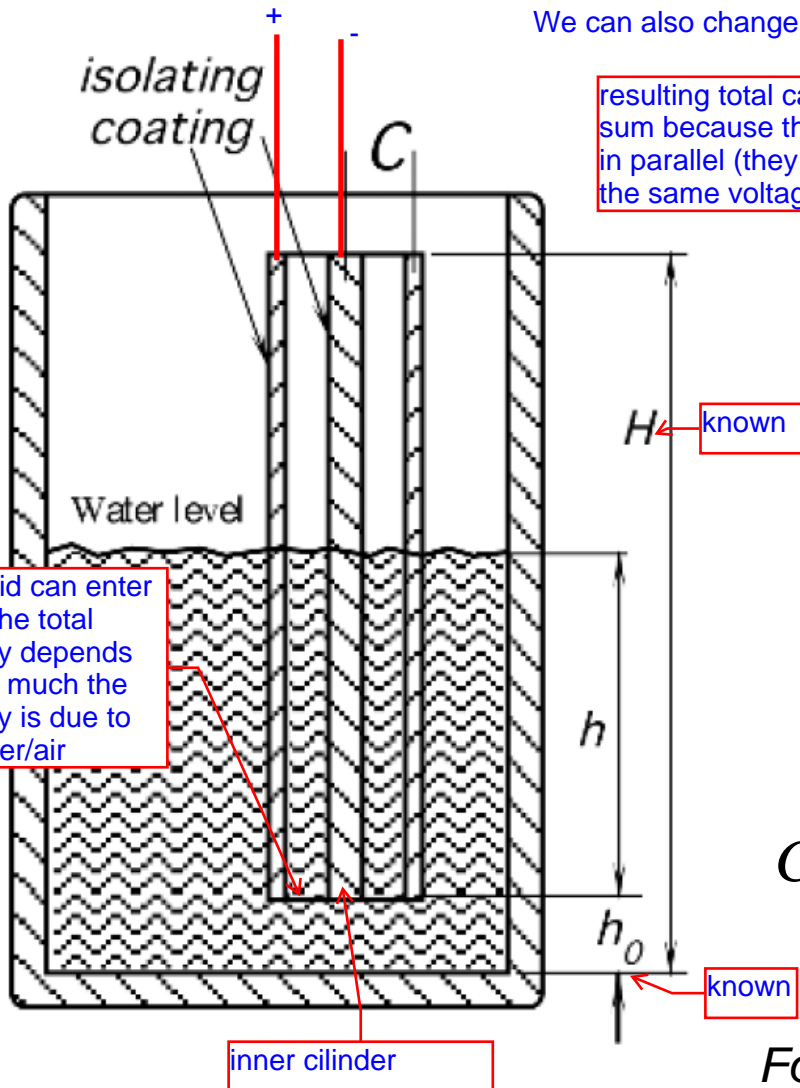
Dove non è inserito NON e' contanto come capacità, infatti è un elettrodo, NON è un dielettrico!

$$C = \varepsilon_0 \varepsilon_r G = \frac{2\pi \varepsilon_0 \varepsilon_r \ell}{\ln(b/a)}$$



Capacitive sensor for liquid level measurement

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We can also change the dielectric

resulting total capacity, sum because they are in parallel (they have the same voltage)

$$C_h = C_1 + C_2 = \epsilon_0 G_1 + \epsilon_0 \epsilon_r G_2$$

air

shape factor

water

$$C_1 = \frac{2\pi\epsilon_0(H-h-h_0)}{\ln(b/a)}$$

$$C_2 = \frac{2\pi\epsilon_0\epsilon_r h}{\ln(b/a)}$$

$$C = C_1 + C_2 = \frac{2\pi\epsilon_0}{\ln(b/a)} [H - h(1 - \epsilon_r) - h_0]$$

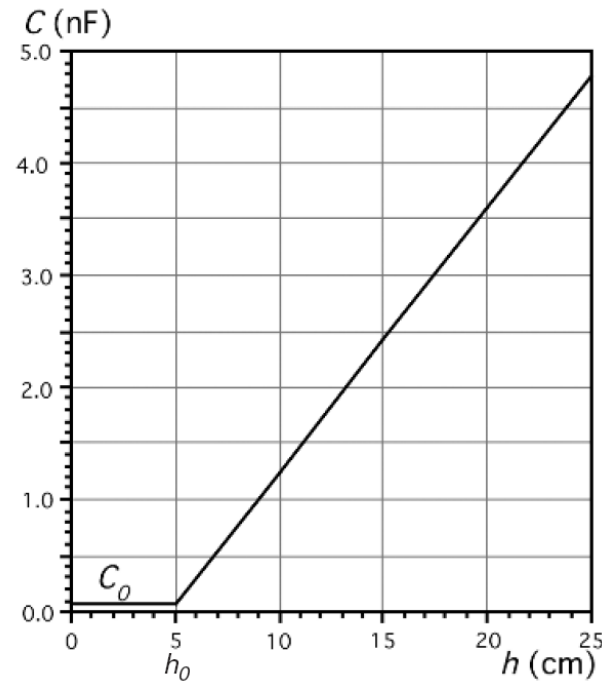
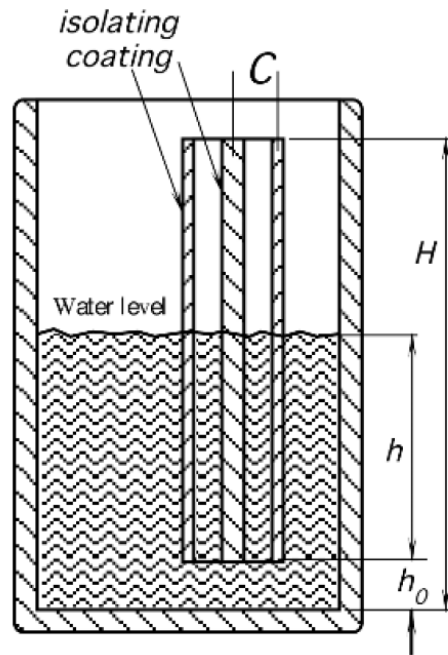
For liquid height $\leq h_0$: $C_0 = \frac{2\pi\epsilon_0(H-h_0)}{\ln(b/a)}$

ofc it's constant



Capacitive sensor for liquid level measurement

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$a = 10 \text{ mm}$
 $b = 12 \text{ mm}$
 $H = 200 \text{ mm}$
Liquid: H_2O

$$C = C_1 + C_2 = \frac{2\pi\epsilon_0}{\ln(b/a)} [H - h(1 - \epsilon_r) - h_0]$$

For liquid height $\leq h_0$:

$$C_0 = \frac{2\pi\epsilon_0(H - h_0)}{\ln(b/a)}$$



A capacitor filled in with air can be considered a humidity sensor. In fact, any change of water vapour pressure in the air determines a change of air electric permittivity (ϵ_r) according to the following relationship:

$$\epsilon_r = 1 + \frac{211}{T} \left(P + \frac{48P_s}{T} RH \right) 10^{-6}$$

Change in permittivity used to measure the humidity.

where

T: absolute temperature (K)

P: humid air pressure (mmHg)

P_s : saturated water vapor pressure at temperature T (mmHg)

RH: relative humidity (%)

it's basically an empty capacitance where air can pass, and of course the permittivity of the air changes with humidity, and we keep the other values constant.



Instead of air, insulating materials whose permittivity varies significantly with humidity are used as dielectric.

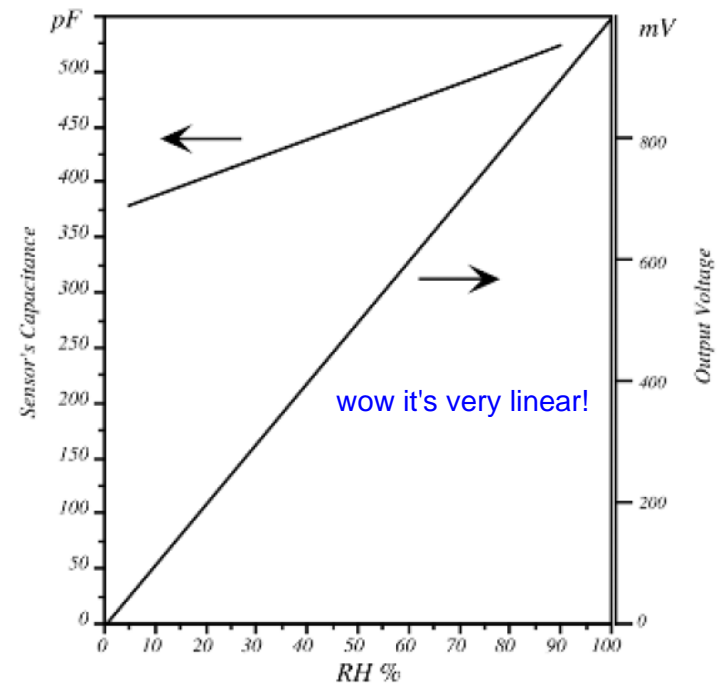
These include polymeric hygroscopic films (e.g., thin hydrophilic polymeric films (8-12 μm thickness) made of cellulose acetate butyrate)

basically material that absorbs water. The sensitivity increases because the water is absorbed easily and changes a lot the values.

In this case, sensor capacitance is approximately proportional to relative humidity RH:

$$C_h \approx C_0(1 + \alpha_h RH)$$

relative to a given humidity.



Capacitive hygrometer with integrated heater and temperature sensors

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we can create cap hyg with integrated heater. Just like we have seen before, we have a very thin membrane where we deposit different structures, and then we obtain a dew point hygrometer

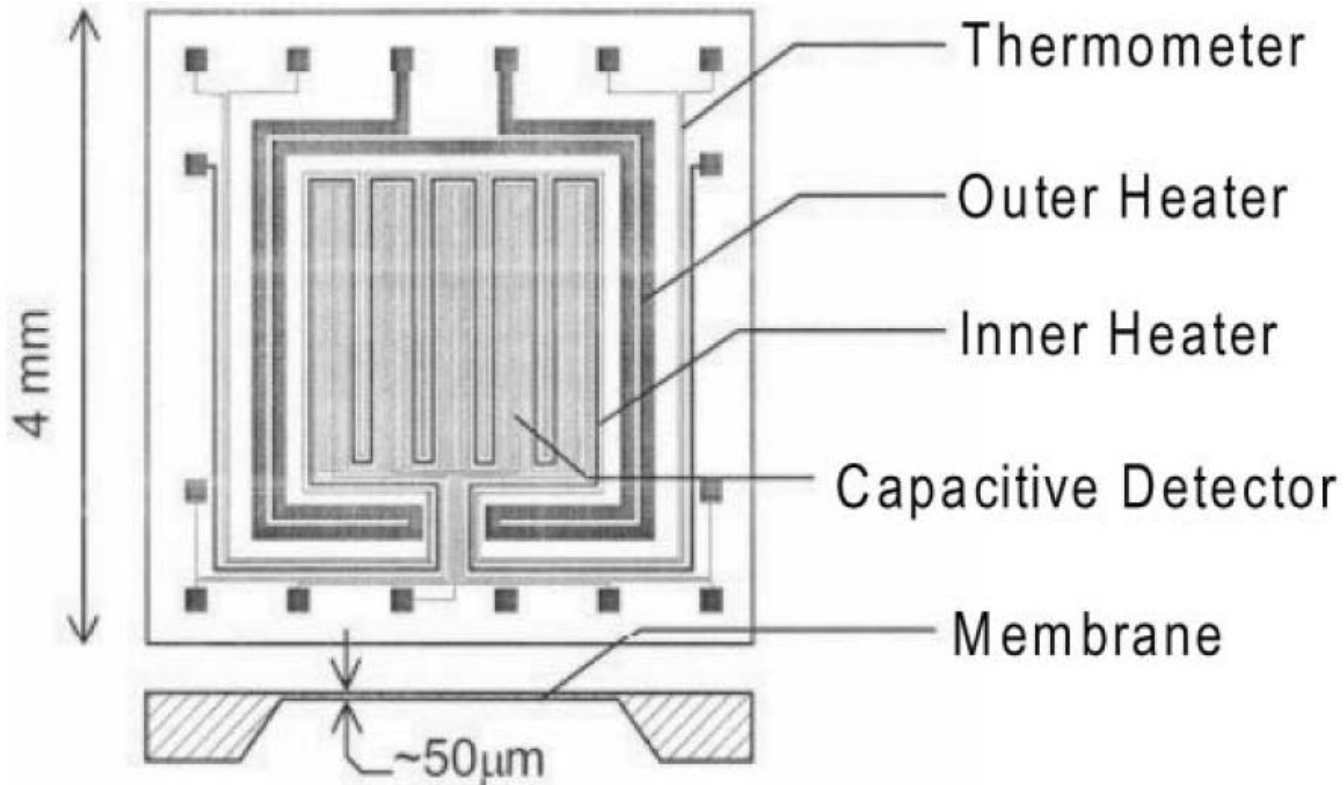


Fig. 6. Silicon dew point hygrometer with integrated heater and temperature sensors, by Jachowicz and Weremczuk [89].

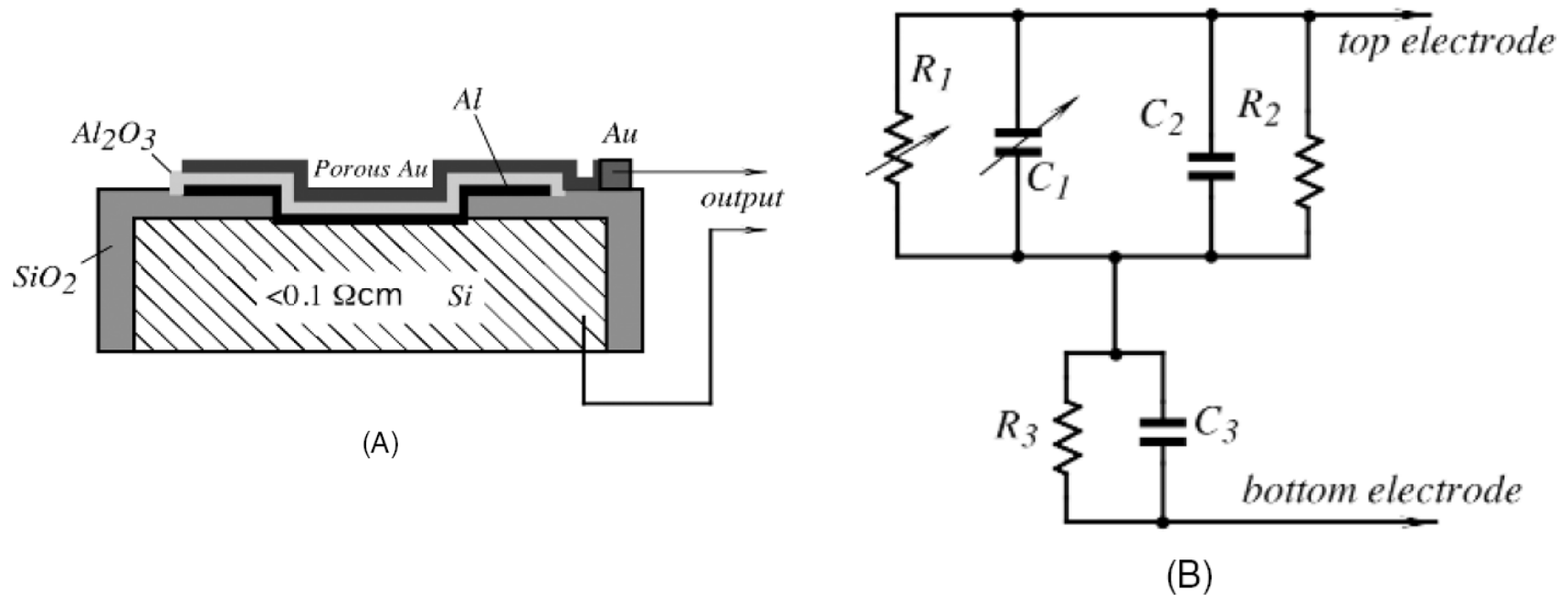


Fig. 13.7. (A) Structure of Al_2O_3 thin film moisture sensor; (B) simplified equivalent circuit of the sensor. R_1 and C_1 are moisture-dependent variable terms; R_2 and C_2 are shunting terms of bulk oxide between pores (unaffected by moisture); R_3 and C_3 are series terms below pores (unaffected by moisture).

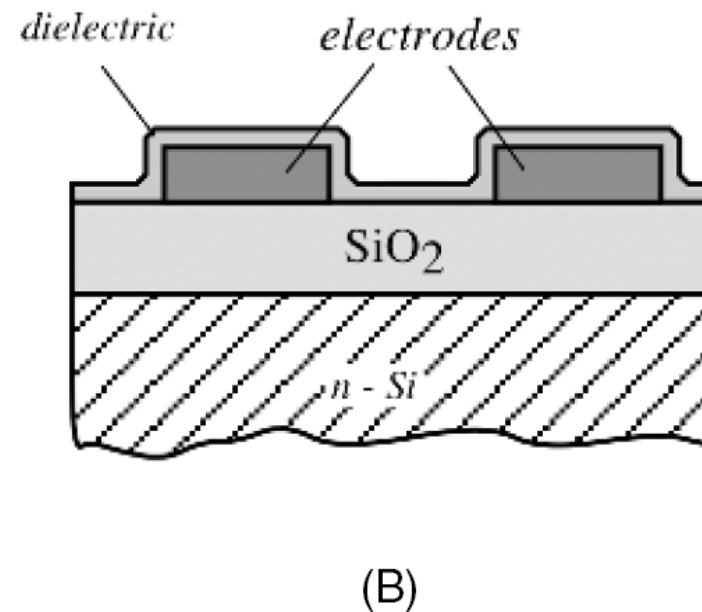
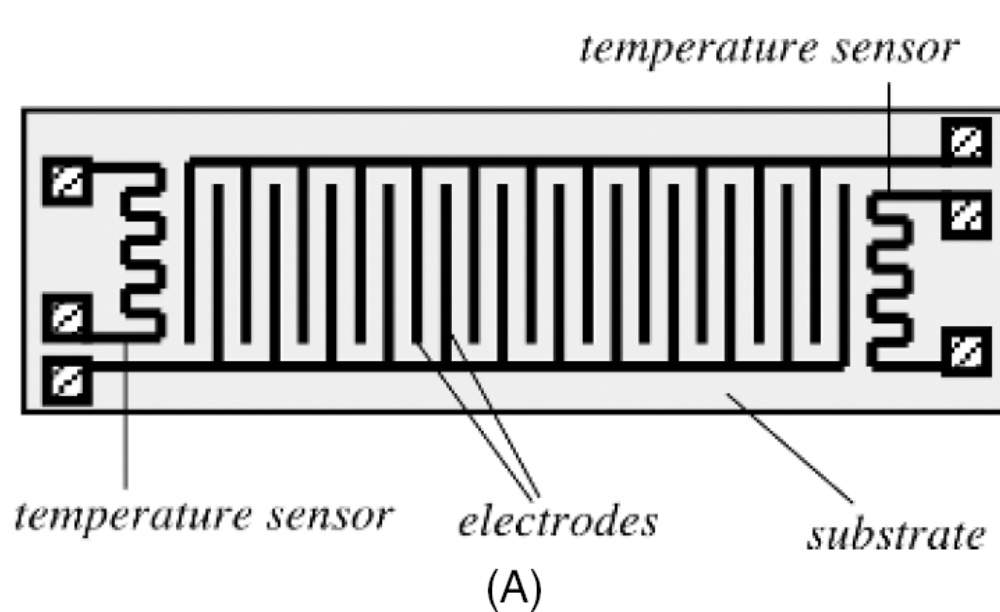


Fig. 13.4. Capacitive thin-film humidity sensor: (A) interdigitized electrodes form capacitor plates; (B) cross section of the sensor.

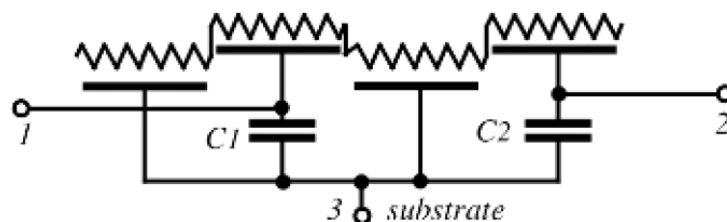


Fig. 13.5. Simplified equivalent electric circuit of a capacitive thin-film humidity sensor.



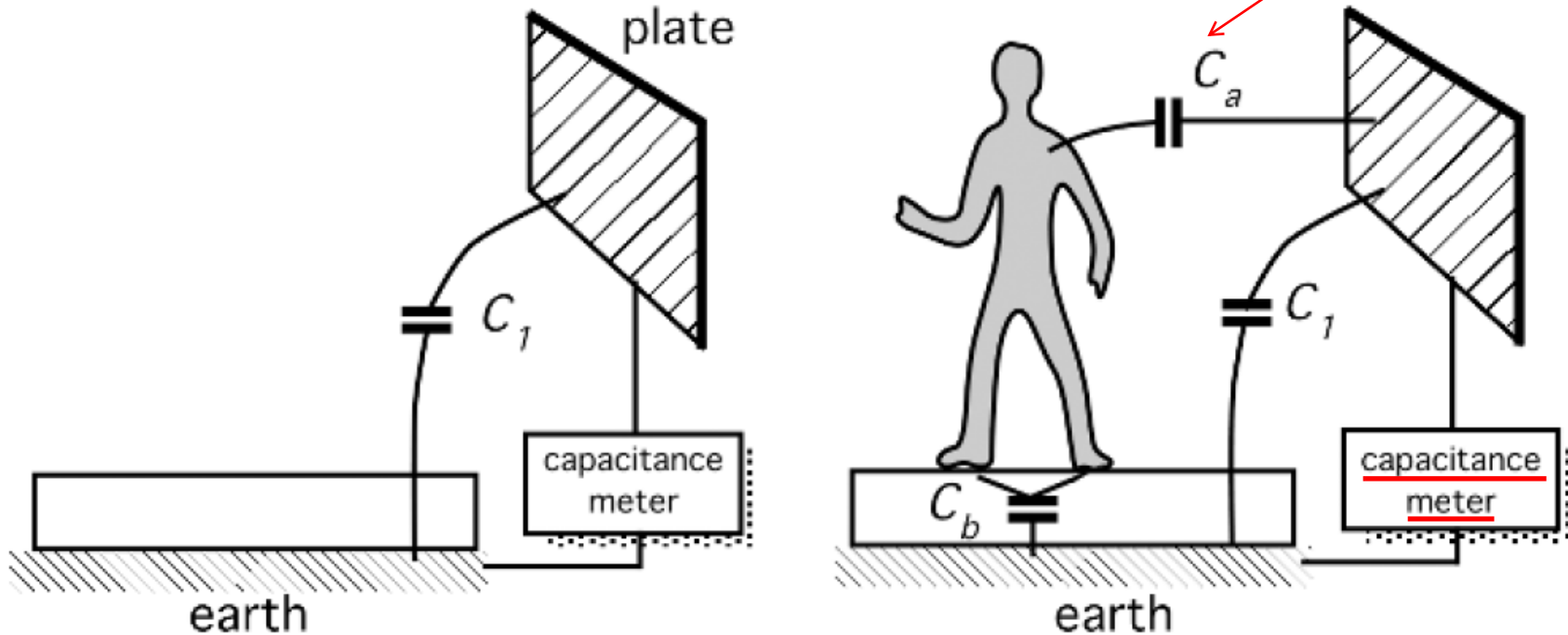
Capacitive sensor of intrusion

(generally presence)

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saranno in serie

(example of proximity sensor as a loading mode)

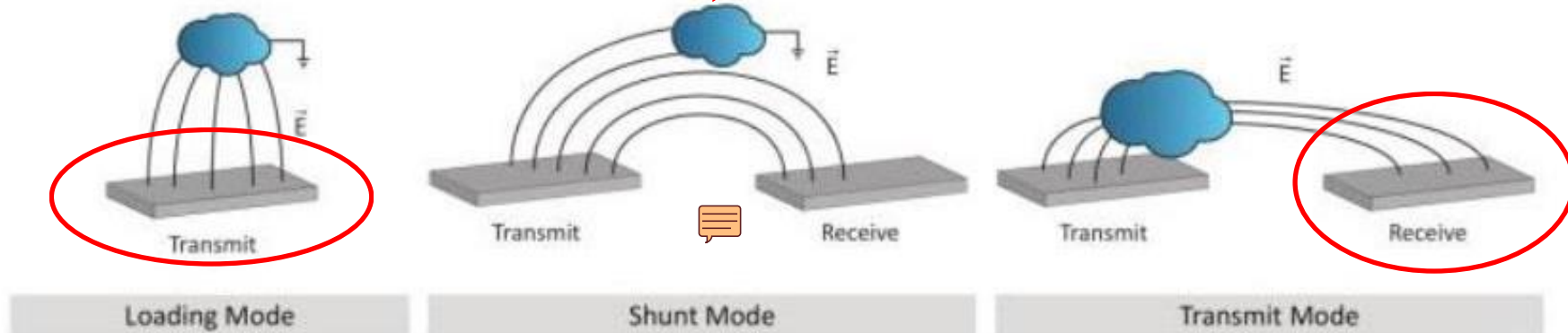


$$C = C_1 + \Delta C = C_1 + \frac{C_a C_b}{C_a + C_b}$$

added when the
human body is
present



it's shunting portions of the el. field!



Three measurement modes:

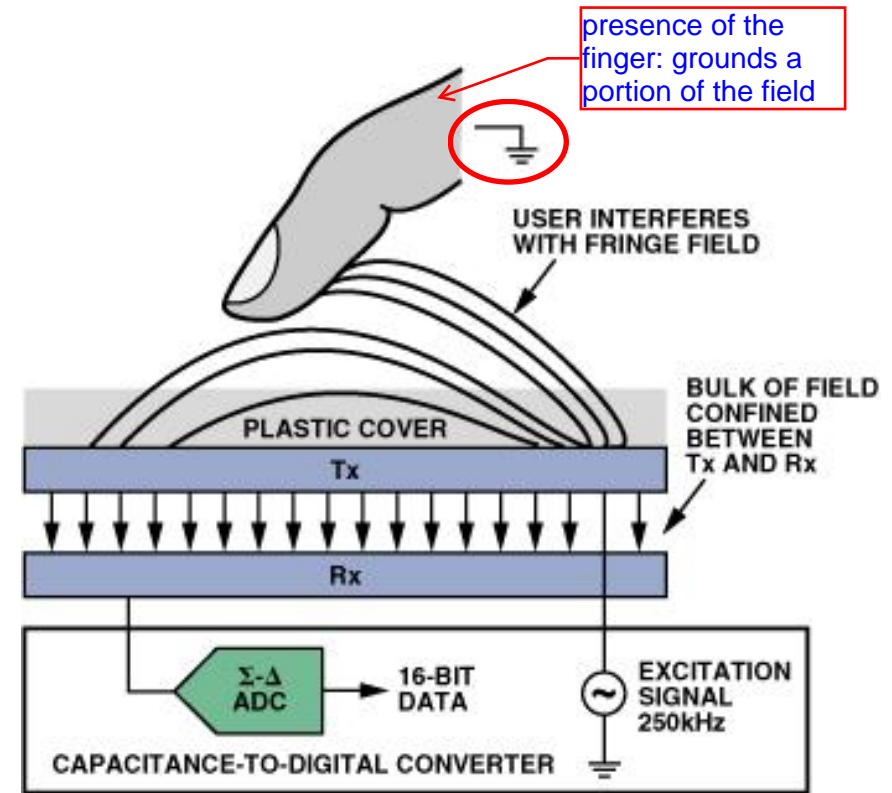
- 1) **Transmit mode** uses a transmitting electrode that is coupled to a conductive object, typically the human body. The properties of an electric field generated with respect to a receiving electrode will therefore depend on the distance of this body, thus extending the achievable range.
- 2) **Shunt mode** also uses receiving and transmitting electrodes that generate a field between each other. However, as there is no coupled body, any conductive object will ground the field, thus reducing the amount of energy stored. This setup works with various transmitters on a single receiver. This generates a larger amount of “virtual sensors” using limited hardware.
- 3) **Loading mode**, in which a single electrode creates an electric field grounded by any suitable object in the environment. Thus, any approaching grounded object increases the capacitance of the system. This is measured periodically.



Capacitance Sensors for Human Interfaces to Electronic Equipment

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A basic sensor includes a receiver and a transmitter, each of which consists of metal traces formed on layers of a printed circuit board (PCB). The systems have an on-chip excitation source, which is connected to the transmitter trace of the sensor. Between the receiver and the transmitter trace, an electric field is formed. Most of the field is concentrated between the two layers of the sensor PCB. However, a fringe electric field extends from the transmitter, out of the PCB, and terminates back at the receiver. The field strength at the receiver is measured by the on-chip capacitance-to-digital converter.



The electrical environment changes when a human hand invades the fringe field, with a portion of the electric field being shunted to ground instead of terminating at the receiver. The resultant decrease in capacitance—on the order of femtofarads as compared to picofarads for the bulk of the electric field—is detected by the converter.

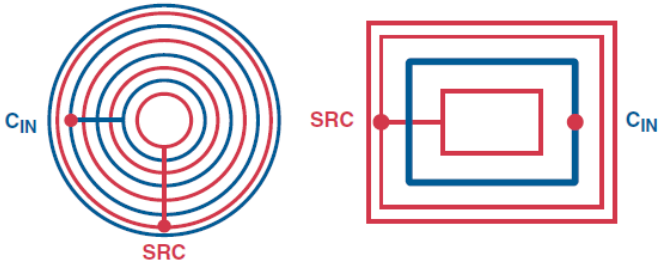
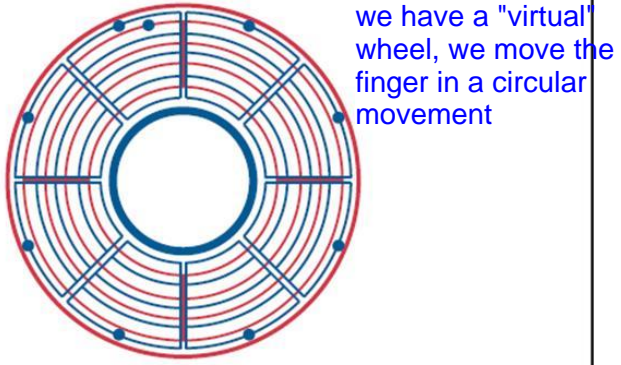
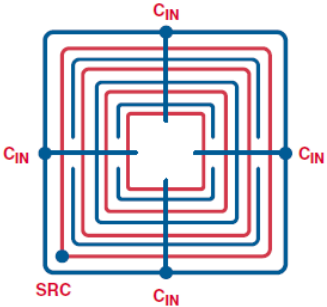
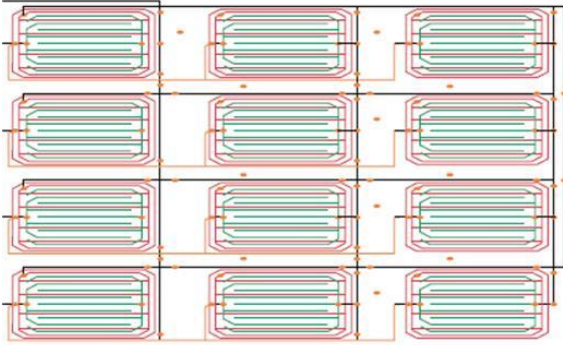
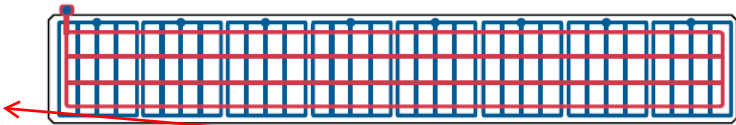
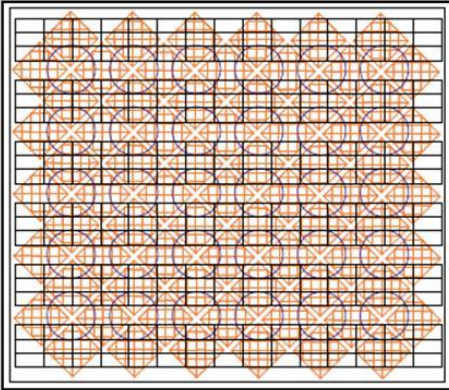
very small changes!



Implementation of the user interface

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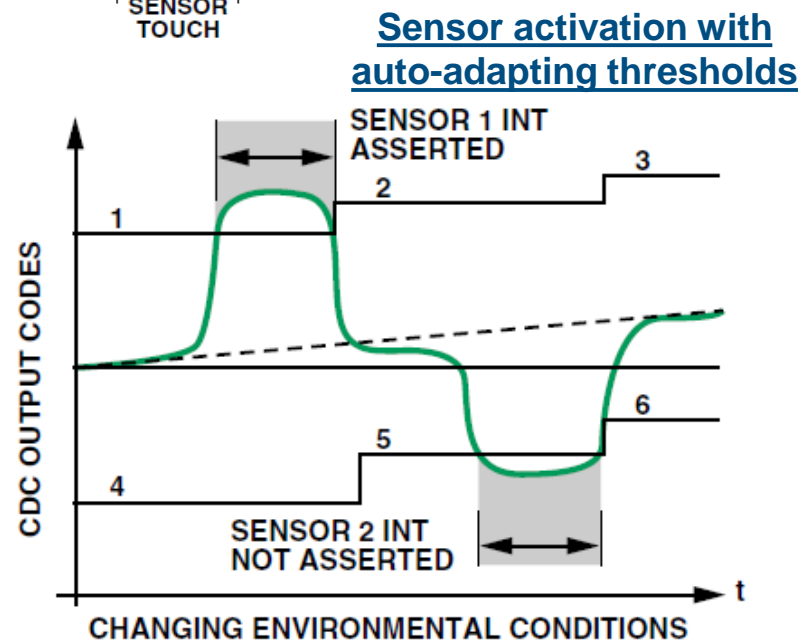
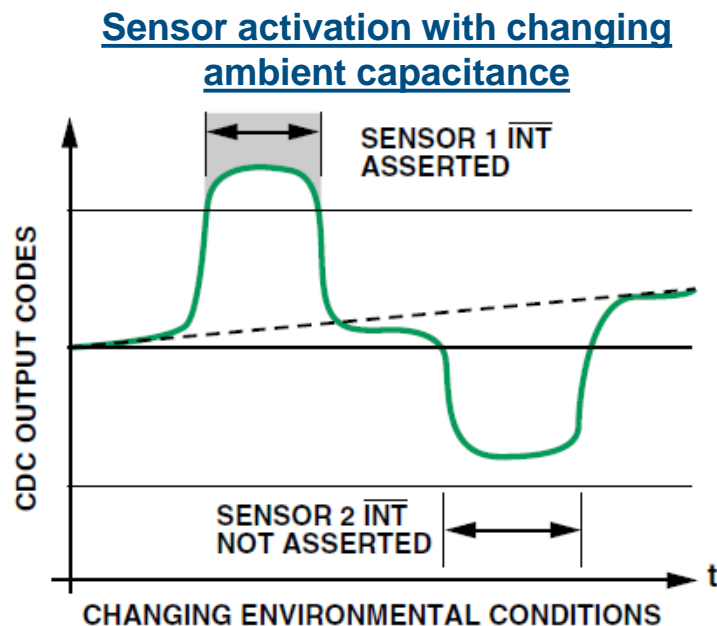
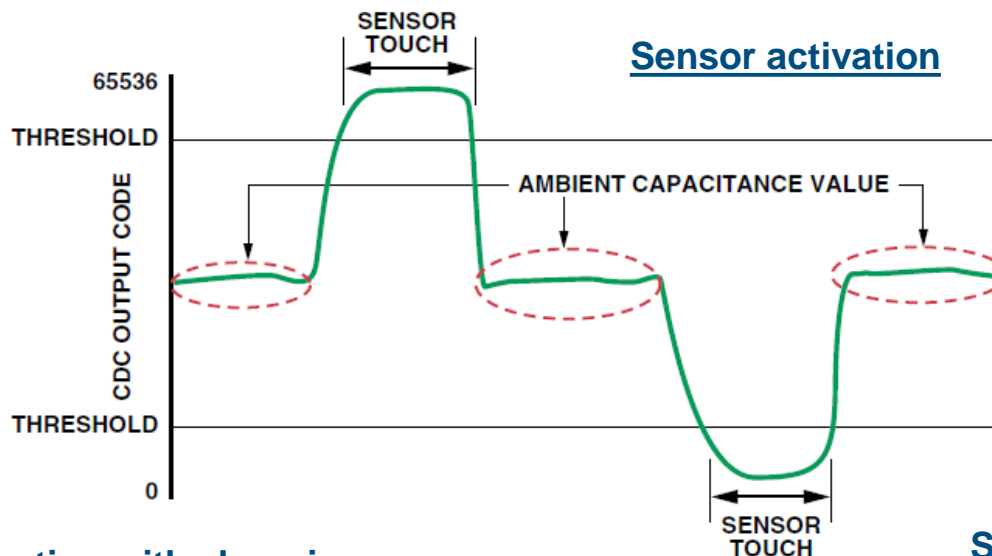
how they are implemented

Button		Wheel	
8-Way Switch		Keypad	
Slider	 <p>distributed in an horizontal way, now the element can detect the presence of the finger at a given level, to indicate the position. It's very precise. (?)</p>	Touchpad	



in all of these situations the change in capacitance is detected, in respect to the "ambient capacity level". We basically have to pass through a threshold, but these have to be autoadaptive, because the capacity has a drift so we need to adapt the level of the threshold

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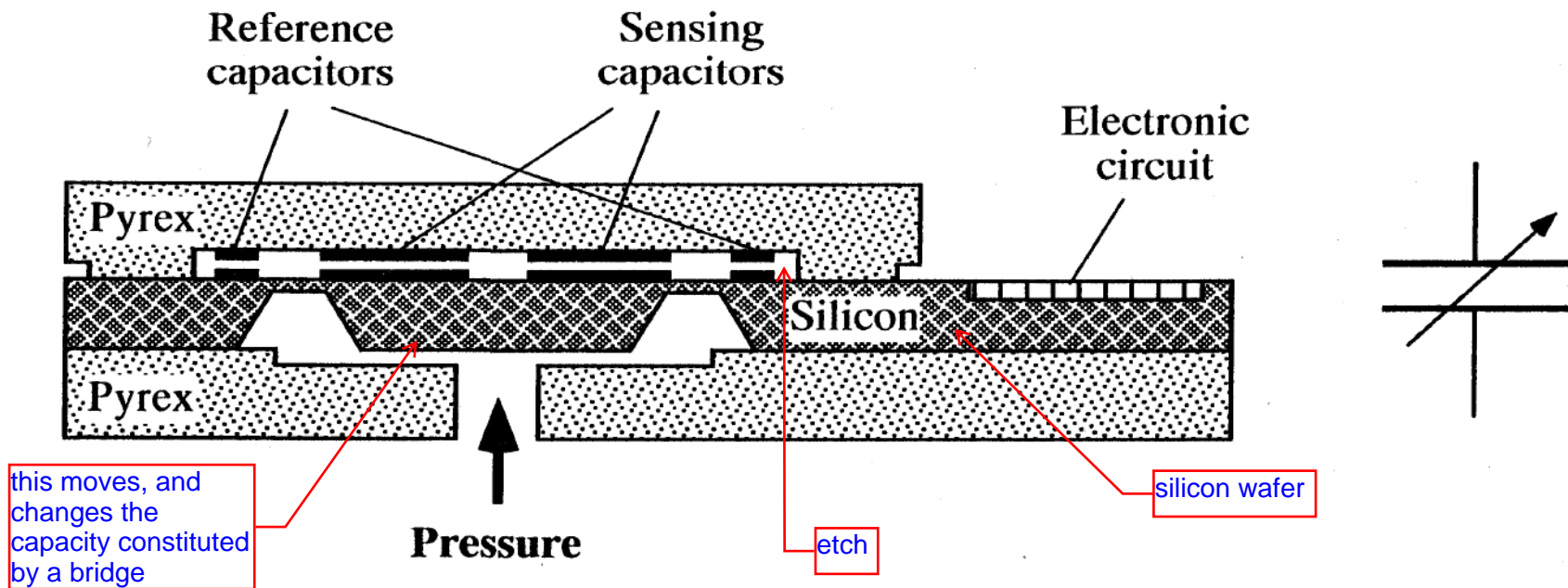




microsystem

Chip dimensions: 8.4 mm x 6.2 mm

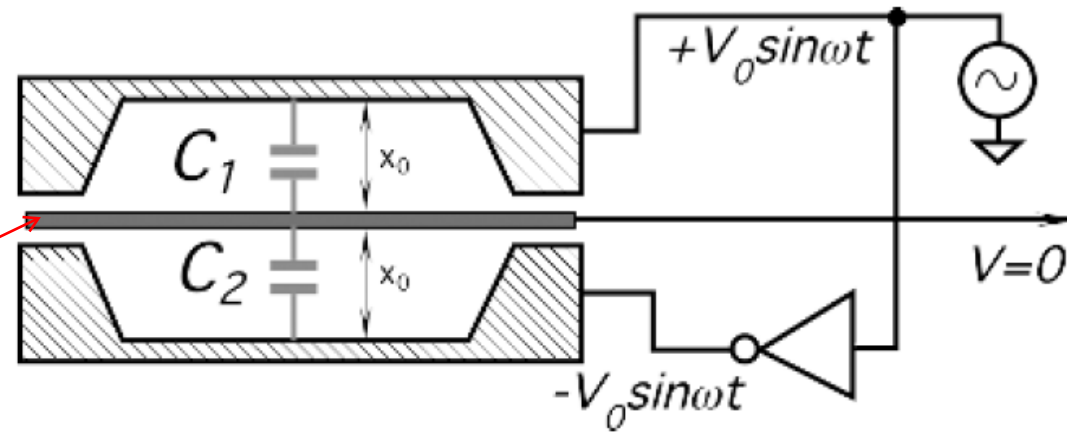
Fabrication: anisotropic etching



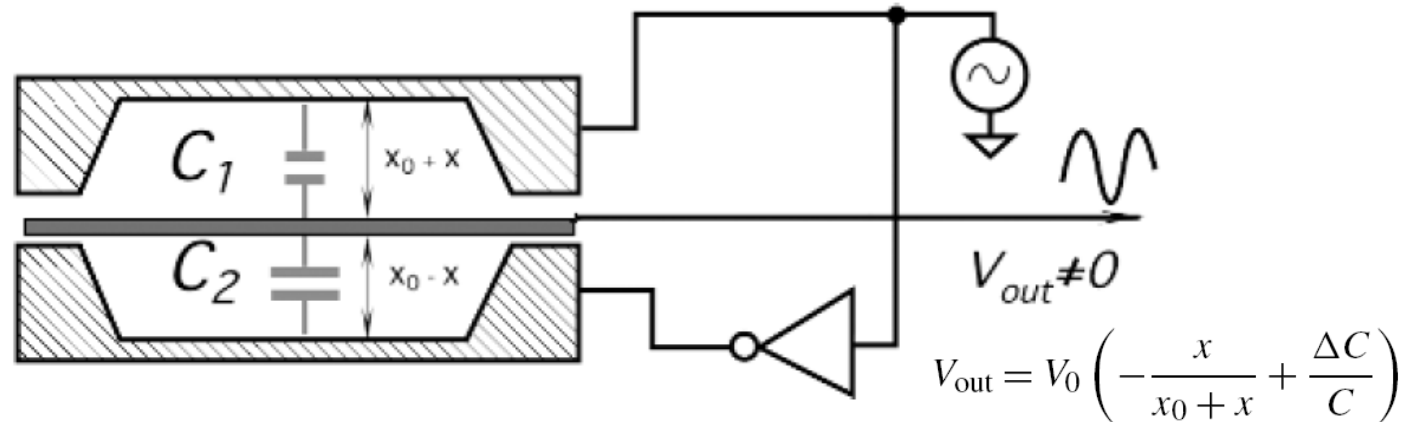


the previous example can be changed in order to have a bridge with 2 cap across the bridge, one changing increasing, and the other decreasing

like the diaphragm example



(A)

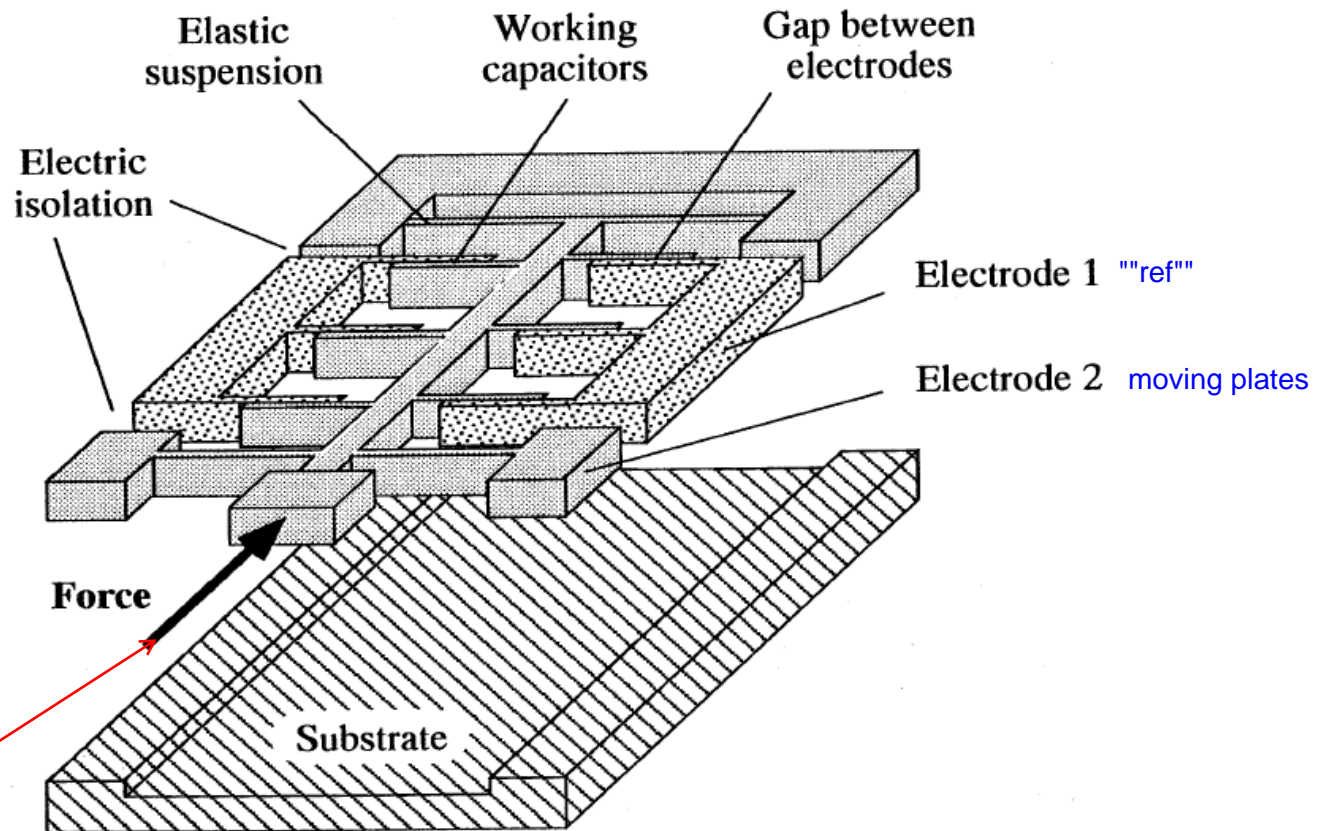


(B)

$$C_1 = \frac{\epsilon A}{x_0 + x} \quad \text{and} \quad C_2 = \frac{\epsilon A}{x_0 - x},$$



microstructure



$$V_o = V_I \frac{C_1 - C_2}{C_1 + C_2}$$

the output is the difference between the two capacitors

Fabrication: anisotropic etching

used also for dynamic forces, in particular acceleration

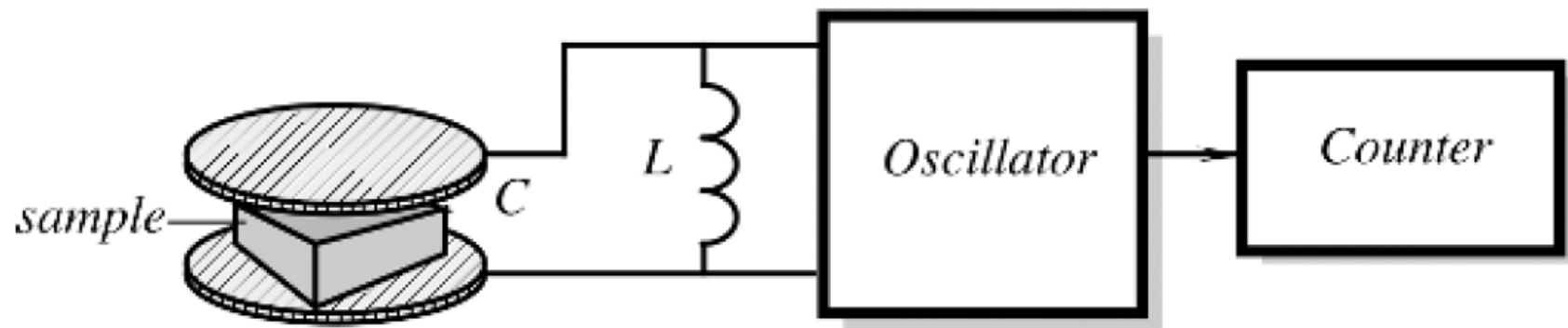


Fig. 13.3. Capacitive moisture sensing system.