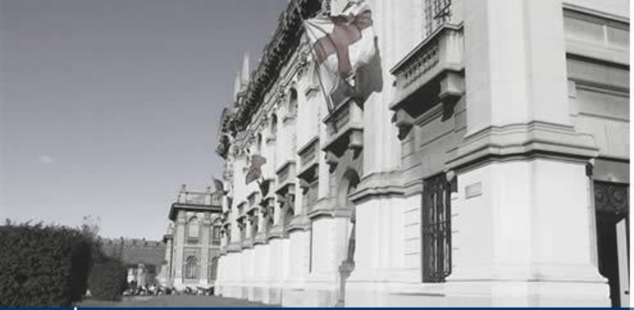


DIPARTIMENTO di ELETTRONICA, INFORMAZIONE e BIOINGEGNERIA

POLITECNICO DI MILANO

# 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*

# Humidity resistive sensors (resistive hygrometers)



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

If a hygroscopic mean (e.g. litium cloride, 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

# Resistive humidity sensors

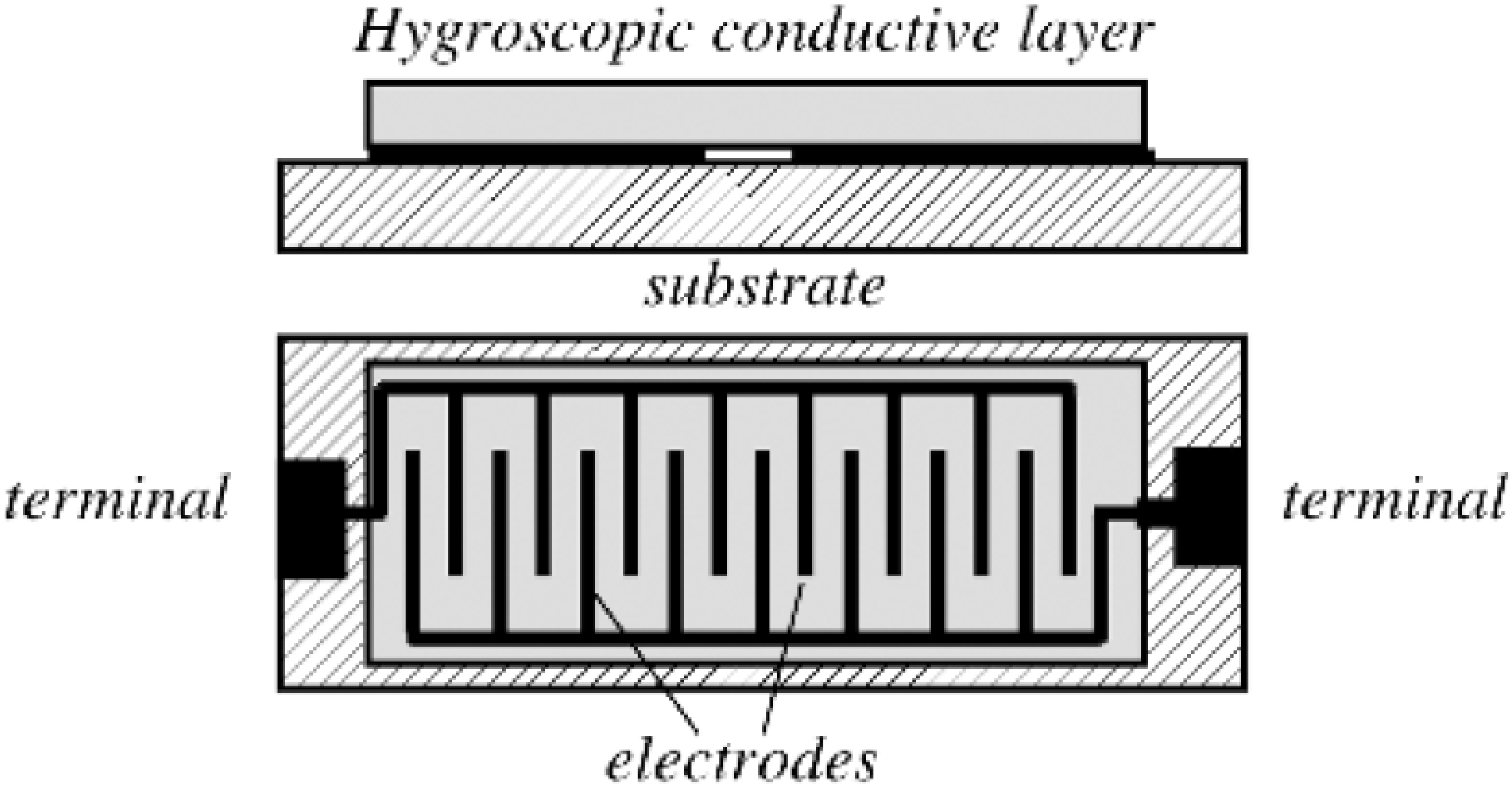



**Fig. 13.6.** Composition of a conductive humidity sensor.

# Resistive hygrometers



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 capacitve 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.

# Resistive humidity sensors

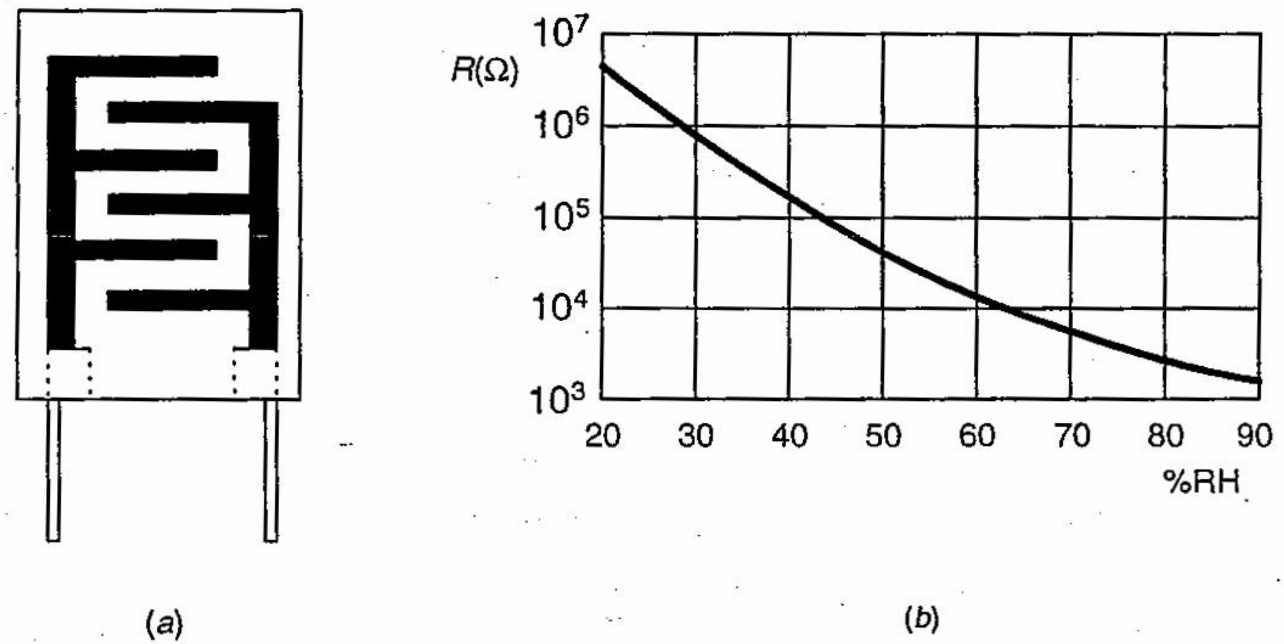



**Figure 2.30** Resistive humidity sensor based on a bulk polymer and its resistance–humidity characteristic (from Ohmic Instruments).

**TABLE 2.8 Specifications of Bulk Polymer Resistive Hygrometers**

| Parameter | EMD-2000 | UPS-500 |
|---|---|---|
| RH range | 0% to 100% | 15% to 95% |
| Accuracy | ±1% RH | ±2% RH |
| Hysteresis | ±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.

# “Dew point” (1/2)



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.

# “dew point” (2/2)



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

If Patm↑ (without changing the molar fraction), the dew point ↑ 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↑ (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.

# “dew point” sensors



- 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

# dew point optical sensor

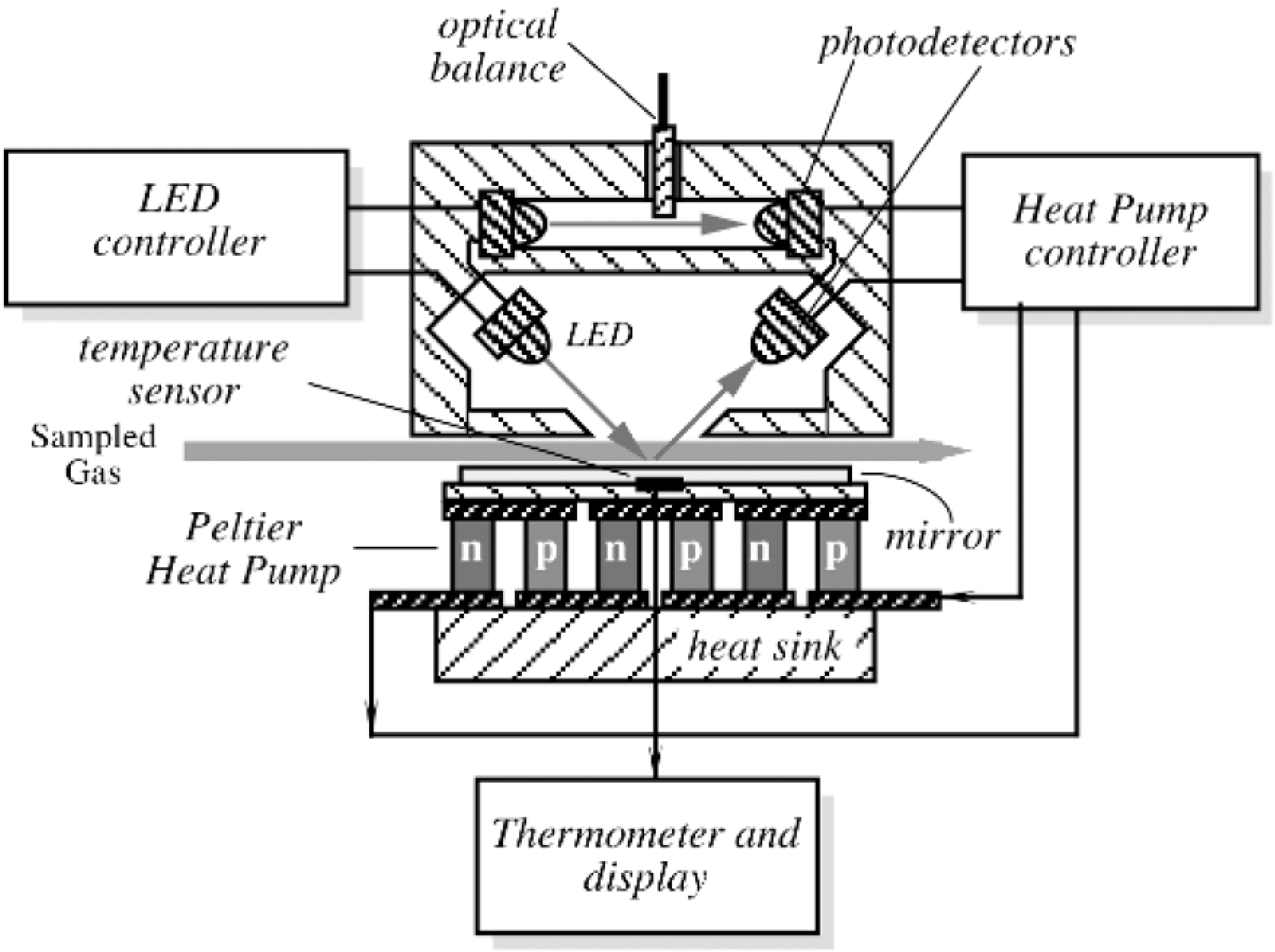
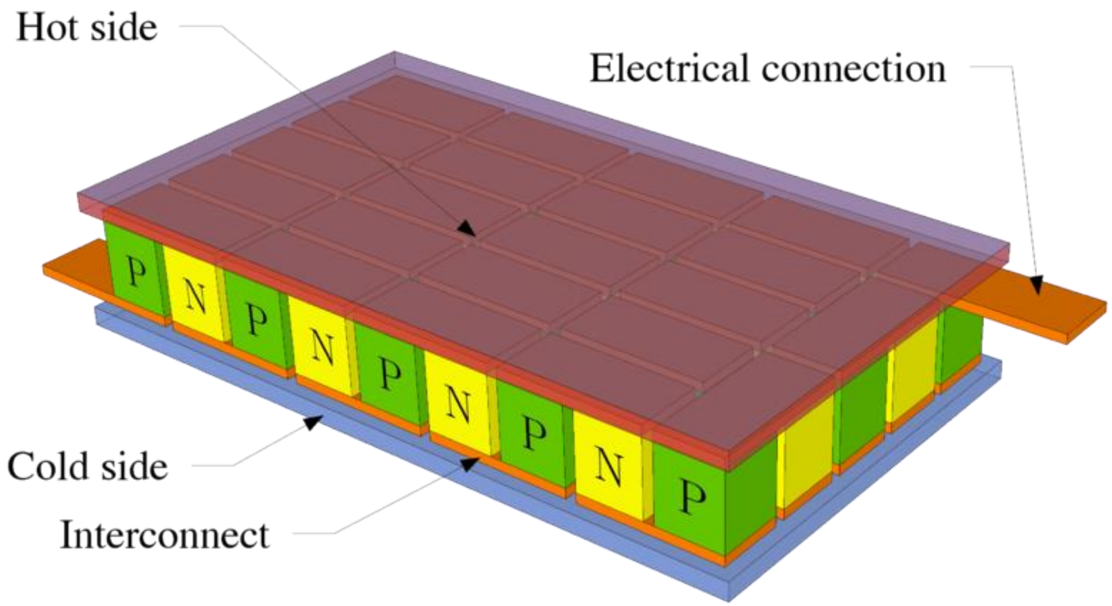


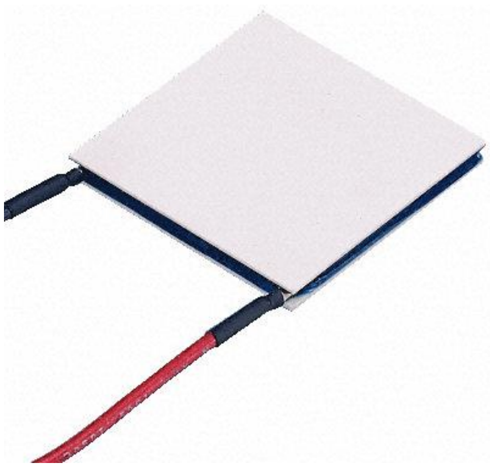

**Fig. 13.9.** Chilled-mirror dew-point sensor with an optical bridge.

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

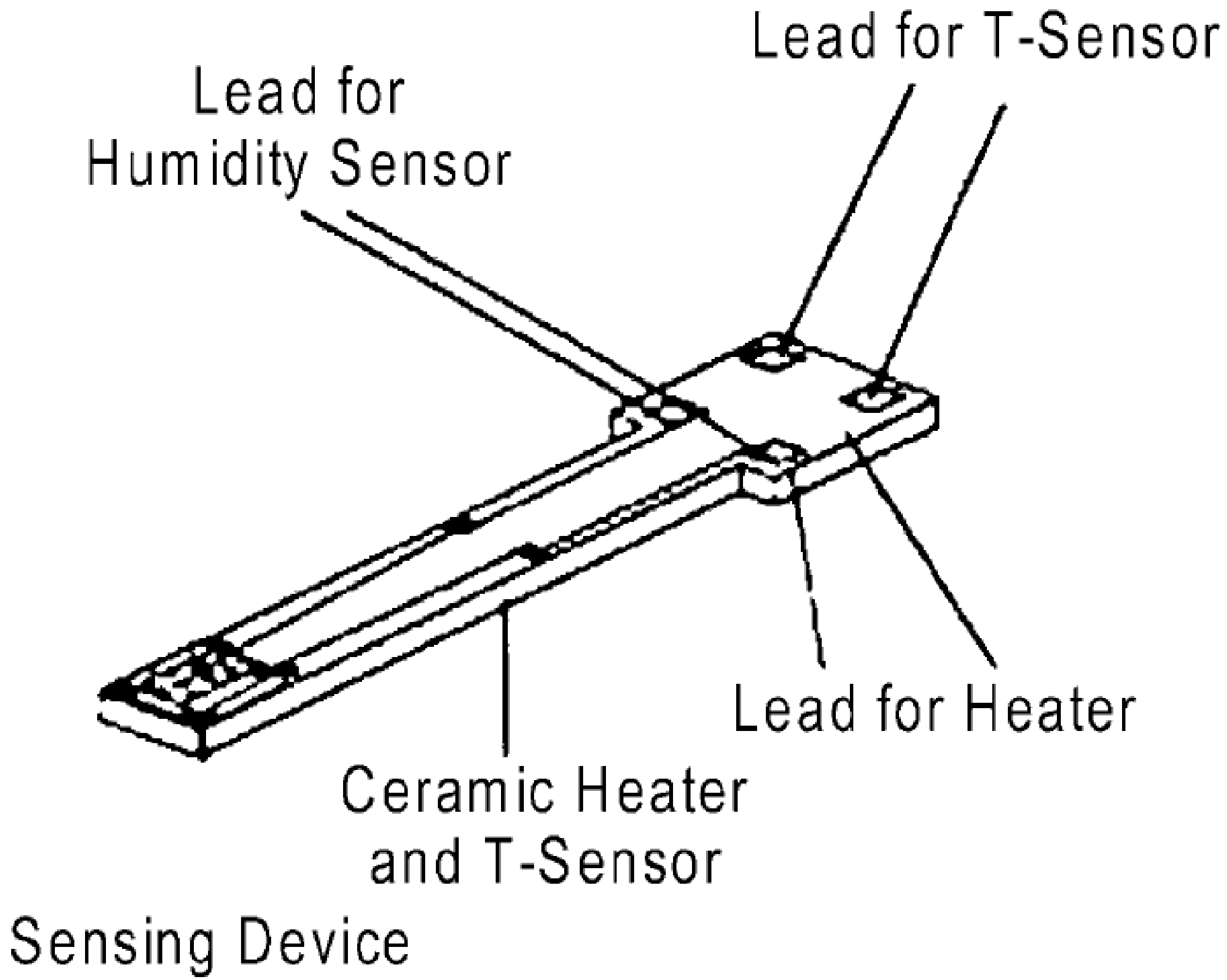
A Peltier cooler is a solid-state active heat pump which transfers heat from one side of the device to the other, with consumption of electrical energy, depending on the direction of the current.

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



# dew point resistive sensor




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, $C= Q/V$

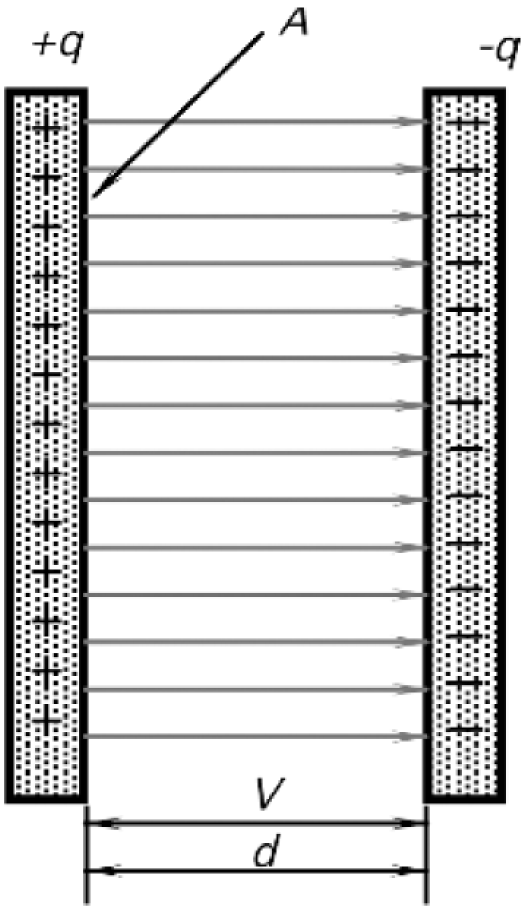
This capacitance depends on:

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

$C=C(\varepsilon, G)$

(G: ‘geometry’ or ‘shape’ factor)

# Capacitor with flat and parallel plates




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

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

$$\Rightarrow \quad C = \frac{\varepsilon_0 \varepsilon_r A}{d} = \varepsilon_0\, \varepsilon_r\, G$$

*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 $\varepsilon_r$, the capacitance is

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

where $\varepsilon_0$ =8.85 pF/m is the dielectric constant for vacuum. Therefore, any **measurand producing a variation in $\varepsilon_r$ , 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.

# Capacitive sensors

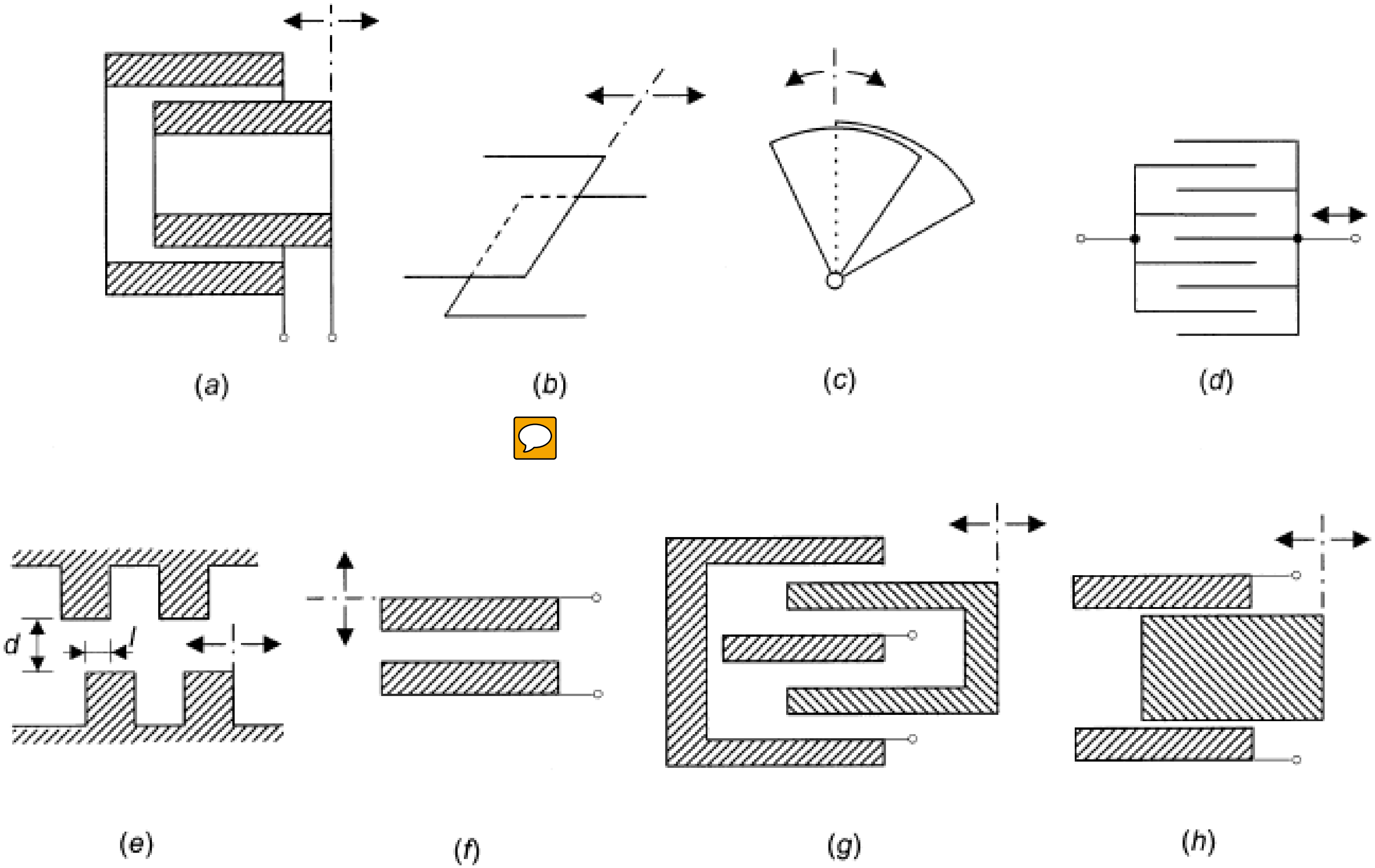



**Figure 4.3** Different arrangements for capacitive sensors based on (*a–e*) a variation of area, (*f*) plate separation, and (*g*, *h*) dielectric.

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

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

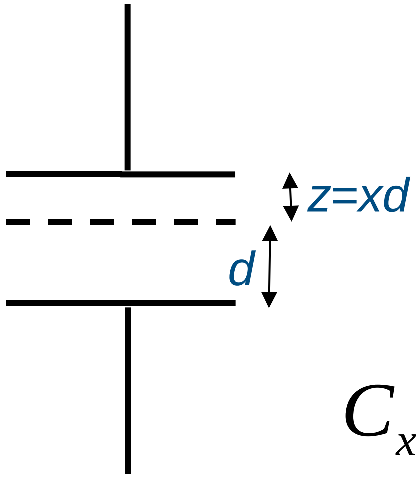
but the relative sensitivity remains the same, dC/C = ˆdA/A. Thus they provide a larger capacitance but the same percent change.
C usually ranges from 1 pF to 500 pF and the supply frequency is normally selected higher than 10 kHz in order to reduce the sensor output impedance.

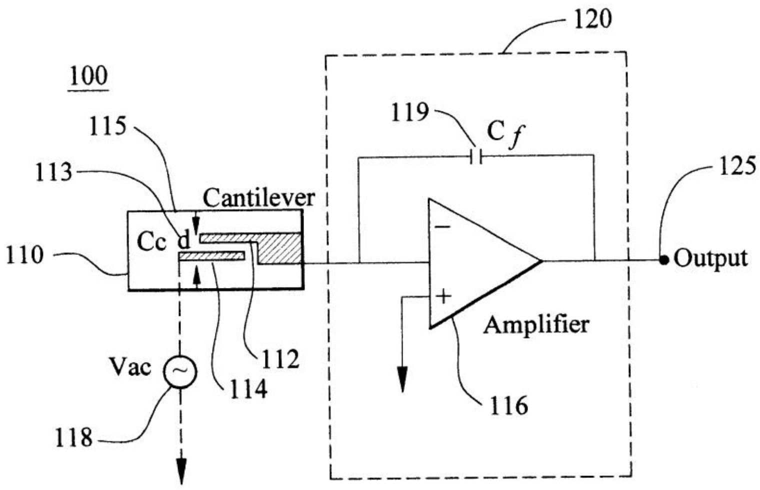
# Dielectric constant of materials

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

| Material | $\kappa$ | Frequency (Hz) | Material | $\kappa$ | 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 | $40 \times 10^6$ | Tallium chloride | 46.9 | $10^8$ |
| Flesh (fat, bones) | 15 | $40 \times 10^6$ | Teflon | 2.04 | $10^3$–$10^8$ |
| Lead nitrate | 37.7 | $6 \times 10^7$ | 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)



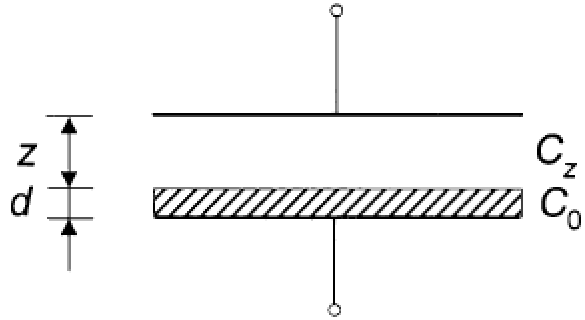




$$C_x = \varepsilon \frac{A}{d+z} = \varepsilon \frac{A}{d+xd} = \varepsilon \frac{A}{d(1+x)}$$

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

→ 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 $C=\varepsilon A/z$, the sensitivity is $-\varepsilon A/z^2$, also nonlinear.




Adding a dielectric, yields for each part of the capacitor, $C_z=\varepsilon_0 A/z$ and $C_0=\varepsilon_r\varepsilon_0 A/d$.

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

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

The sensitivity is now:

$$\frac{dC}{dz} = -\frac{\epsilon_r \epsilon_0 A \epsilon_r}{(d + \epsilon_r z)^2} = -\frac{\epsilon_r^2 \epsilon_0 A}{d^2} \frac{1}{\left(1 + \frac{\epsilon_r z}{d}\right)^2}$$

$$\approx -\frac{C_0}{d}\epsilon_r[1 - 2\epsilon_r x + 3(\epsilon_r x)^2 - \cdots]$$

which is more linear than $\varepsilon A/z^2$.
Equation (1) also shows the effect of a dielectric covering an electrode plate for example, for electrical insulation.

# Capacitive sensors: applications

- **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.

# Capacitive sensors: applications



- **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 Ics with a sensitivity of 1.5g. With this sensitivity, the device can be used as a tiltmeter.

# Capacitive sensors: examples of biomedical applications

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

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.

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

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.

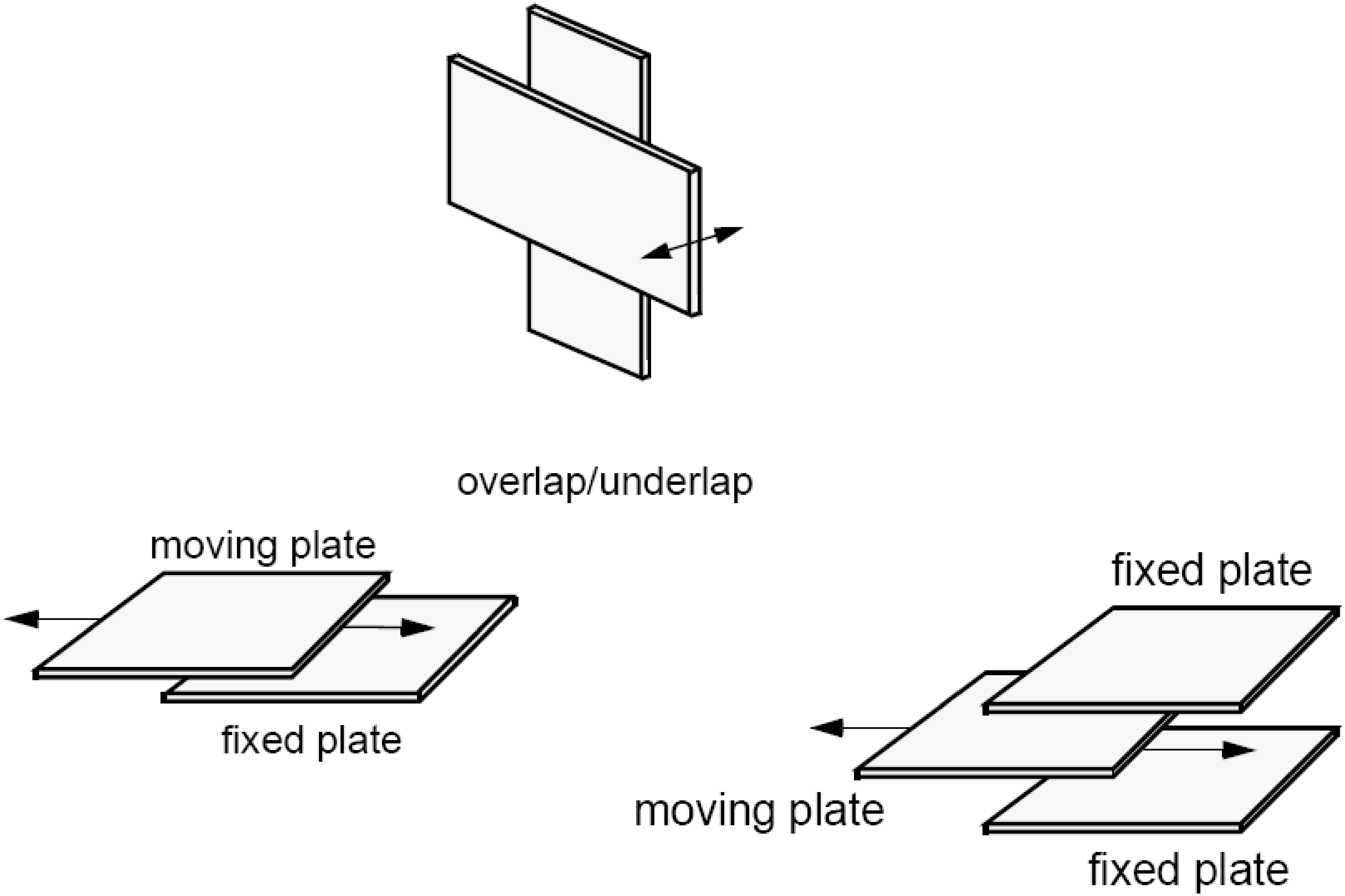
# Capacitive sensors: examples of biomedical applications

**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 $\mu$m 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**.

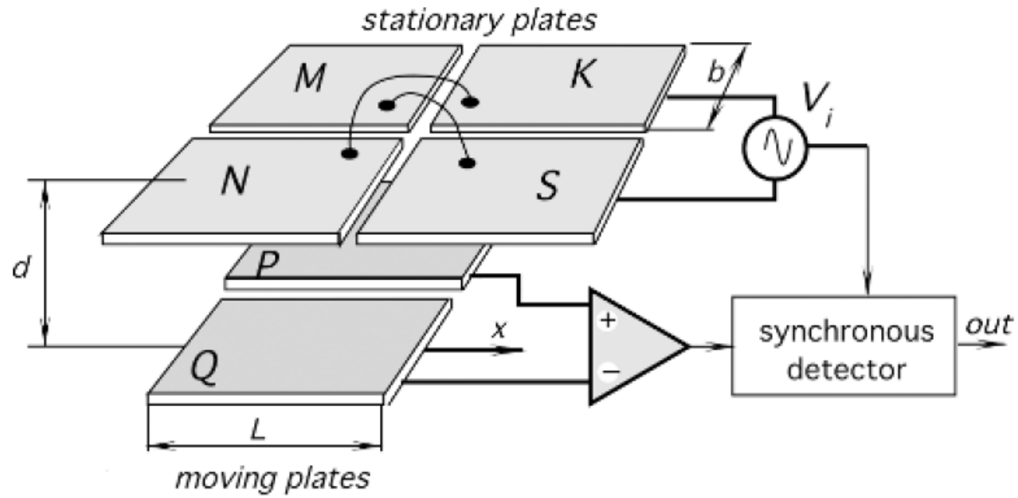
**Humidity sensors** for the diagnosis of pulmonary diseases

# Capacitive motion sensors



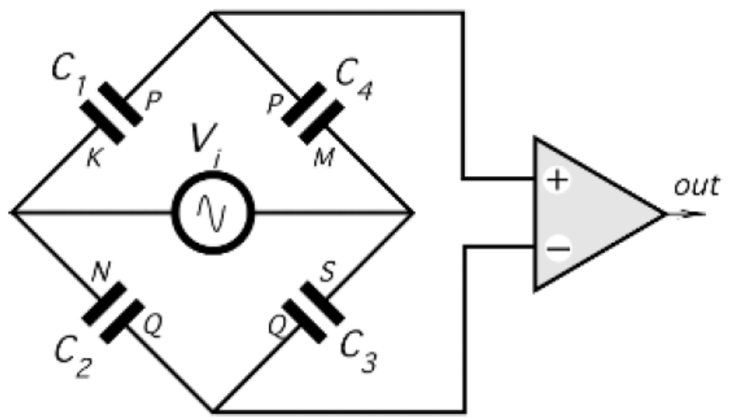
# Bridge capacitive motion sensor






(A)

$$C_1 = \frac{\varepsilon_0 b}{d}\left(\frac{L}{2} + x\right)$$




(B)

# Cylindrical Capacitor

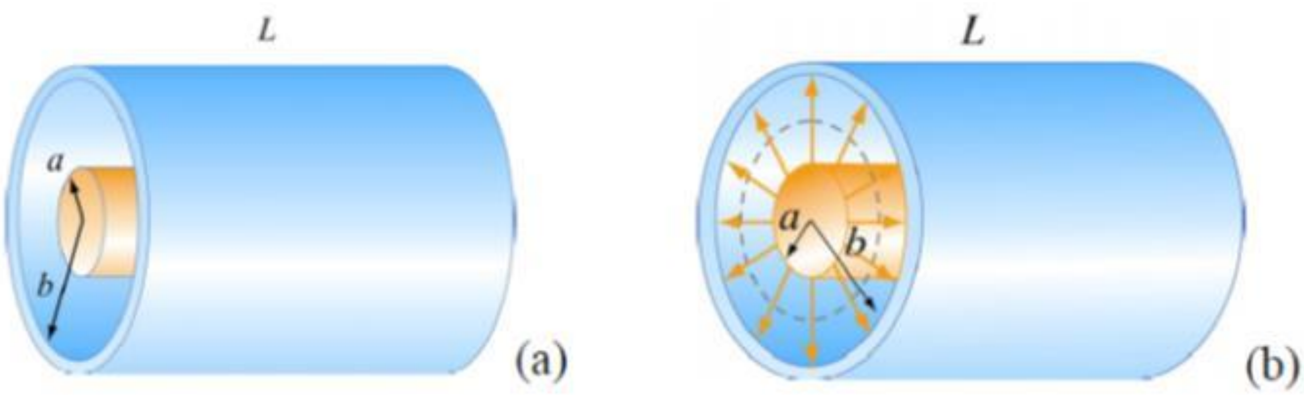



**Figure 5.2.4** (a) A cylindrical capacitor. (b) End view of the capacitor. The electric field is non-vanishing only in the region $a < r < b$.

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

$$\oiint_S \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = EA = E(2\pi r \ell) = \frac{\lambda \ell}{\varepsilon_0} \quad \Rightarrow \quad E = \frac{\lambda}{2\pi\varepsilon_0 r} \tag{5.2.5}$$

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

$$\Delta V = V_b - V_a = -\int_a^b E_r\, dr = -\frac{\lambda}{2\pi\varepsilon_0}\int_a^b \frac{dr}{r} = -\frac{\lambda}{2\pi\varepsilon_0}\ln\left(\frac{b}{a}\right) \tag{5.2.6}$$

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

$$\boxed{C = \frac{Q}{|\Delta V|} = \frac{\lambda L}{\lambda \ln(b/a)/2\pi\varepsilon_0} = \frac{2\pi\varepsilon_0 L}{\ln(b/a)}} \tag{5.2.7}$$

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

# Cylindrical Capacitor

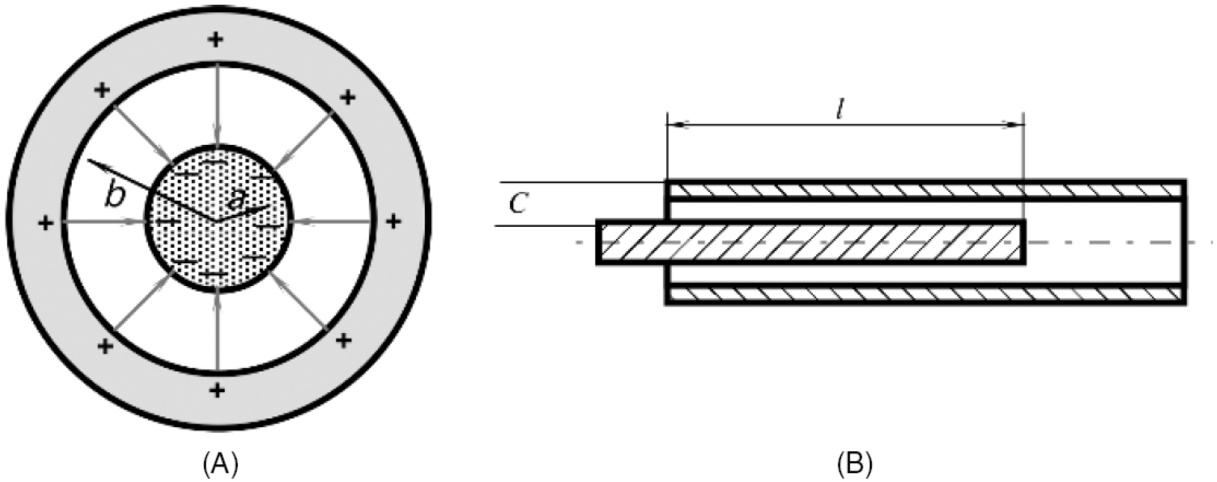


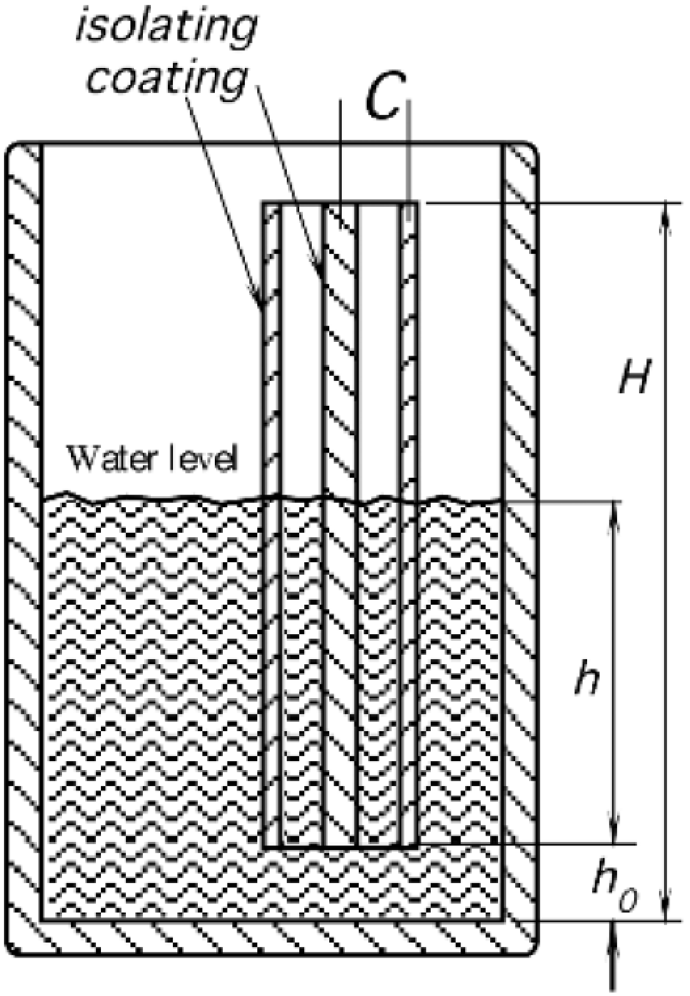

**Fig. 3.5.** Cylindrical capacitor (A); capacitive displacement sensor (B).

*if l>>b*

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

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

# Capacitive sensor for liquid level measurement




$$C_h = C_1 + C_2 = \varepsilon_0 G_1 + \varepsilon_0 \varepsilon_r G_2$$

$$C_1 = \frac{2\pi\varepsilon_0 (H - h - h_0)}{ln(b/a)}$$

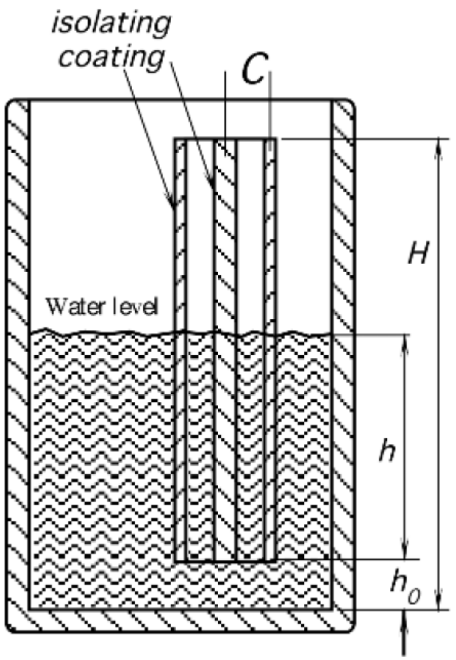
$$C_2 = \frac{2\pi\varepsilon_0 \varepsilon_r h}{\ln(b/a)}$$

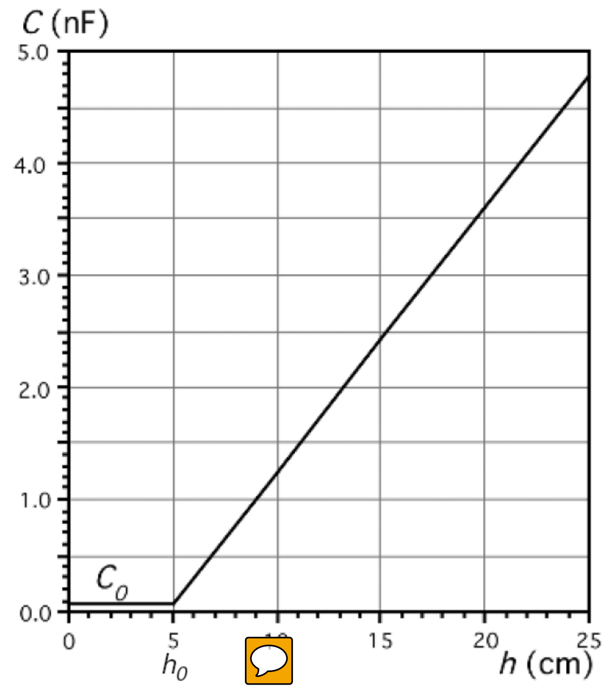
$$C = C_1 + C_2 = \frac{2\pi\varepsilon_0}{ln(b/a)}[H - h(1 - \varepsilon_r) - h_0]$$

*For liquid height ≤$h_0$:* $C_0 = \dfrac{2\pi\varepsilon_0 (H - h_0)}{ln(b/a)}$

# Capacitive sensor for liquid level measurement






*a =10 mm*
*b=12 mm*
*H =200 mm*
*Liquid: $H_2O$*

$$C = C_1 + C_2 = \frac{2\pi\varepsilon_0}{ln(b/a)}\left[H - h(1-\varepsilon_r) - h_0\right]$$

*For liquid height ≤$h_0$:* $$C_0 = \frac{2\pi\varepsilon_0 (H - h_o)}{ln(b/a)}$$

# Capacitive hygrometers

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 ($\varepsilon_r$) according to the following relationship:

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

where

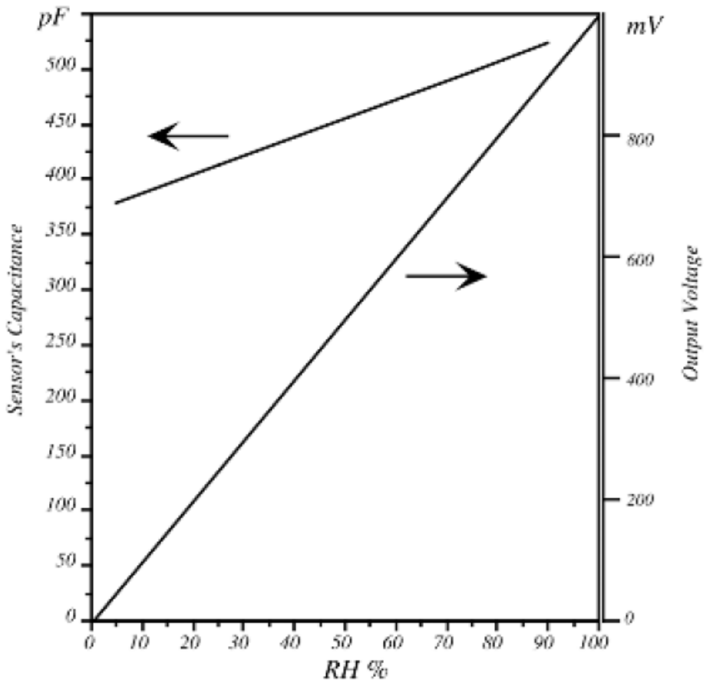
T: absolute temperature (K)
P: humid air pressure (mmHg)
$P_S$: saturated water vapor pressure at temperature T (mmHg)
RH: relative humidity (%)

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

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

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

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



# Capacitive hygrometer with integrated heater and temperature sensors

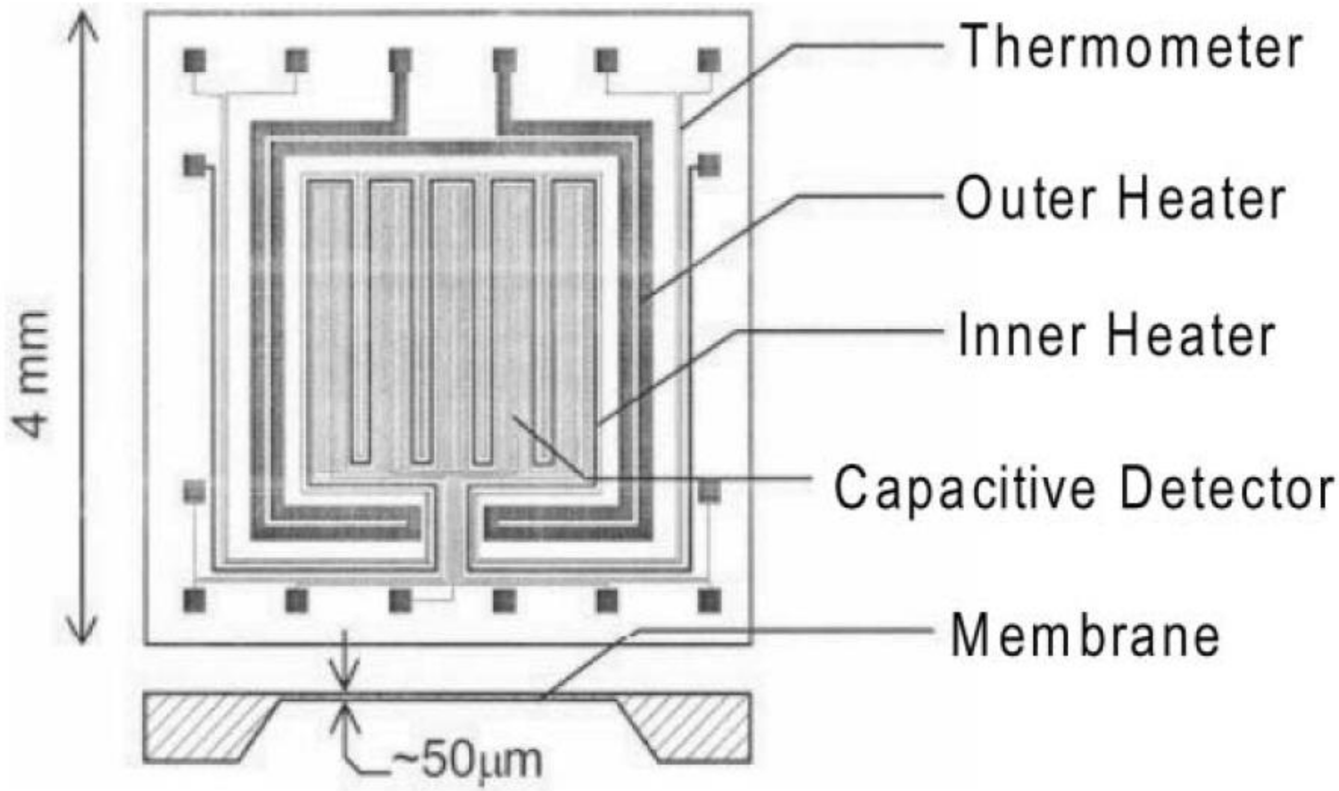



Fig. 6. Silicon dew point hygrometer with integrated heater and temperature sensors, by Jachowicz and Weremczuk [89].

# Capacitive thin-film humidity sensor (1)

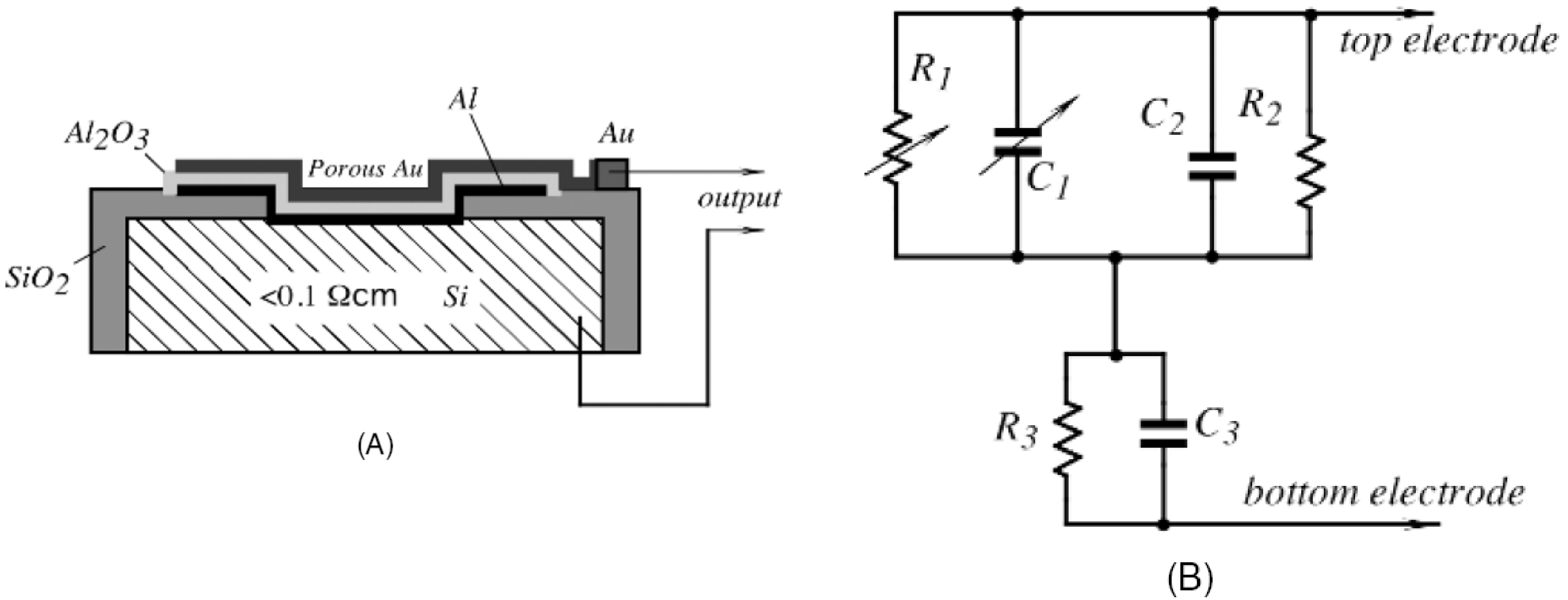



**Fig. 13.7.** (A) Structure of $Al_2O_3$ thin film moisture sensor; (B) simplified equivalent circuit of the sensor. $R_1$ and $C_1$ are moisture-dependent variable terms; $R_2$ and $C_2$ are shunting terms of bulk oxide between pores (unaffected by moisture); $R_3$ and $C_3$ are series terms below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

# Capacitive thin-film humidity sensor (2)



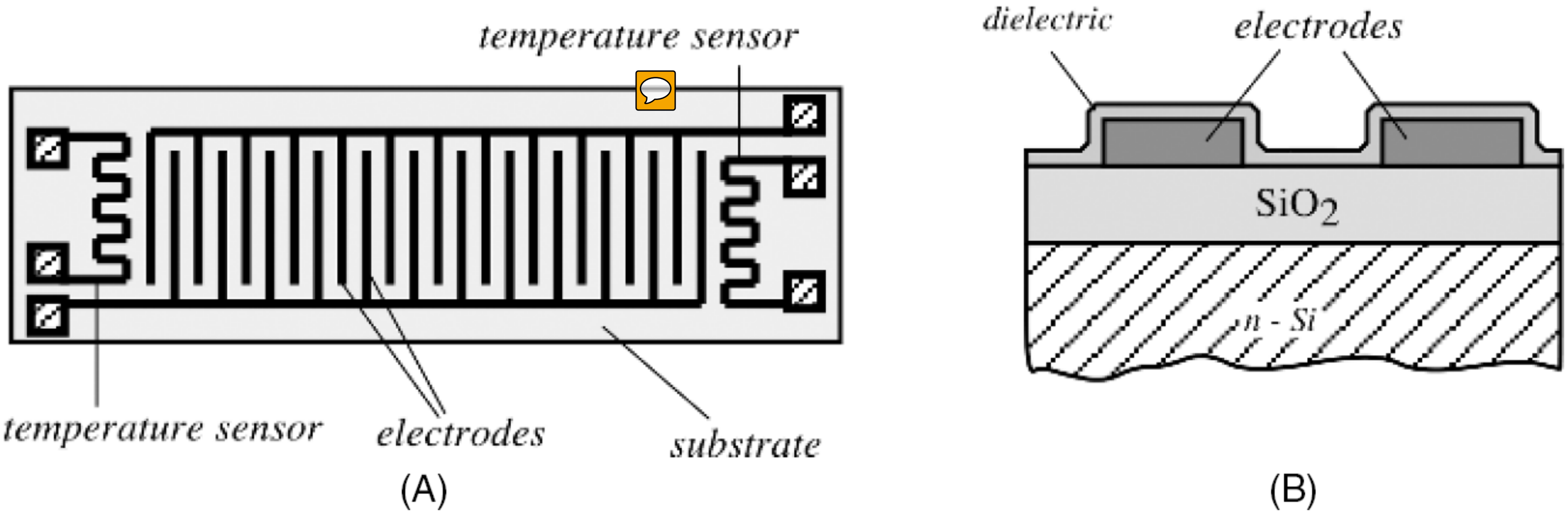



**Fig. 13.4.** Capacitive thin-film humidity sensor: (A) interdigitized electrodes form capacitor plates; (B) cross section of the sensor.

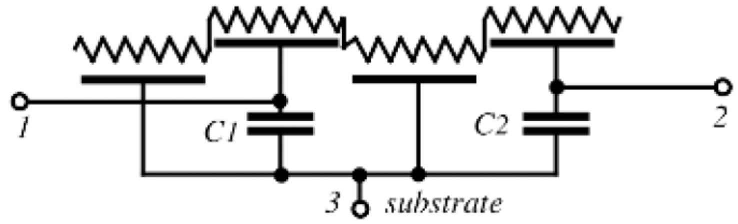
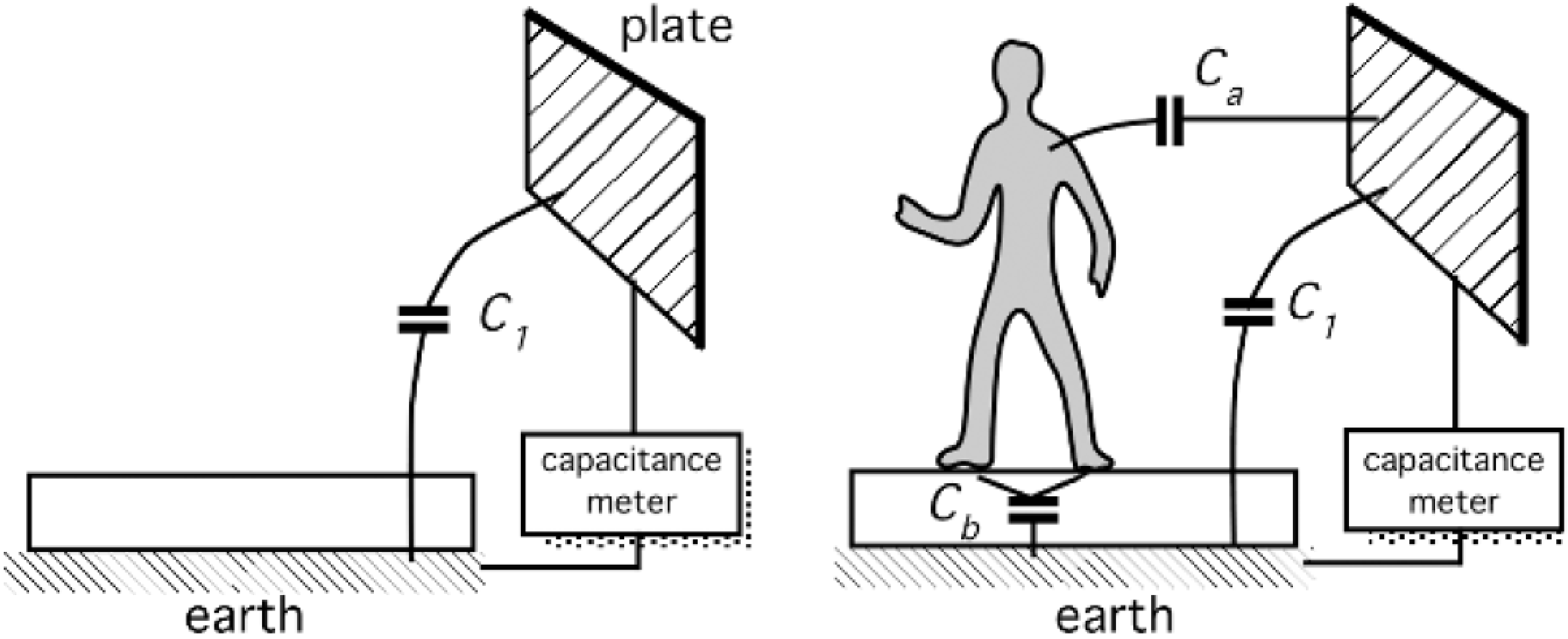



**Fig. 13.5.** Simplified equivalent electric circuit of a capacitive thin-film humidity sensor.

# Capacitive sensor of intrusion

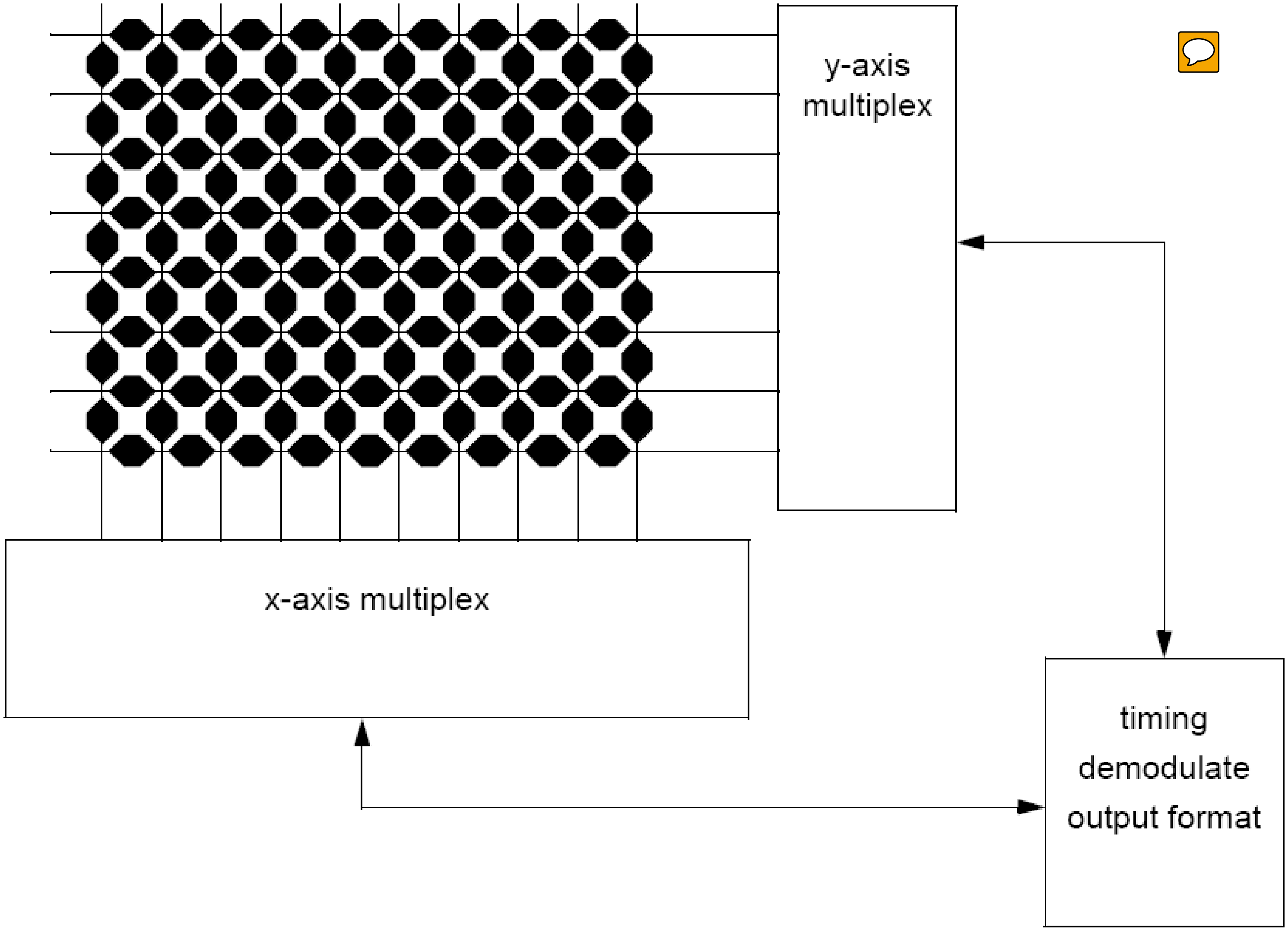




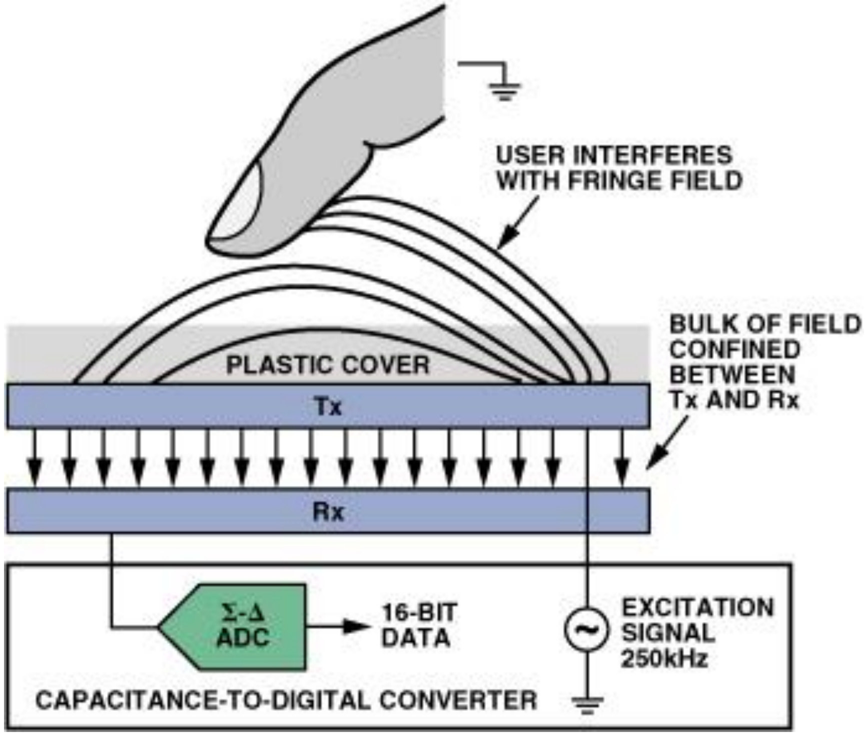

$$C = C_1 + \Delta C = C_1 + \frac{C_a C_b}{C_a + C_b}$$

# X-Y tablets

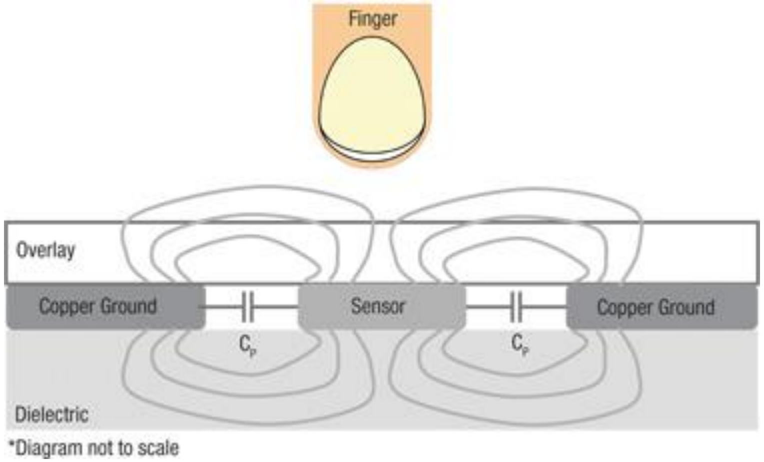



y-axis
multiplex
x-axis multiplex
timing
demodulate
output format

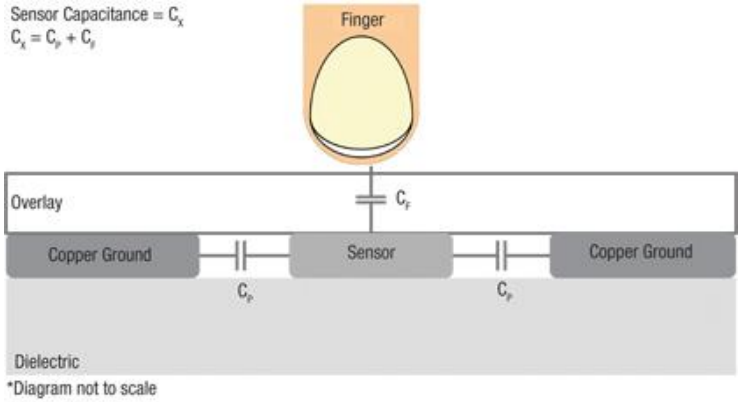
A basic sensor includes a receiver and a transmitter, each of which consists of metal traces formed on layers of a printed circuit board (PCB). The systems have an on-chip excitation source, which is connected to the transmitter trace of the sensor. Between the receiver and the transmitter trace, an 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.

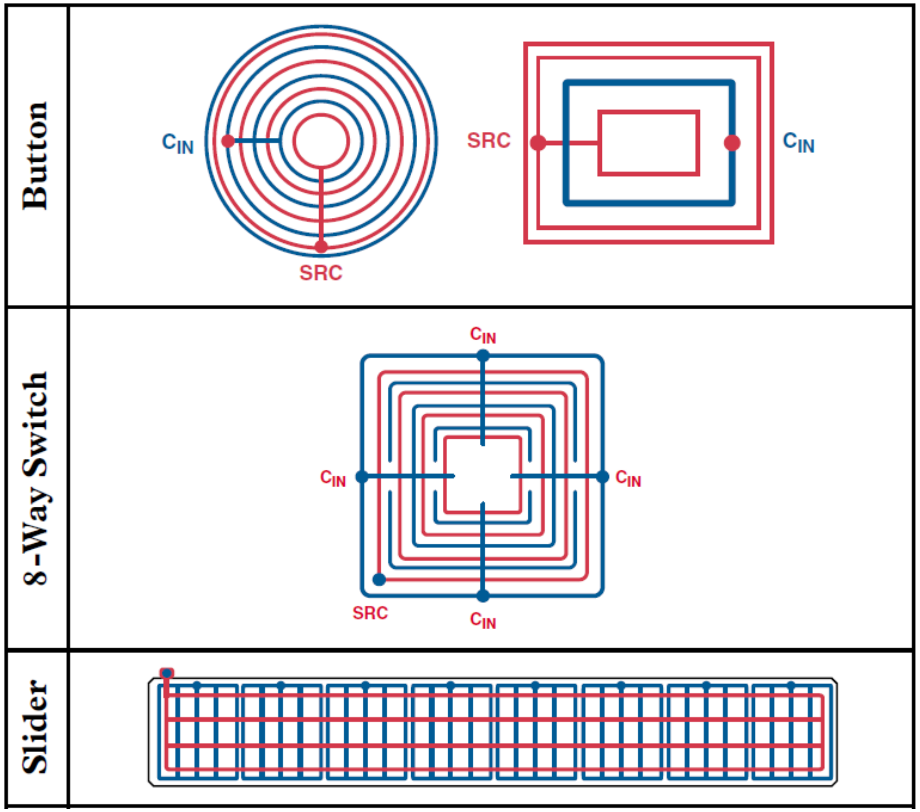


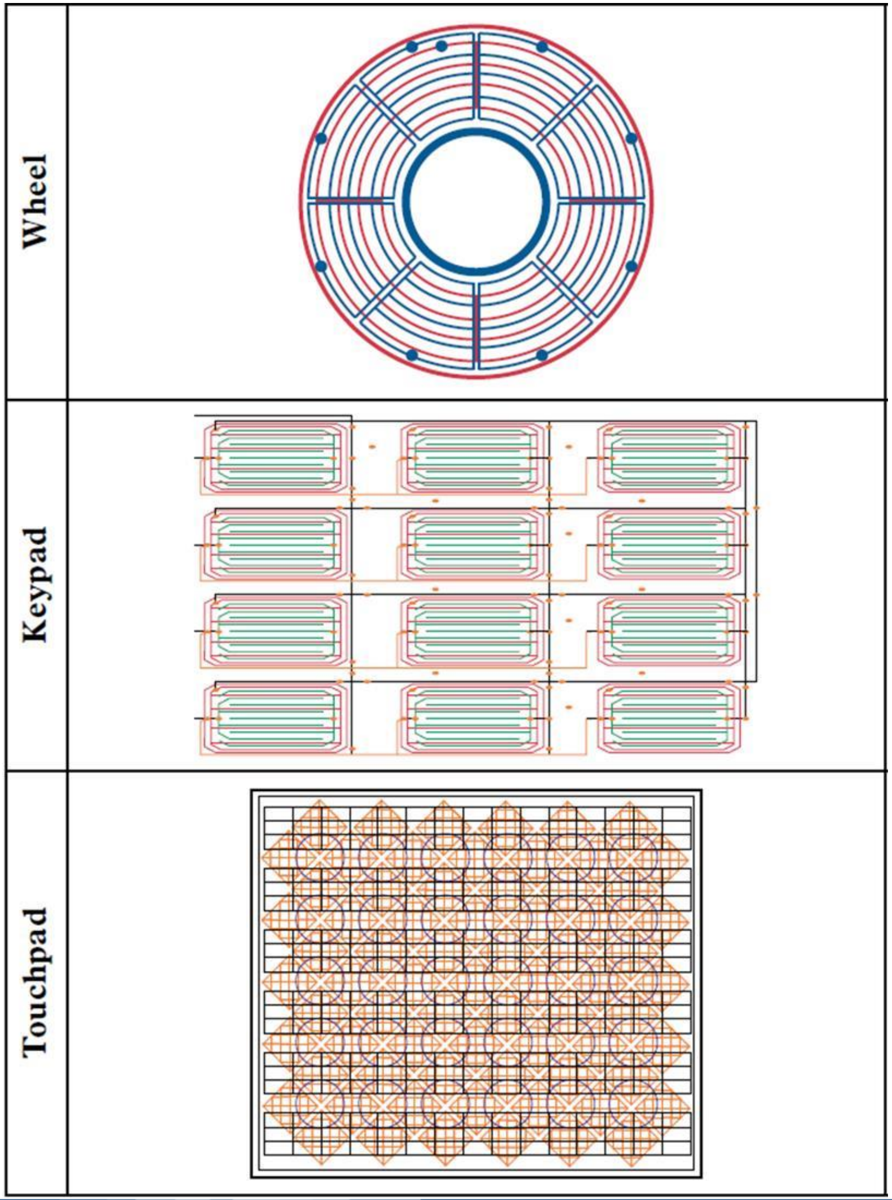
Finger
Overlay
Copper Ground
Sensor
Copper Ground
$C_P$
$C_P$
Dielectric
*Diagram not to scale

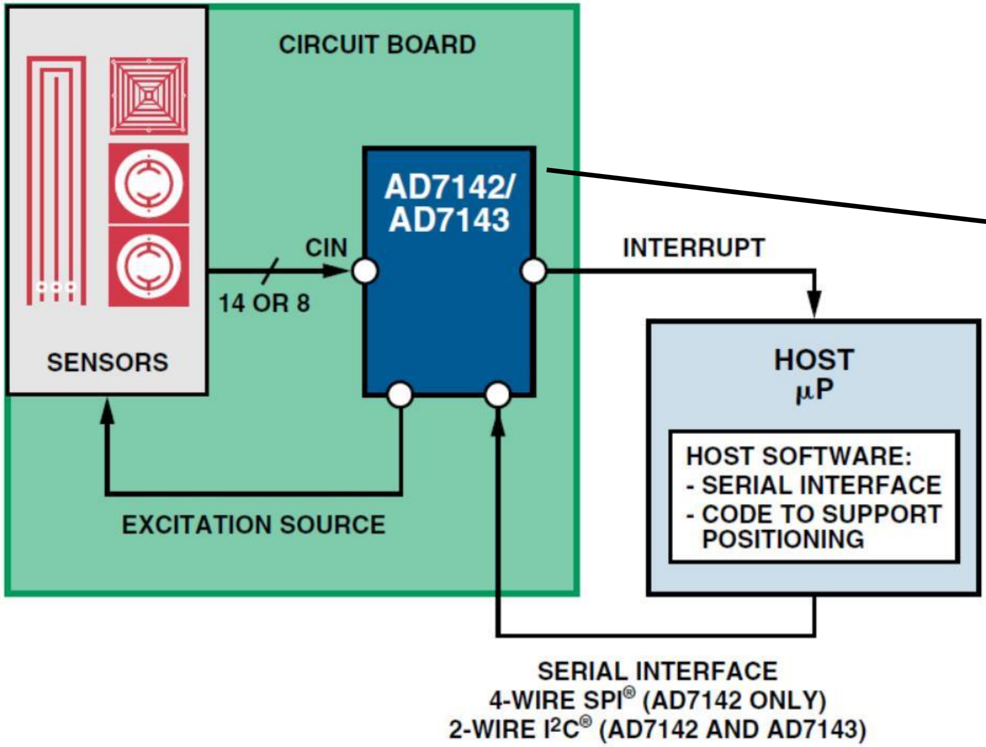



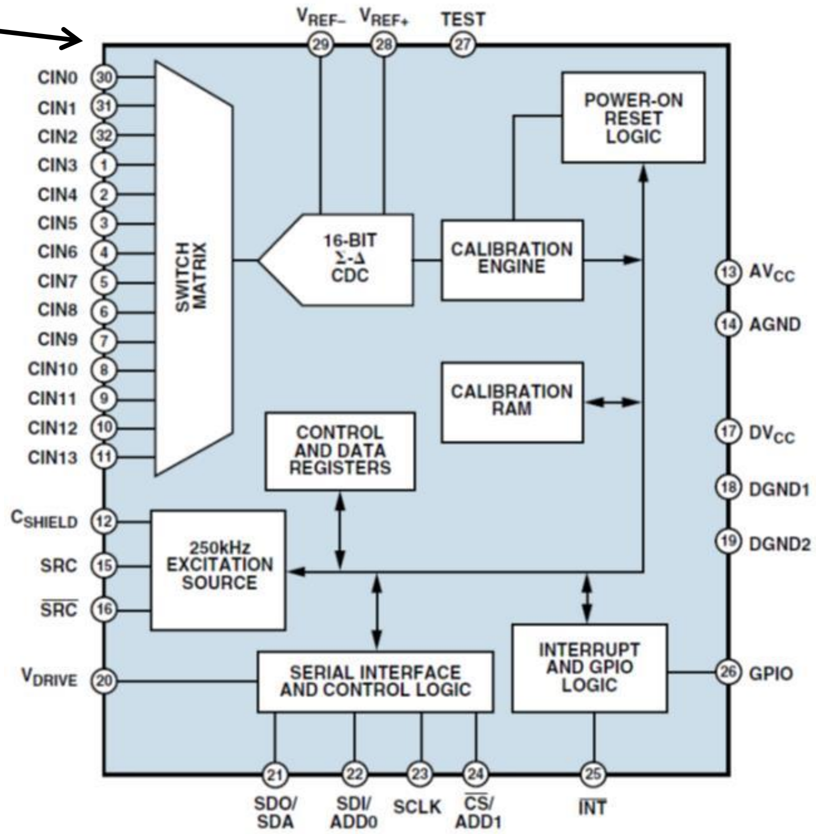
Sensor Capacitance = $C_X$
$C_X = C_P + C_F$
Finger
Overlay
$C_F$
Copper Ground
Sensor
Copper Ground
$C_P$
$C_P$
Dielectric
*Diagram not to scale

# Implementation of the user interface

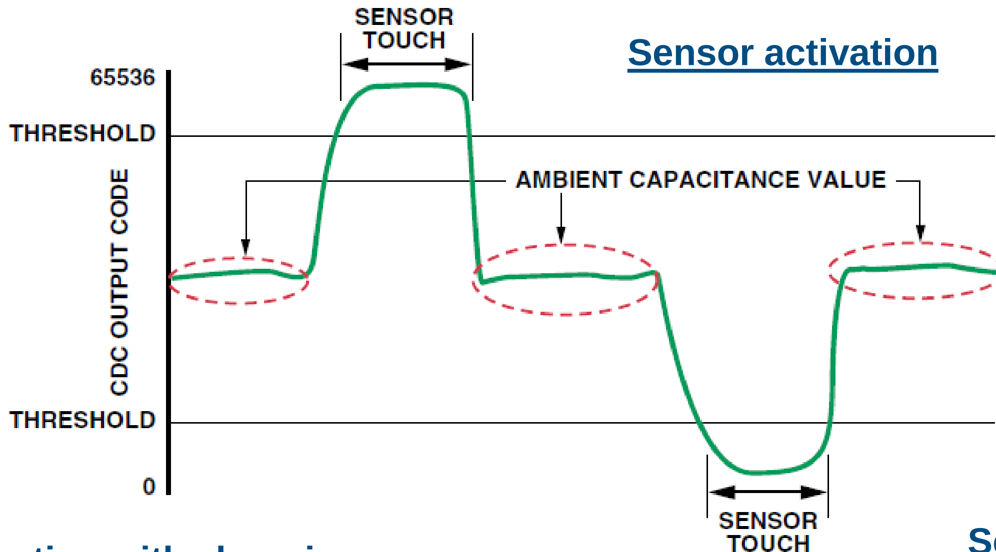


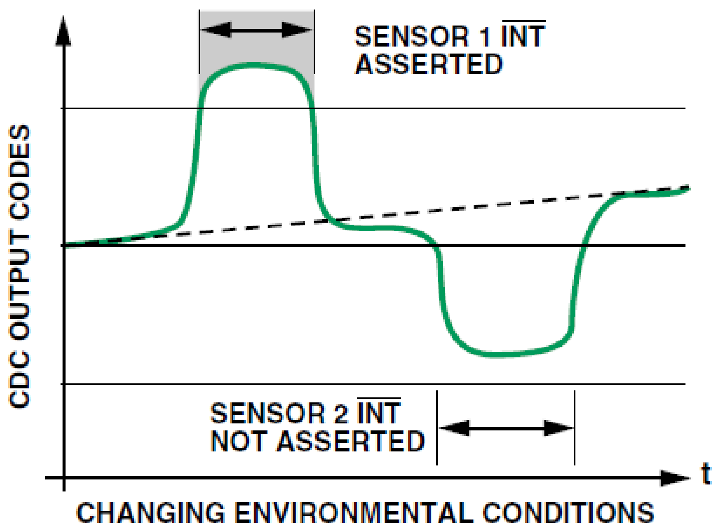

CIRCUIT BOARD
SENSORS
CIN
14 OR 8
AD7142/
AD7143
INTERRUPT
HOST
µP
HOST SOFTWARE:
- SERIAL INTERFACE
- CODE TO SUPPORT
POSITIONING
EXCITATION SOURCE
SERIAL INTERFACE
4-WIRE SPI® (AD7142 ONLY)
2-WIRE I2C® (AD7142 AND AD7143)


VREF–
VREF+
TEST
CIN0
CIN1
CIN2
CIN3
CIN4
CIN5
CIN6
CIN7
CIN8
CIN9
CIN10
CIN11
CIN12
CIN13
CSHIELD
SRC
SRC
VDRIVE
SWITCH MATRIX
16-BIT
Σ-Δ
CDC
CALIBRATION ENGINE
POWER-ON RESET LOGIC
CALIBRATION RAM
CONTROL AND DATA REGISTERS
250kHz EXCITATION SOURCE
SERIAL INTERFACE AND CONTROL LOGIC
INTERRUPT AND GPIO LOGIC
AVCC
AGND
DVCC
DGND1
DGND2
GPIO
SDO/
SDA
SDI/
ADD0
SCLK
CS/
ADD1
INT

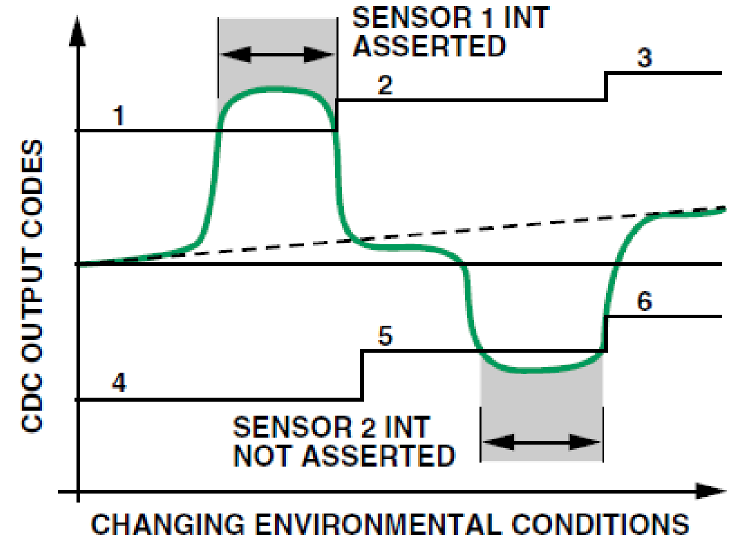
## Sensor activation




## Sensor activation with changing ambient capacitance



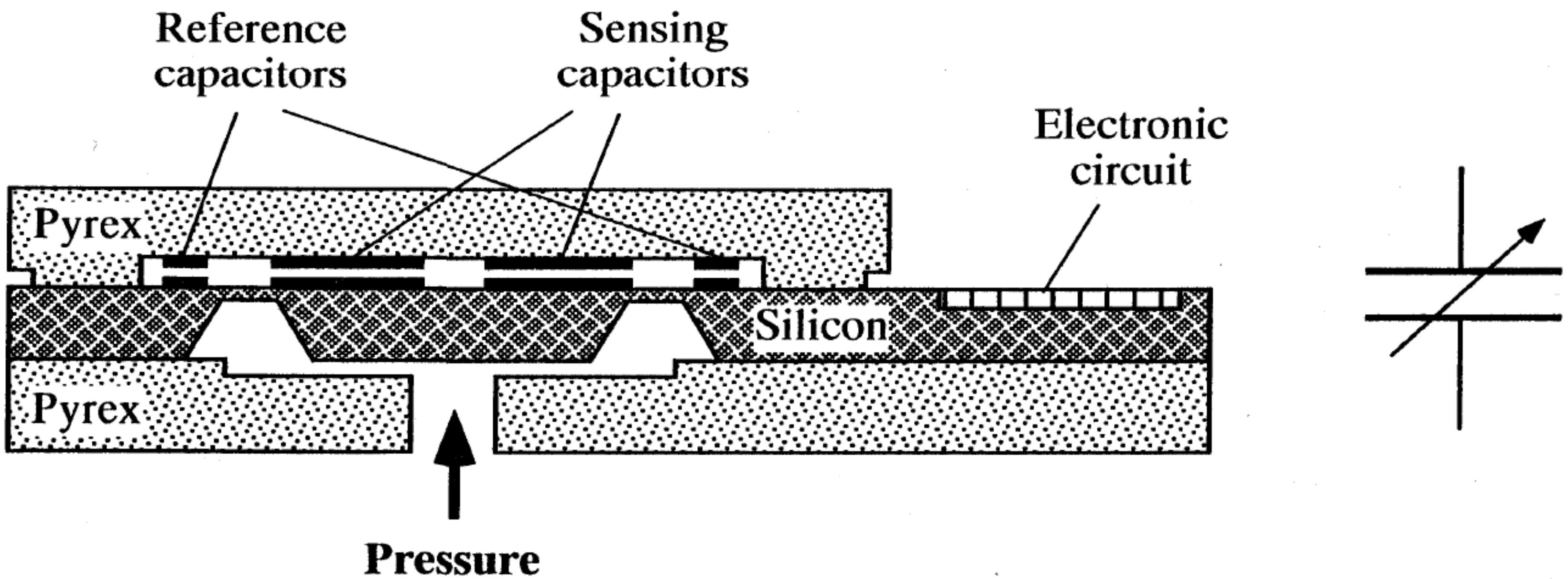

## Sensor activation with auto-adapting thresholds



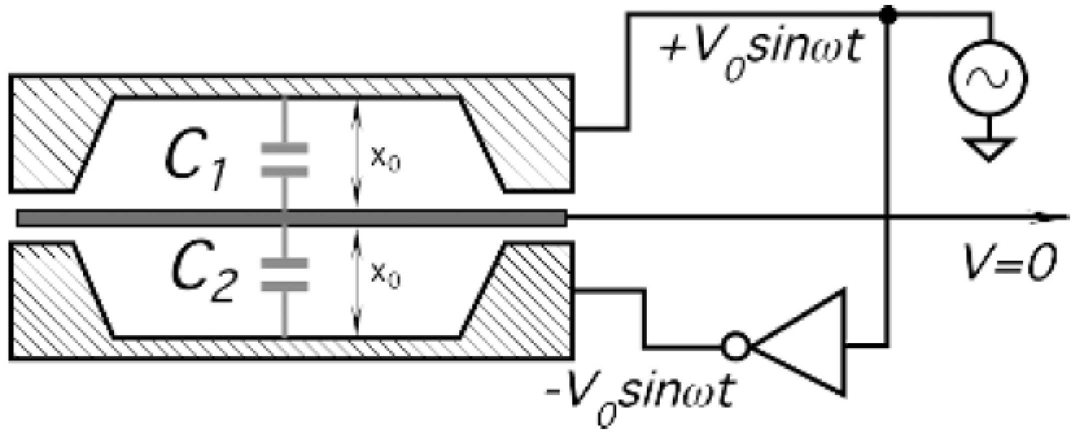
# Capacitive pressure sensor

Chip dimensions: 8.4 mm x 6.2 mm

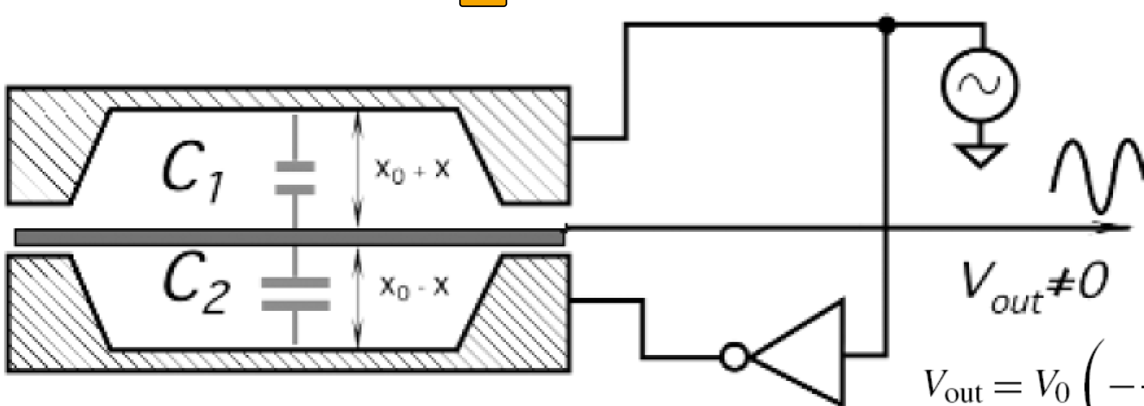
**Fabrication**: anisotropic etching



# Capacitive motion sensors




(A)



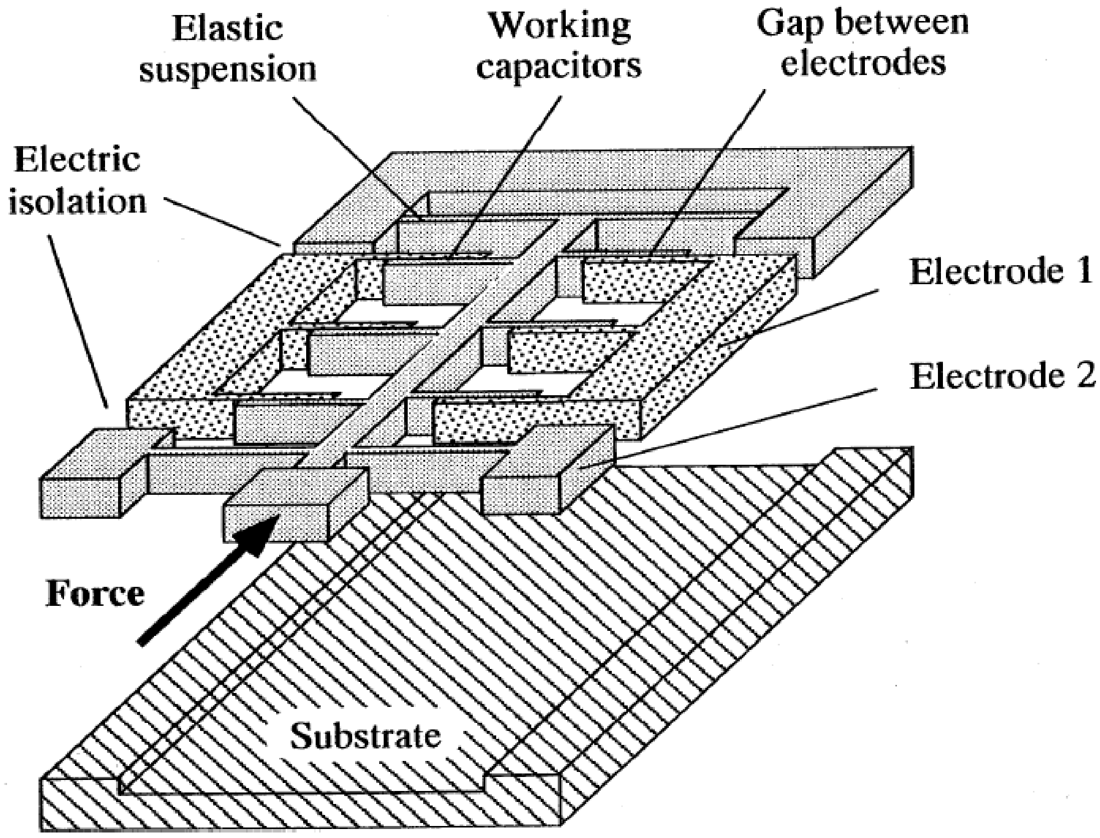

$$V_{\text{out}} = V_0 \left( -\frac{x}{x_0 + x} + \frac{\Delta C}{C} \right)$$

(B)

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

# Capacitive force sensor






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

**Fabrication**: anisotropic etching

# Conditioning of capacitive sensors (introduction, see next lecture)

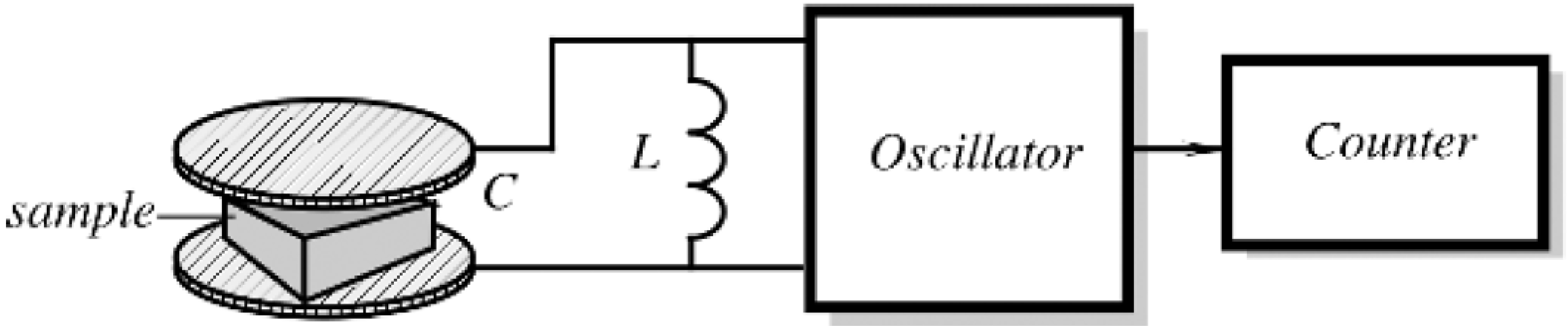



**Fig. 13.3.** Capacitive moisture sensing system.