نظم القياس الإلكترونية
Electronic Measurement Systems (EMS)

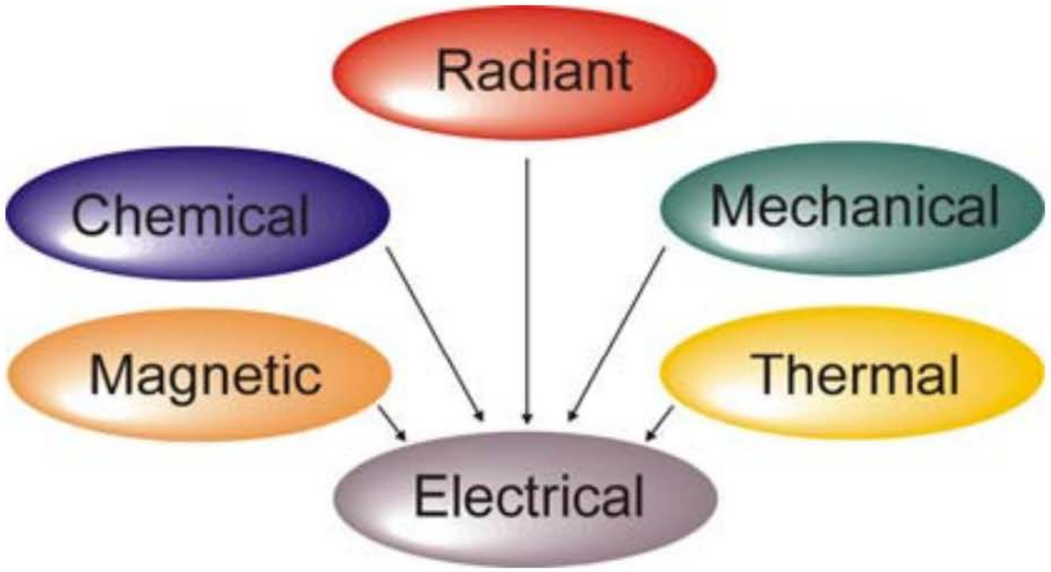
كلية الهندسة الكهربائية والالكترونية – جامعة حلب
د. أسعد كعدان

المحاضرة 3 – الحساسات والمبدلات

مصادر المحاضرة

- Electronic Instrumentation, Prof. Dr. Kofi Makinwa https://ocw.tudelft.nl/courses/electronic-instrumentation/
  - Lecture 2 - Transduction of Information

What Is A Sensor?



- A device that converts information from one energy domain into the **electrical** domain
- Where it can be easily (digitally) processed and stored

The World Is Analog

- So sensors output **analog** information
- Requires **analog-to-digital** conversion
- Note: transducer = sensor OR actuator

Transduction

Signal domains:

- Magnetic (Ma),
- Mechanical (Me),
- Thermal (Th),
- Optical (Op),
- Chemical (Ch) and
- Electrical (El).

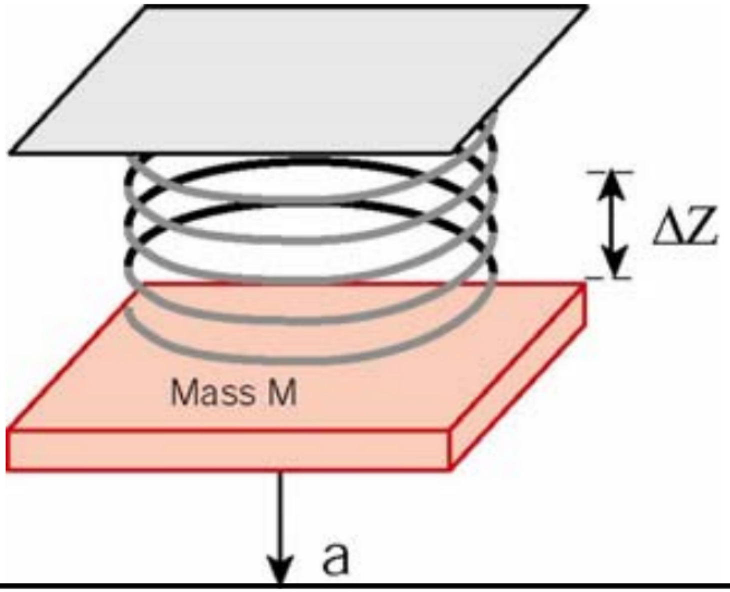
Sources of uncertainty (error) :

- Source loading by the measurement
- Sensitivity to unintended el. and non-el. quantities
- Electro-magnetic interference
- **Thermal noise**
- Many more…..

Transduction

Transduction matrix:

$$\begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} = \begin{pmatrix} t_{ma,ma} & t_{me,ma} & t_{th,ma} & t_{opt,ma} & t_{ch,ma} & t_{el,ma} \\ t_{ma,me} & t_{me,me} & t_{th,me} & t_{opt,me} & t_{ch,me} & t_{el,me} \\ t_{ma,th} & t_{me,th} & t_{th,th} & t_{opt,th} & t_{ch,th} & t_{el,th} \\ t_{ma,opt} & t_{me,opt} & t_{th,opt} & t_{opt,opt} & t_{ch,opt} & t_{el,opt} \\ t_{ma,ch} & t_{me,ch} & t_{th,ch} & t_{opt,ch} & t_{ch,ch} & t_{el,ch} \\ t_{ma,el} & t_{me,el} & t_{th,el} & t_{opt,el} & t_{ch,el} & t_{el,el} \end{pmatrix} \begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} + \begin{pmatrix} Ma_{os} \\ Me_{os} \\ Th_{os} \\ Opt_{os} \\ Ch_{os} \\ El_{os} \end{pmatrix}$$

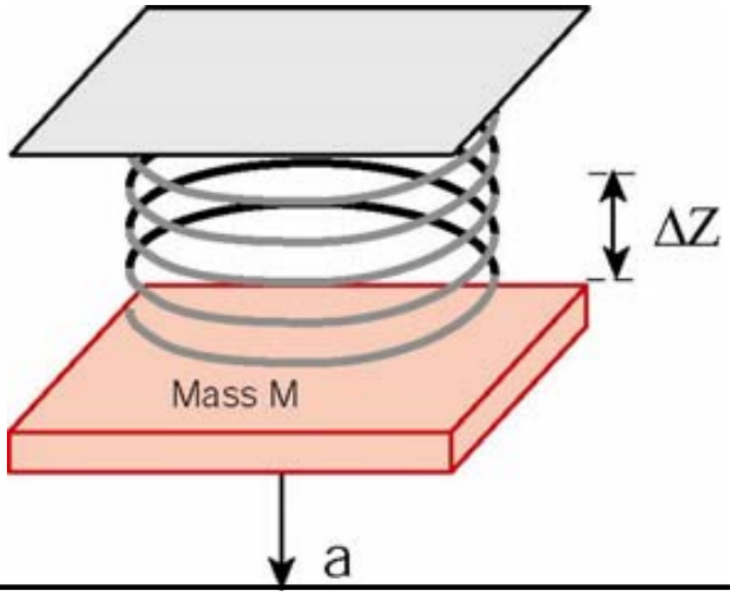


Acceleration to displ. = Transduction from mechanical to mechanical

Transduction

Transduction matrix (red text ⇒ non-zero coefs):

$$\begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} = \begin{pmatrix} t_{ma,ma} & t_{me,ma} & t_{th,ma} & t_{opt,ma} & t_{ch,ma} & t_{el,ma} \\ t_{ma,me} & t_{me,me} & t_{th,me} & t_{opt,me} & t_{ch,me} & t_{el,me} \\ t_{ma,th} & t_{me,th} & t_{th,th} & t_{opt,th} & t_{ch,th} & t_{el,th} \\ t_{ma,opt} & t_{me,opt} & t_{th,opt} & t_{opt,opt} & t_{ch,opt} & t_{el,opt} \\ t_{ma,ch} & t_{me,ch} & t_{th,ch} & t_{opt,ch} & t_{ch,ch} & t_{el,ch} \\ t_{ma,el} & t_{me,el} & t_{th,el} & t_{opt,el} & t_{ch,el} & t_{el,el} \end{pmatrix} \begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} + \begin{pmatrix} Ma_{os} \\ Me_{os} \\ Th_{os} \\ Opt_{os} \\ Ch_{os} \\ El_{os} \end{pmatrix}$$

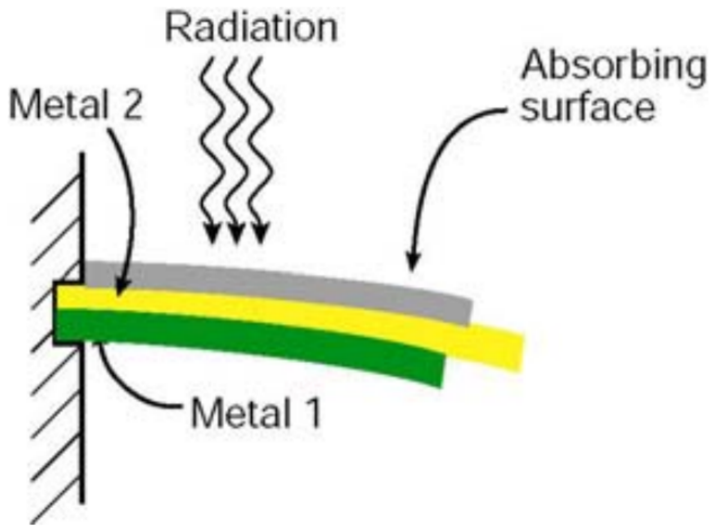


Acceleration to displ. = Transduction from mechanical to mechanical

Transduction

Transduction matrix:

$$\begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} = \begin{pmatrix} t_{ma,ma} & t_{me,ma} & t_{th,ma} & t_{opt,ma} & t_{ch,ma} & t_{el,ma} \\ t_{ma,me} & t_{me,me} & t_{th,me} & t_{opt,me} & t_{ch,me} & t_{el,me} \\ t_{ma,th} & t_{me,th} & t_{th,th} & t_{opt,th} & t_{ch,th} & t_{el,th} \\ t_{ma,opt} & t_{me,opt} & t_{th,opt} & t_{opt,opt} & t_{ch,opt} & t_{el,opt} \\ t_{ma,ch} & t_{me,ch} & t_{th,ch} & t_{opt,ch} & t_{ch,ch} & t_{el,ch} \\ t_{ma,el} & t_{me,el} & t_{th,el} & t_{opt,el} & t_{ch,el} & t_{el,el} \end{pmatrix} \begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} + \begin{pmatrix} Ma_{os} \\ Me_{os} \\ Th_{os} \\ Opt_{os} \\ Ch_{os} \\ El_{os} \end{pmatrix}$$

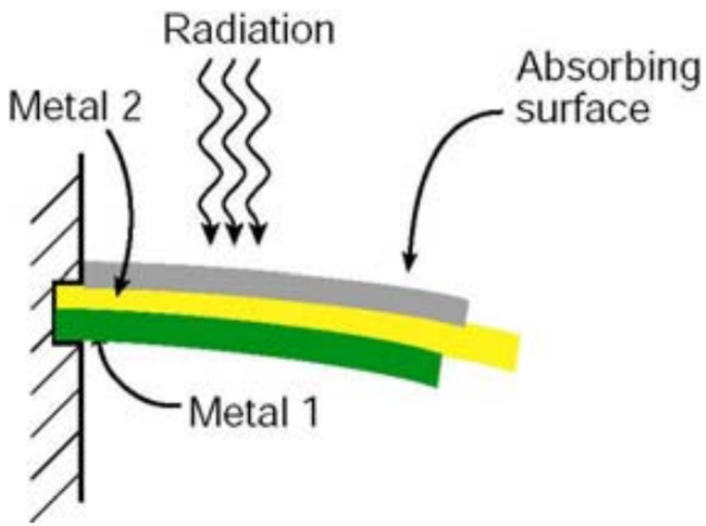


Transduction in two steps:
1. from optical to thermal, followed by
2. thermal to mechanical

= tandem transducer

Transduction

Tandem transduction:



Transduction in two steps:
1. from optical to thermal, followed by
2. thermal to mechanical

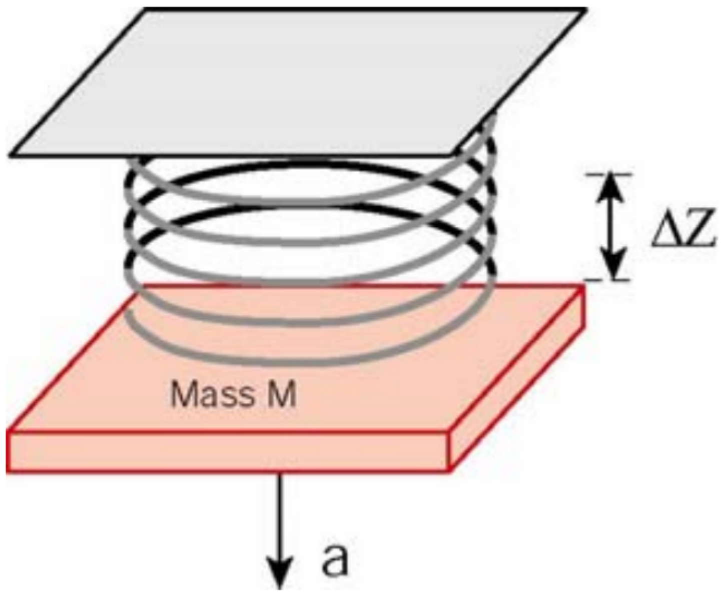
= tandem transducer

$$Me = \left(s_{ma,me}\ s_{me,me}\ s_{th,me}\ s_{opt,me}\ s_{ch,me}\ s_{el,me} \right) \bullet$$

$$\left(\begin{pmatrix} t_{ma,ma} & t_{me,ma} & t_{th,ma} & t_{opt,ma} & t_{ch,ma} & t_{el,ma} \\ t_{ma,me} & t_{me,me} & t_{th,me} & t_{opt,me} & t_{ch,me} & t_{el,me} \\ t_{ma,th} & t_{me,th} & t_{th,th} & t_{opt,th} & t_{ch,th} & t_{el,th} \\ t_{ma,opt} & t_{me,opt} & t_{th,opt} & t_{opt,opt} & t_{ch,opt} & t_{el,opt} \\ t_{ma,ch} & t_{me,ch} & t_{th,ch} & t_{opt,ch} & t_{ch,ch} & t_{el,ch} \\ t_{ma,el} & t_{me,el} & t_{th,el} & t_{opt,el} & t_{ch,el} & t_{el,el} \end{pmatrix} \begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} + \begin{pmatrix} Ma_{os} \\ Me_{os} \\ Th_{os} \\ Opt_{os} \\ Ch_{os} \\ El_{os1} \end{pmatrix} \right) + Me_{os2}$$

Transduction

Tandem transduction requires an intermediate *non-electrical* domain:



So:

1. Acceleration to displacement (within mechanical domain),

followed by

2. displacement to capacitance (to the electrical domain)

$\Rightarrow$ not a tandem transducer

Transduction

Transduction to the electrical domain:

$$\begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} = \begin{pmatrix} t_{ma,ma} & t_{me,ma} & t_{th,ma} & t_{opt,ma} & t_{ch,ma} & t_{el,ma} \\ t_{ma,me} & t_{me,me} & t_{th,me} & t_{opt,me} & t_{ch,me} & t_{el,me} \\ t_{ma,th} & t_{me,th} & t_{th,th} & t_{opt,th} & t_{ch,th} & t_{el,th} \\ t_{ma,opt} & t_{me,opt} & t_{th,opt} & t_{opt,opt} & t_{ch,opt} & t_{el,opt} \\ t_{ma,ch} & t_{me,ch} & t_{th,ch} & t_{opt,ch} & t_{ch,ch} & t_{el,ch} \\ t_{ma,el} & t_{me,el} & t_{th,el} & t_{opt,el} & t_{ch,el} & t_{el,el} \end{pmatrix} \begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} + \begin{pmatrix} Ma_{os} \\ Me_{os} \\ Th_{os} \\ Opt_{os} \\ Ch_{os} \\ El_{os} \end{pmatrix}$$

One sensitivity plus up to 5 cross-sensitivities

Example: A photodiode

Sensitivity: $t_{opt,el}$

Cross-sensitivities: $t_{el,el}$ (?) $t_{th,el}$ (?)

Offset: due to dark current

Transduction

Transduction to the electrical domain:

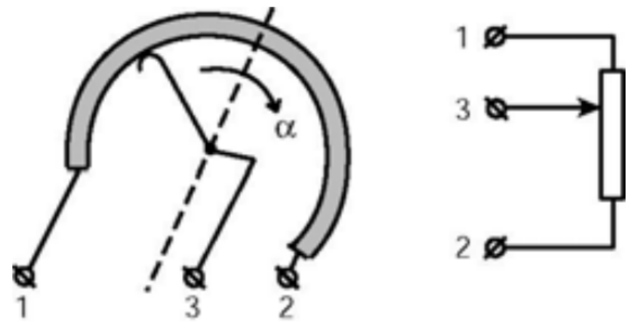
$$\begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} = \begin{pmatrix} t_{ma,ma} & t_{me,ma} & t_{th,ma} & t_{opt,ma} & t_{ch,ma} & t_{el,ma} \\ t_{ma,me} & t_{me,me} & t_{th,me} & t_{opt,me} & t_{ch,me} & t_{el,me} \\ t_{ma,th} & t_{me,th} & t_{th,th} & t_{opt,th} & t_{ch,th} & t_{el,th} \\ t_{ma,opt} & t_{me,opt} & t_{th,opt} & t_{opt,opt} & t_{ch,opt} & t_{el,opt} \\ t_{ma,ch} & t_{me,ch} & t_{th,ch} & t_{opt,ch} & t_{ch,ch} & t_{el,ch} \\ t_{ma,el} & t_{me,el} & t_{th,el} & t_{opt,el} & t_{ch,el} & t_{el,el} \end{pmatrix} \begin{pmatrix} Ma \\ Me \\ Th \\ Opt \\ Ch \\ El \end{pmatrix} + \begin{pmatrix} Ma_{os} \\ Me_{os} \\ Th_{os} \\ Opt_{os} \\ Ch_{os} \\ El_{os} \end{pmatrix}$$

Two types of sensors:

- Self generating sensors
- Modulating sensors

Transduction

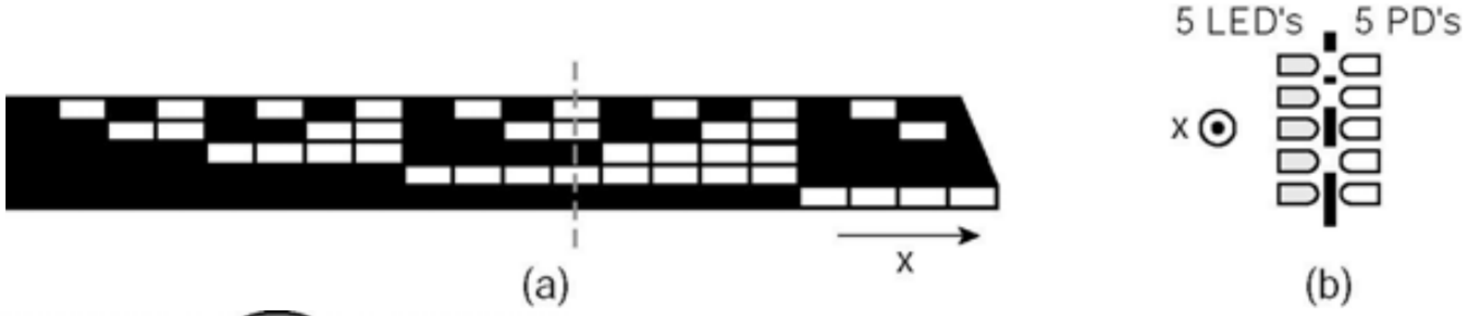
Self-generating sensors:
Example: Potentiometer

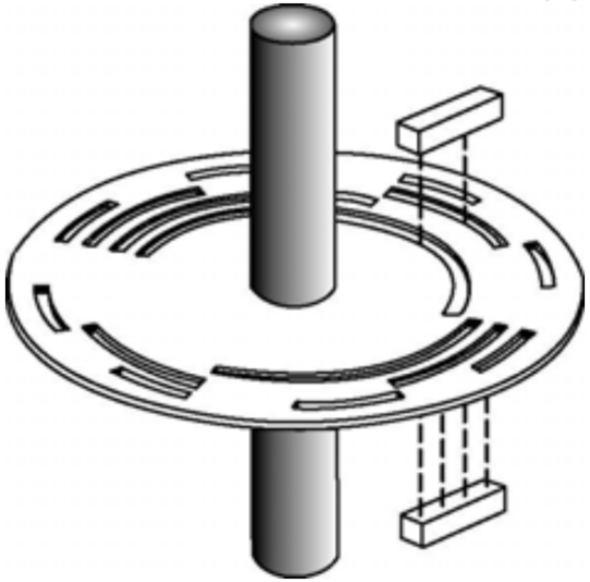


+ No additional sources of uncertainty
+ No external power supply
- Draws all its energy from the measurand (mechanical source loading)

Transduction

Modulating sensors:
Example: Optical encoder



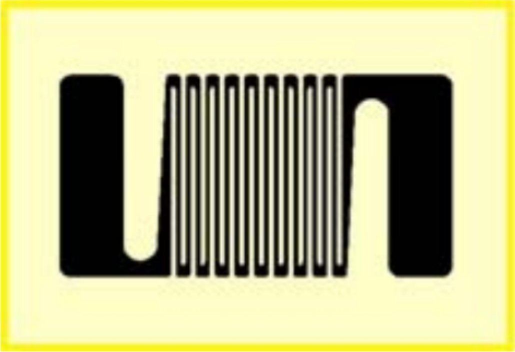


- Optical domain ⇒ additional sources of uncertainty (e.g. light intensity)
+ Takes less energy from the measurand (non-contact displacement measurement)

Force sensors using strain gauges

Resistance value is defined by specific resistivity and dimensions:

$$R = \rho \frac{L}{A}$$



In case of strain (deformation) due to mechanical stress:

$$\frac{\partial R}{R} = \frac{\partial \rho}{\rho} + \frac{\partial L}{L} - \frac{\partial A}{A}$$

When assuming constant volume:

$$\frac{\partial V}{V} = 0 \rightarrow \frac{\partial L}{L} = -\frac{\partial A}{A}$$

Resistive sensors

Force sensors using strain gauges

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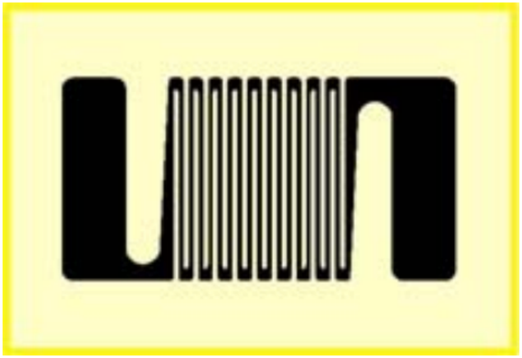

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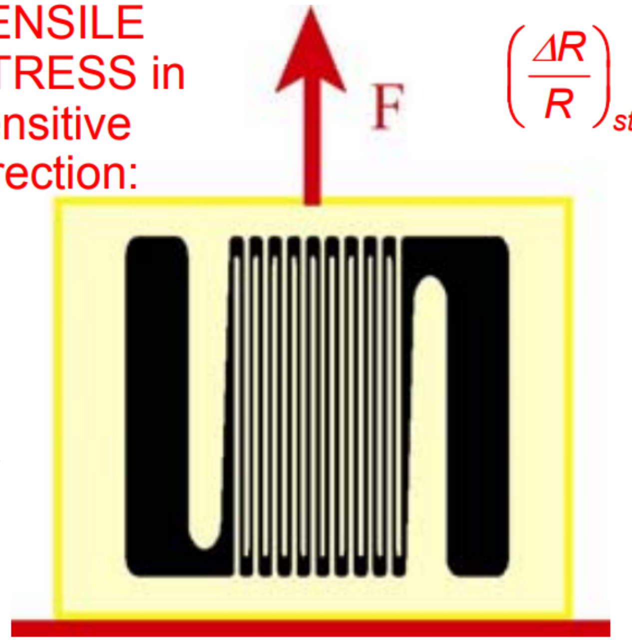
When assuming constant volume:

$$\left.\begin{array}{l} \frac{\partial V}{V} = 0 \rightarrow \frac{\partial L}{L} = -\frac{\partial A}{A} \\ Metal\ film: \frac{\partial \rho}{\rho} \propto \frac{\partial L}{L} \end{array}\right\} \rightarrow \frac{\partial R}{R} = 2\frac{\partial L}{L} = k\frac{\partial L}{L}$$

TENSILE STRESS in sensitive direction:

$$\left(\frac{\Delta R}{R}\right)_{strain} > 0$$



k= gauge factor

Resistive sensors

Force sensors using strain gauges

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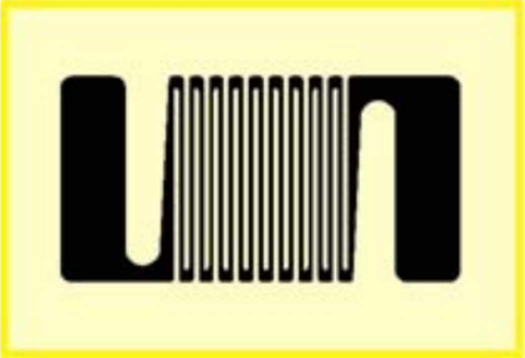

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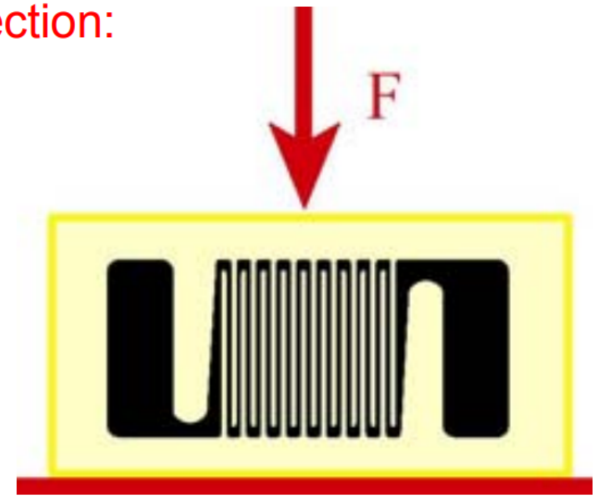
When assuming constant volume:

$$\left.\begin{array}{l} \dfrac{\partial V}{V} = 0 \rightarrow \dfrac{\partial L}{L} = -\dfrac{\partial A}{A} \\ Metal\ film: \dfrac{\partial \rho}{\rho} \ll \dfrac{\partial L}{L} \end{array}\right\} \rightarrow \frac{\partial R}{R} = 2\frac{\partial L}{L} = k\frac{\partial L}{L}$$

k= gauge factor

COMPRESSIVE STRESS in sensitive direction:

$$\left(\frac{\Delta R}{R}\right)_{comp} = -\left(\frac{\Delta R}{R}\right)_{tens}$$



Resistive sensors

Force sensors using strain gauges

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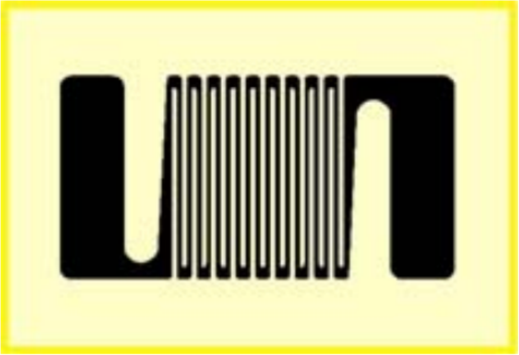

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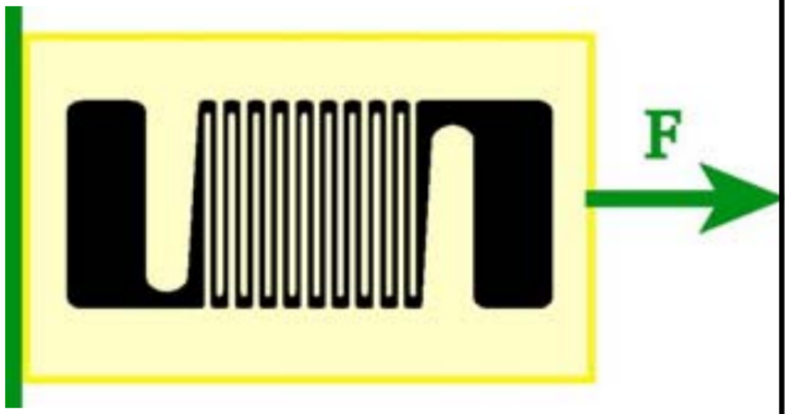
k= gauge factor

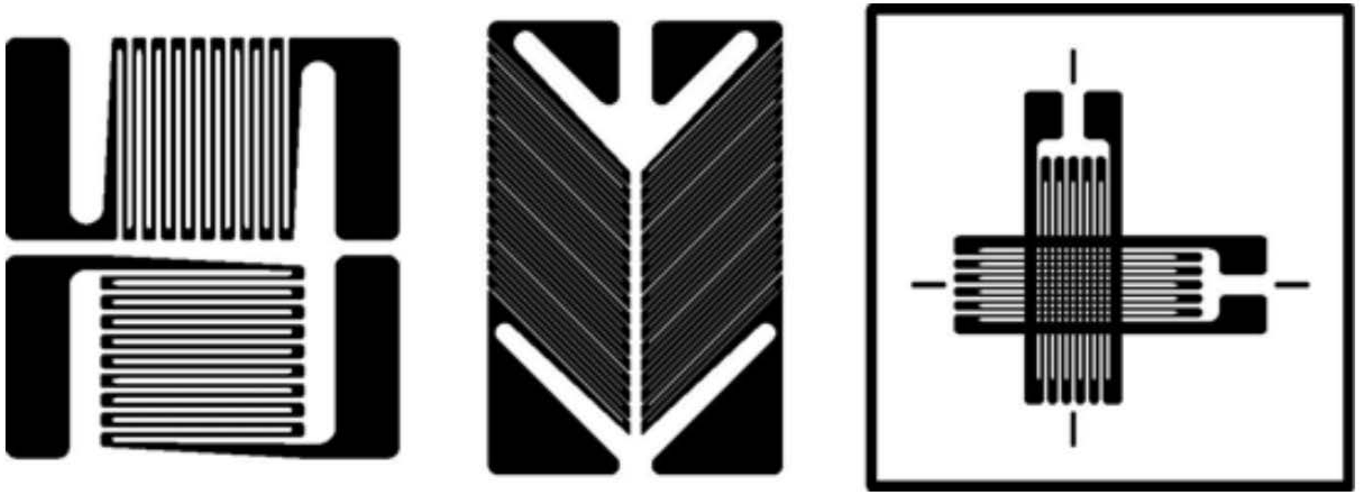
Applying load in insensitive direction:



$$\left(\frac{\Delta R}{R}\right)_{perp.} \approx 0$$

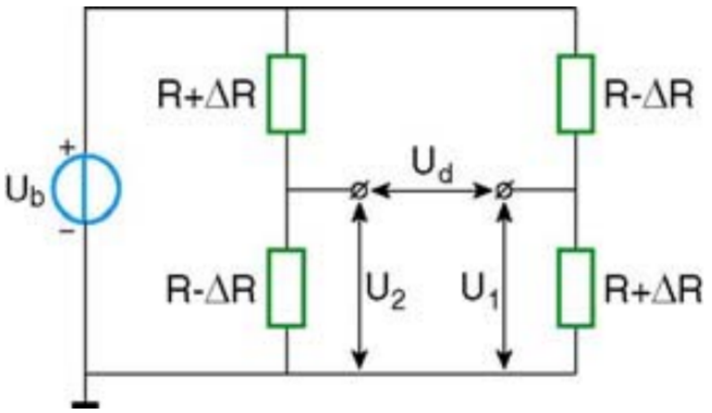
Resistive sensors

Measuring force in two dimensions



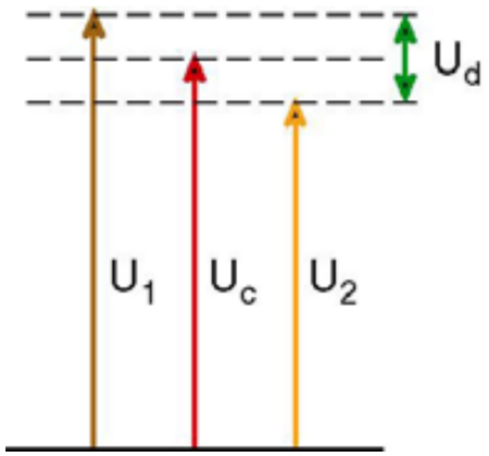
The Wheatstone bridge

Wheatstone bridge:



$$U_1 = \frac{R+\Delta R}{(R+\Delta R)+(R-\Delta R)}U_b = \frac{R+\Delta R}{2R}U_b$$

$$U_2 = \frac{R-\Delta R}{(R+\Delta R)+(R-\Delta R)}U_b = \frac{R-\Delta R}{2R}U_b$$



Information is contained in the differential signal:

$$U_d = U_1 - U_2 = \frac{\Delta R}{R}U_b < 10mV \text{ at } U_b = 10V$$

Which, however, is superimposed on the common-mode signal:

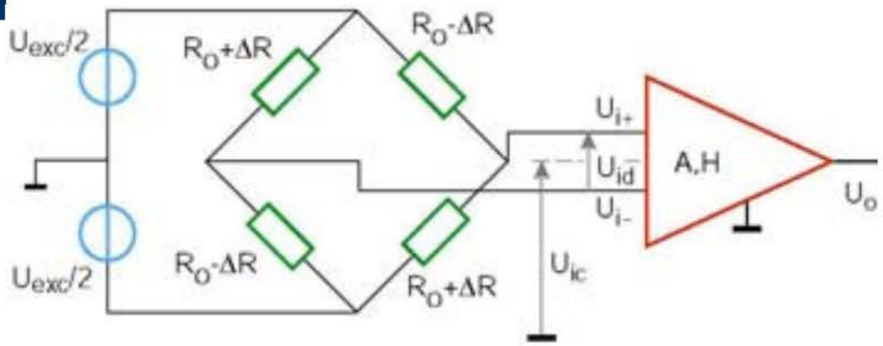
$$U_c = \frac{U_1+U_2}{2} = \frac{U_b}{2} = 5V \text{ at } U_b = 10V$$

TU Delft
Delft University of Technology

Bridge configurations

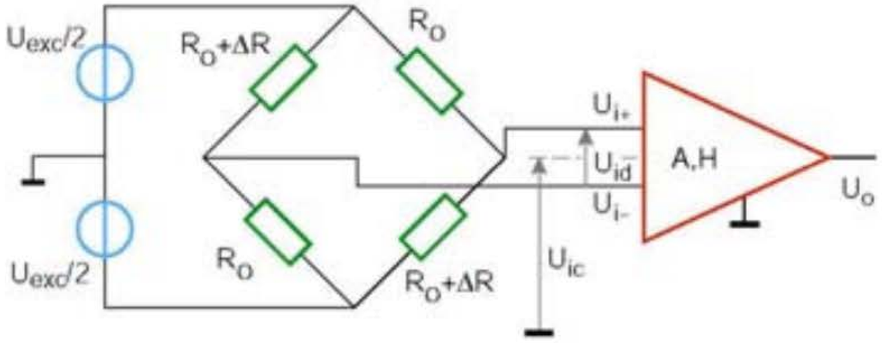
ET8.017
El. Instr.

Full bridge



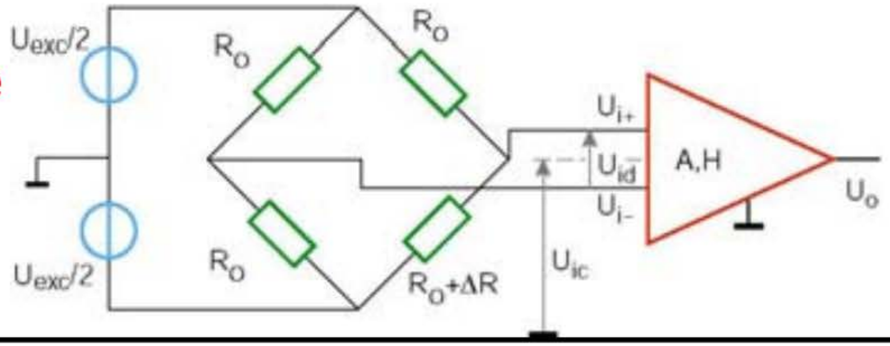
- Linear
- All elements on structure
- Increasing AND decreasing with measurand

1/2 bridge



- Non-linear
- ½ of elements on structure
- Increasing OR decreasing with measurand

1/4 bridge



- Non-linear
- 1/4 of elements on structure-minimum dimensions.

Delft University of Technology

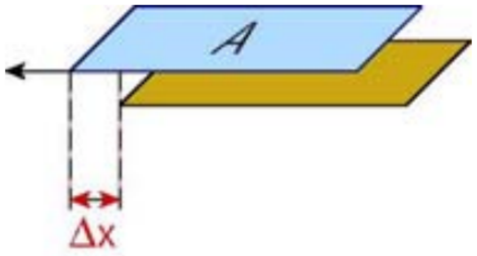
Capacitive sensor readout

ET8.017 El. Instr.

Very suitable for displacement measurements

From the parallel-plate approximation: $C = \varepsilon_o \varepsilon_r \frac{A}{h} = \varepsilon_o \frac{A}{h}$

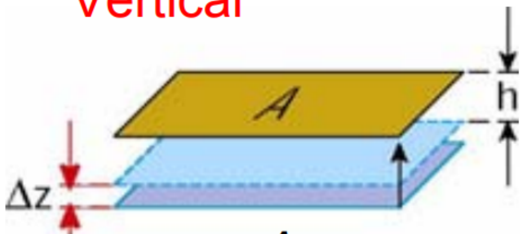
Lateral



$$C = \varepsilon_o \frac{w\left(x_o - \Delta x\right)}{h}$$

Linear

Vertical



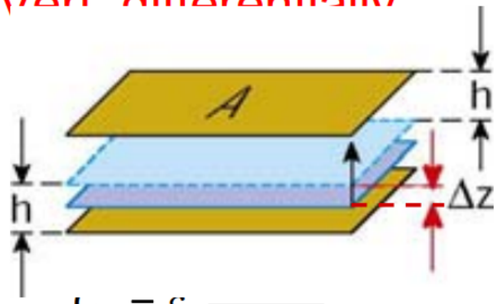
$$C = \varepsilon_o \frac{A}{h + \Delta z}$$

$$C_o = \varepsilon_o \frac{A}{h}$$

$$\Delta C = C_o - C = \varepsilon_o A\left(\frac{1}{h} - \frac{1}{h + \Delta z}\right) = \frac{\varepsilon_o A}{h^2} \frac{\Delta z}{1 + \Delta z / h} \approx \frac{\varepsilon_o A}{h^2} \Delta z$$

Non-linear

Vert. differentially



$$C_u = \varepsilon_o \frac{A}{h + \Delta z}$$

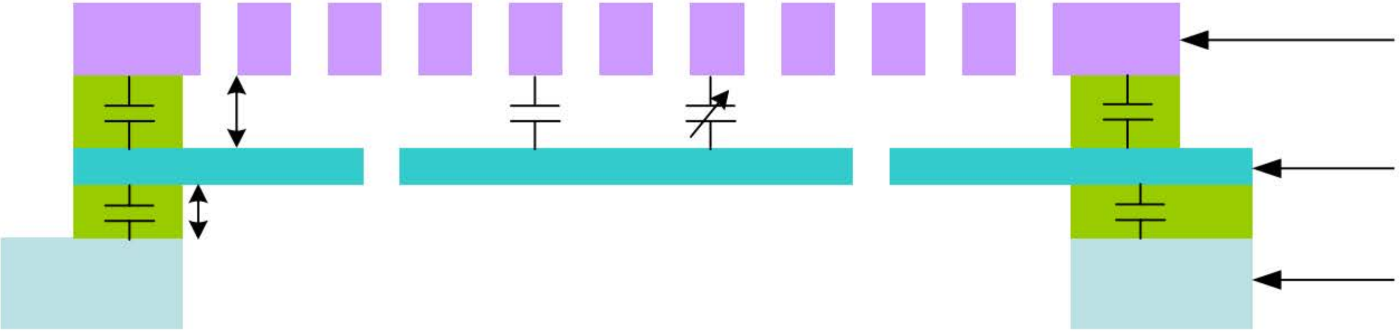
$$C_l = \varepsilon_o \frac{A}{h - \Delta z}$$

$$C_l - C_u = \varepsilon_o \frac{A}{h}\left(\frac{1}{1 - \Delta z / h} - \frac{1}{1 + \Delta z / h}\right) =$$

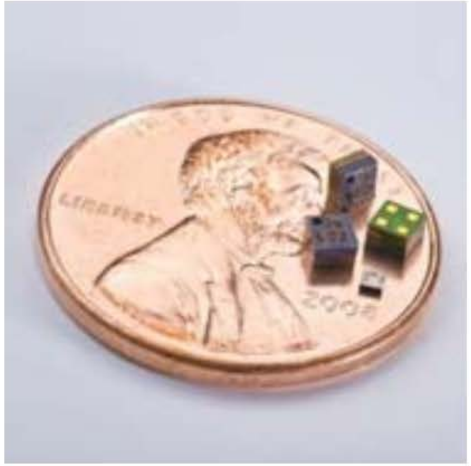
$$\Delta C = \varepsilon_o \frac{A}{h}\left(\frac{2 \Delta z / h}{1 + \left(\Delta z / h\right)^2}\right) \approx \frac{2 \varepsilon_o A}{h^2} \Delta z$$

Non-linearity reduced by differential measurement

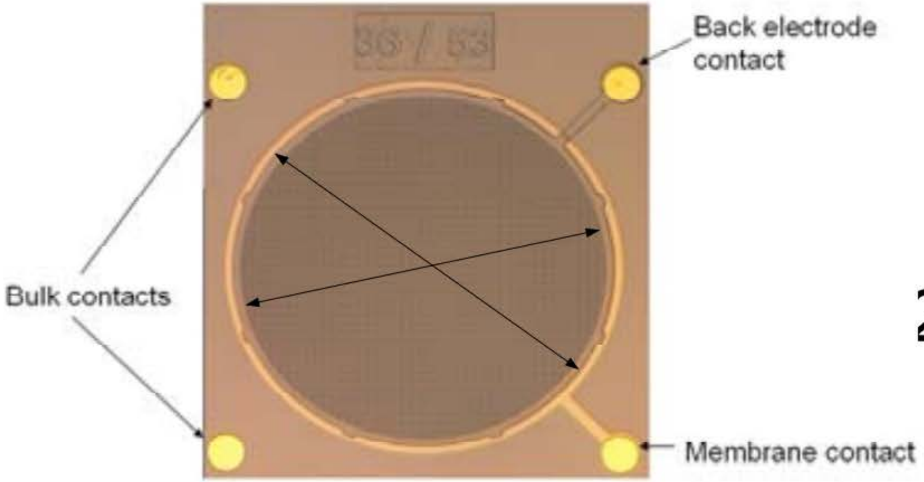
MEMS Microphone



- Sound waves move membrane ⇒ capacitance between the membrane and the fixed back plate varies
- Found in many cell phones



Courtesy: Akustica (website)



Courtesy: R. van Veldhoven, NXP

2

tbox=500n

Capacitive sensor readout

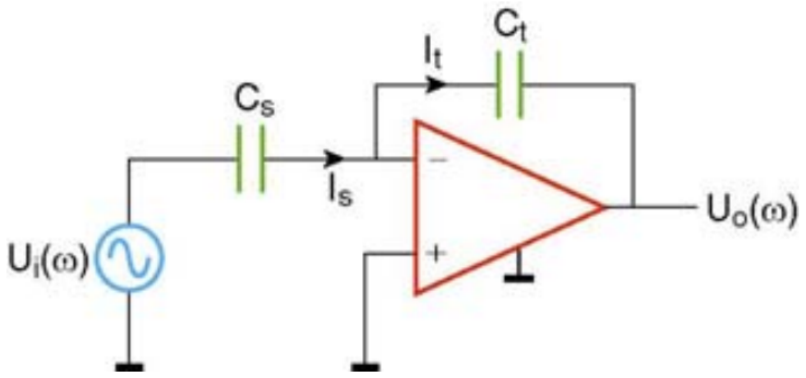
The charge amplifier (1)

For an “ideal” opamp:

(a) $U_- = U_+ = 0$
(b) $I_s(\omega) = j\omega C_s . U_i(\omega)$
(c2) $I_t(\omega) = -j\omega C_t . U_o(\omega)$, hence:

$$U_o(\omega)/ U_i(\omega) = -C_s/C_t$$

(can also be derived from the expression of an inverting amplifier with: $Z_s = 1/ j\omega C_s$ and $Z_t = 1/ j\omega C_t$)



Use C_s for lateral displacement sensing ($U_o \propto A$) and C_t for vertical displacement sensing with linear output ($U_o \propto 1/(1/d) = d$) .

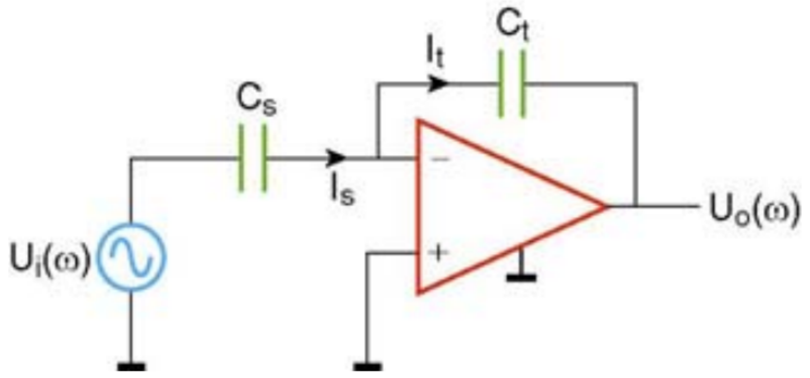
$$C = \varepsilon_o \varepsilon_r \frac{A}{h} = \varepsilon_o \frac{A}{h}$$

Capacitive sensor readout

The charge amplifier (2)

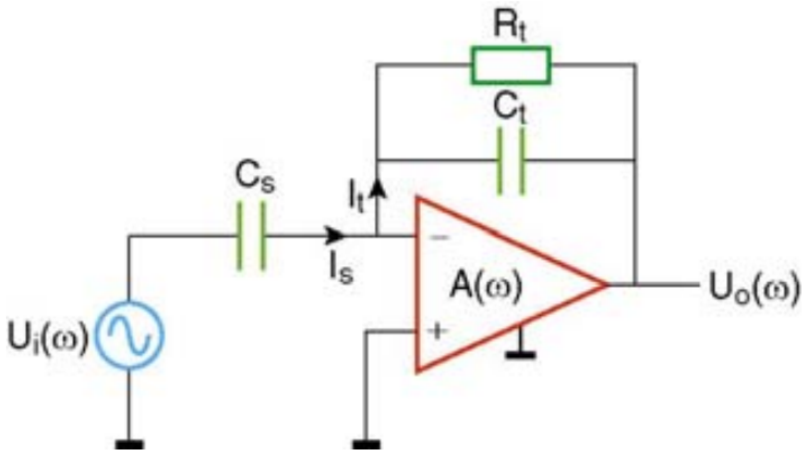
For an "ideal" opamp:

$U_o(\omega)/ U_i(\omega) = -C_s/C_t$



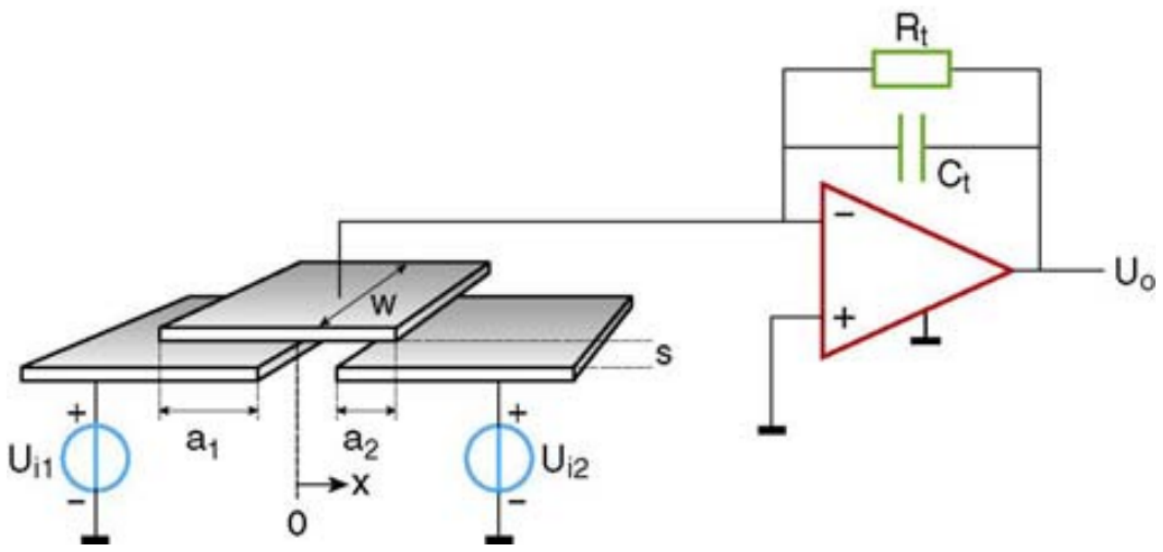
In practice:
1. R_t required to avoid saturation of the output by I_{bias}.

2. Open-loop gain is finite:
$A(\omega) = \quad A_o/(1+j\omega\tau_v)$.



Capacitive sensor readout

Application in differential sensor readout



Topology is often used for the readout of MEMS accelerometers and gyroscopes

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Piezo-electric force sensors

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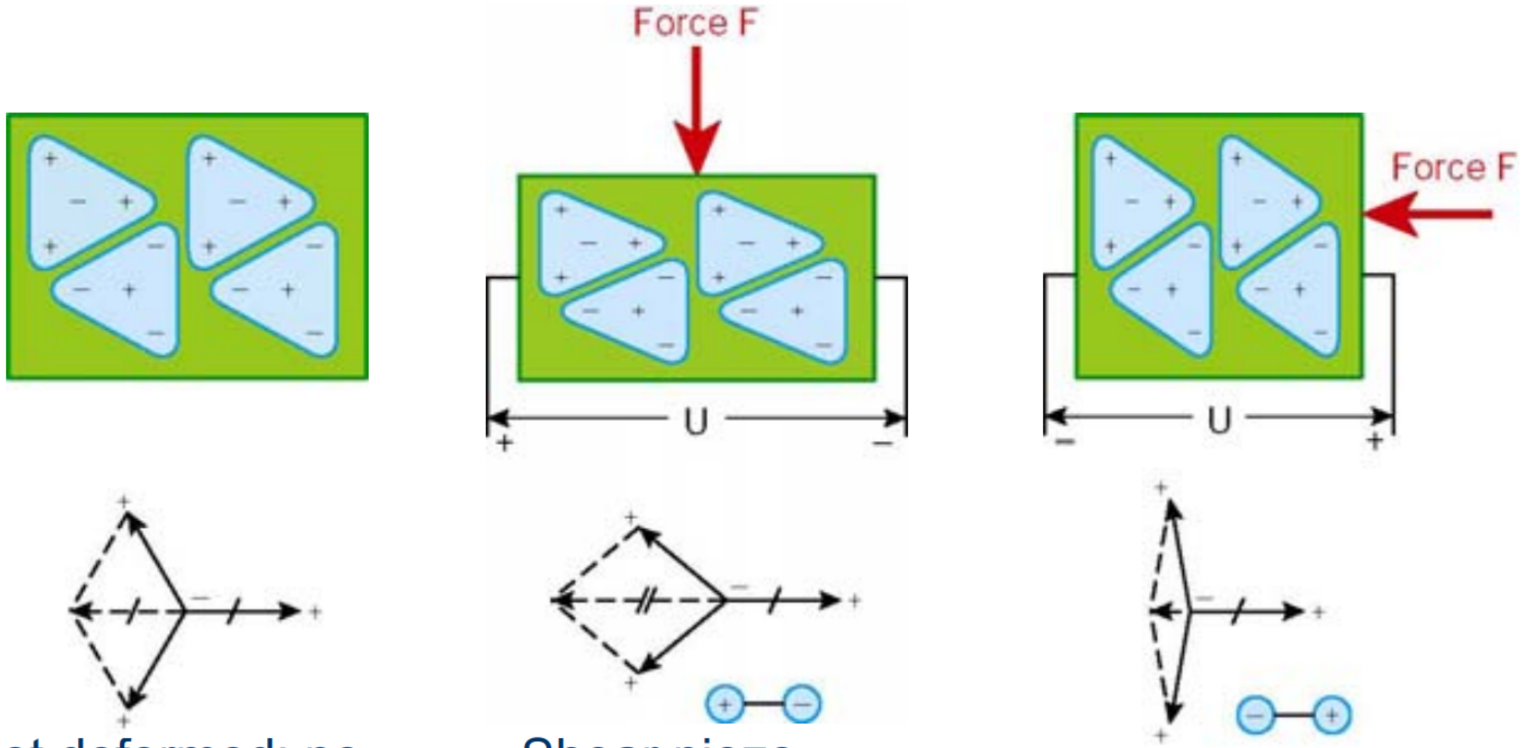
Piezo-electricity



Not deformed: no polarization charge

Shear piezo-electric sensitivity

(Normal) piezo-electric sensitivity

Piezo-electricity is reversible: connecting voltage source results in a deformation and, hence, in force.

Piezo-electricity in all crystal directions: described by a matrix.

Piezo-electric force sensors

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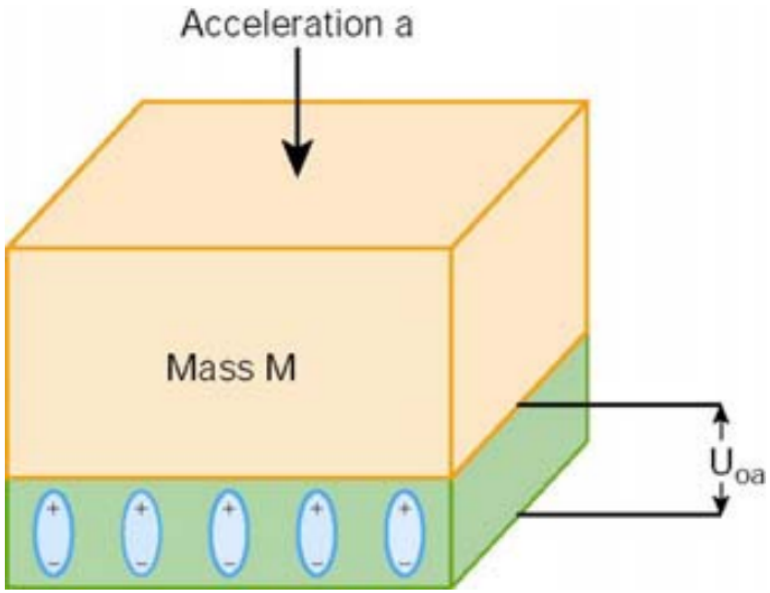
Application in acceleration sensing



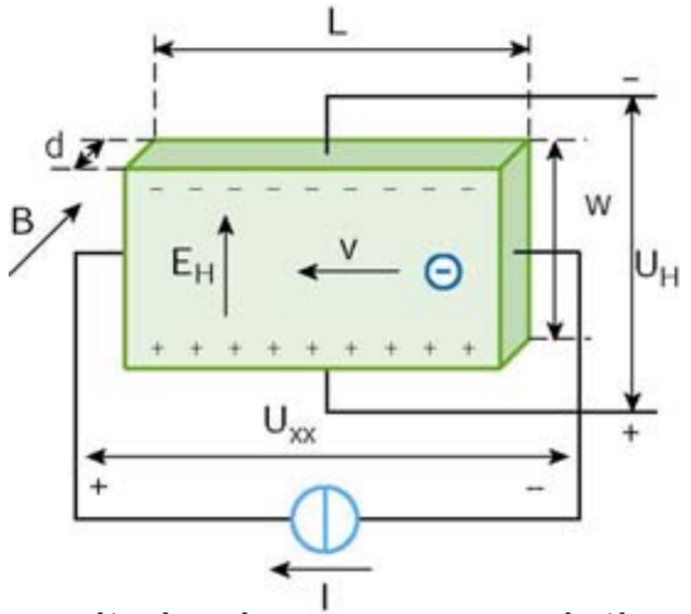
Charge sensitivity: S_q= 5 pC/N.
Capacitance: C_s= 20 pF
Mass: M= 100 g.

U_{oa} @ 1 m/s^2 ?

Force due to load: F= M.a= 0.1 N
Voltage sensitivity: S_u= S_q/C_s= 250 mV/N.
Hence: U_o= 25 mV

Magnetic field sensor using the Hall Effect

The Hall effect is based on the Lorentz force acting on electrons moving through a (semi)conductor.



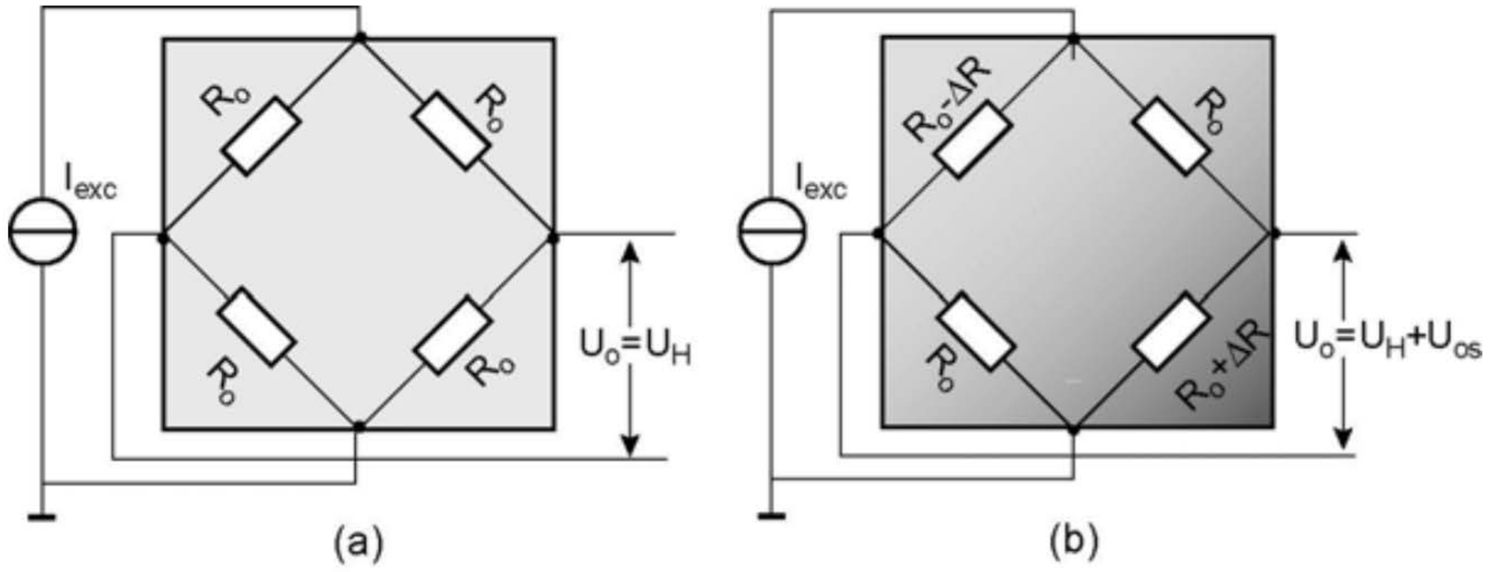
The deflection results in charge accumulation. The electrostatic field due to the charge counteracts the Lorentz force and equilibrium is reached at the Hall field, $E_H = F_L/e = vB$.

The Hall voltage $U_H = E_H.w$ is the output signal and is proportional to both I and B.

Note that $U_H/I = f(B)$ is like a resistance measured in a 4-terminal resistance measurement.

Magnetic field sensor using the Hall Effect

Stress in the conductive layer results in offset.



Wheatstone bridge not balanced at B= 0 T.

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The spinning current technique

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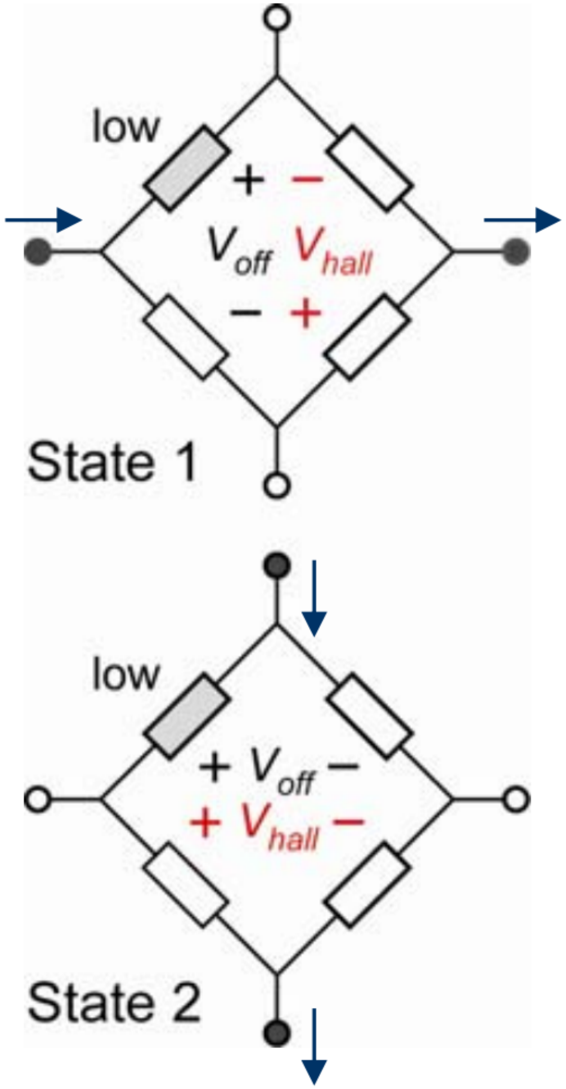


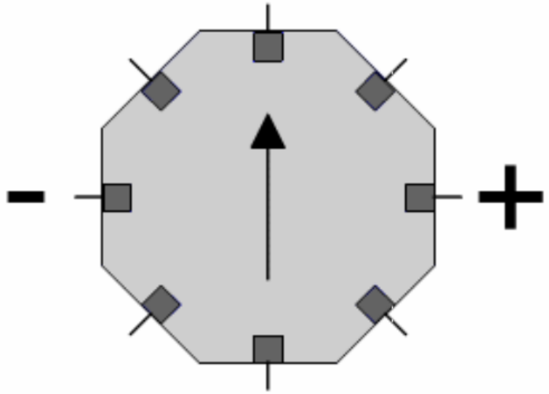
- Changing the **direction** of the bias current changes the **relative** polarity of V_{off} & V_{hall}
- So **averaging** the bridge output cancels V_{off}!

In practice

- n-well resistance depends on current direction (anisotropic)

$\Rightarrow$ 3 current directions needed for optimal offset cancellation!

Spinning-Current Hall Plate



- 3 current directions
  ⇒ Octagonal Hall plate
- Bias current rotated, while Hall voltages are summed
- Cancels offset due to **static** bridge mismatch

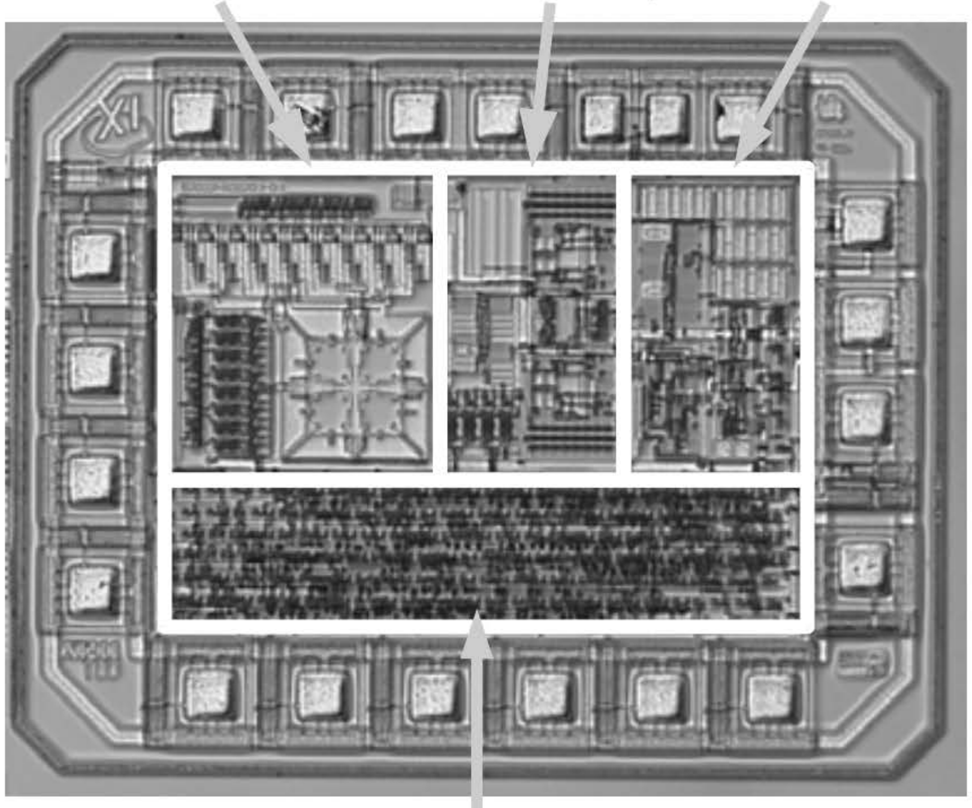
⇒ 10 - 100μT offset

Earth's magnetic field ~ 50μT

So electronic compass applications are possible …

Smart Hall Sensor

Hall Sensor Inst. Amp. ADC



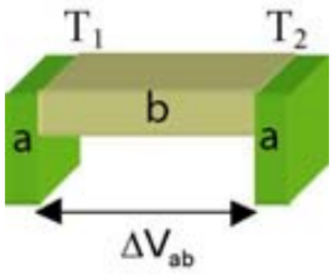
Timing, Control & Interfaces

- Standard 0.5μm CMOS
- Spinning current technique + low-offset amplifier $\Rightarrow$ 4μT offset
- State-of-the-art!

- J. van der Meer et al., ISSCC '05

Temperature sensors

The Seebeck effect



The Seebeck effect is due to the excess kinetic energy of free carriers at the hot side of a (semi)-conducting material, which results in a net diffusion of carriers towards the cold side. The resulting charge build-up creates an internal electric field that opposes further diffusion and is externally measurable as an open-circuit potential, ΔV (conventional).

$$\alpha = \left.\frac{\partial V}{\partial T}\right|_T ,$$

where α is the temperature coef of the Seebeck voltage at temperature T
$\Rightarrow$ the Seebeck coefficient

Equivalent definition: The Seebeck effect is due to the temperature–dependence of the Fermi level in a material (quantum mechanical).

$$\alpha = \left.\frac{1}{q}\frac{\partial E_F}{\partial T}\right|_T$$

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Temperature sensors

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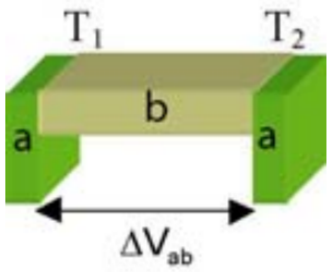
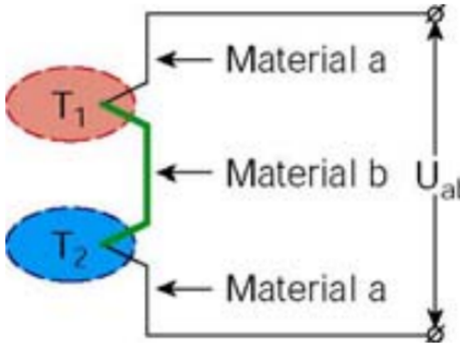


Practical use of the Seebeck effect:
a thermocouple with two different materials
and a temperature difference



$$U_{ab} = \left[\alpha_{a,T1}.T_1 - \alpha_{b,T1}.T_1\right] + \left[\alpha_{b,T2}.T_2 - \alpha_{a,T2}.T_2\right]$$

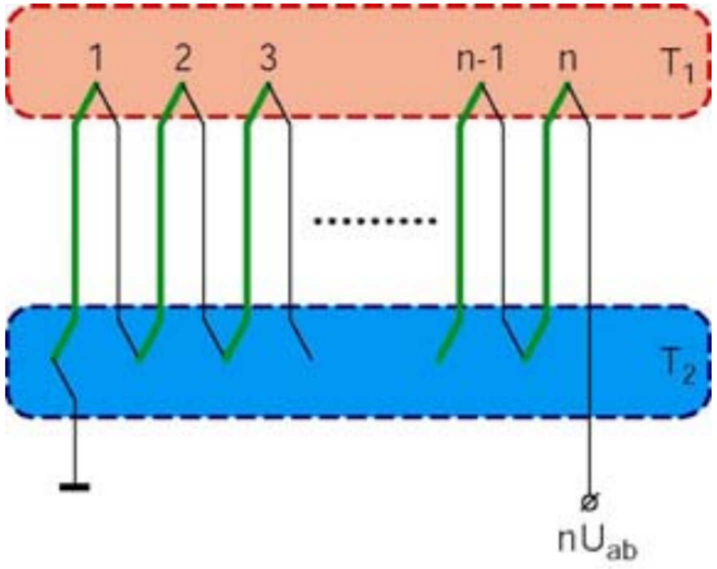
$$\left(\alpha_a - \alpha_b\right)\left(T_1 - T_2\right) = \alpha_{ab}\left(T_1 - T_2\right)$$

MATERIALCOMB.	SENSITIVITY (AT 0°C) [μV/K]	RANGE [°C)]
iron/constantan	45	0..760
copper/constantan	35	-100..370
chromel/alumel	40	0..1260
platinum/Pt+ Rd	5	0..1500

No offset, however very small DC voltages (typ.< 1mV) are generated.

Problem: readout circuit has offset

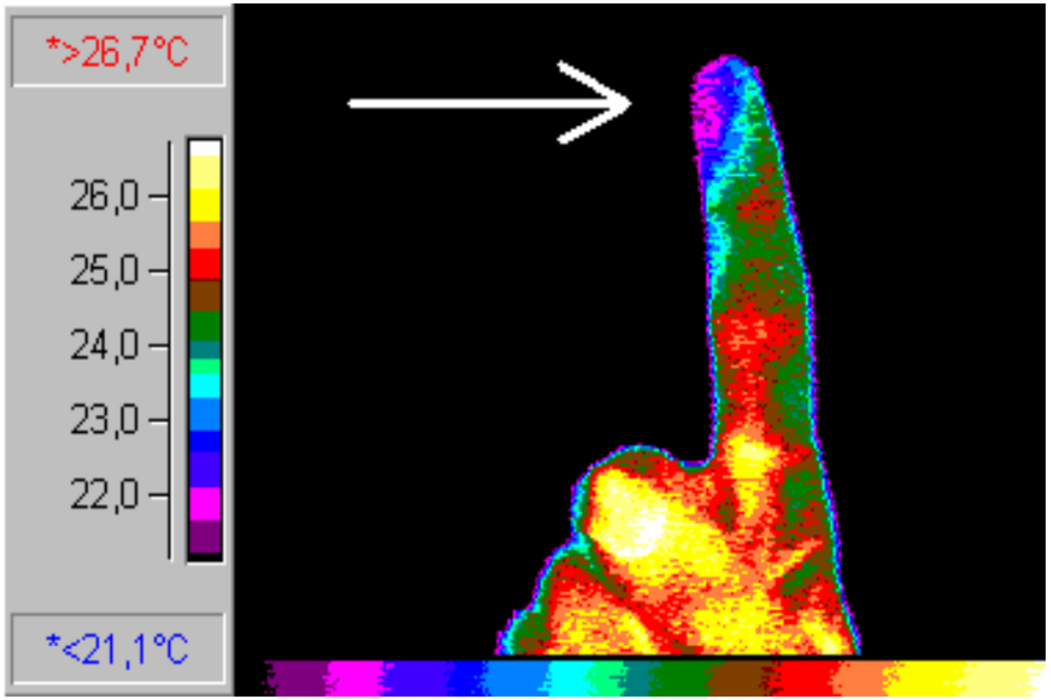
Thermopile for increased output signal



N-times the thermocouple voltage

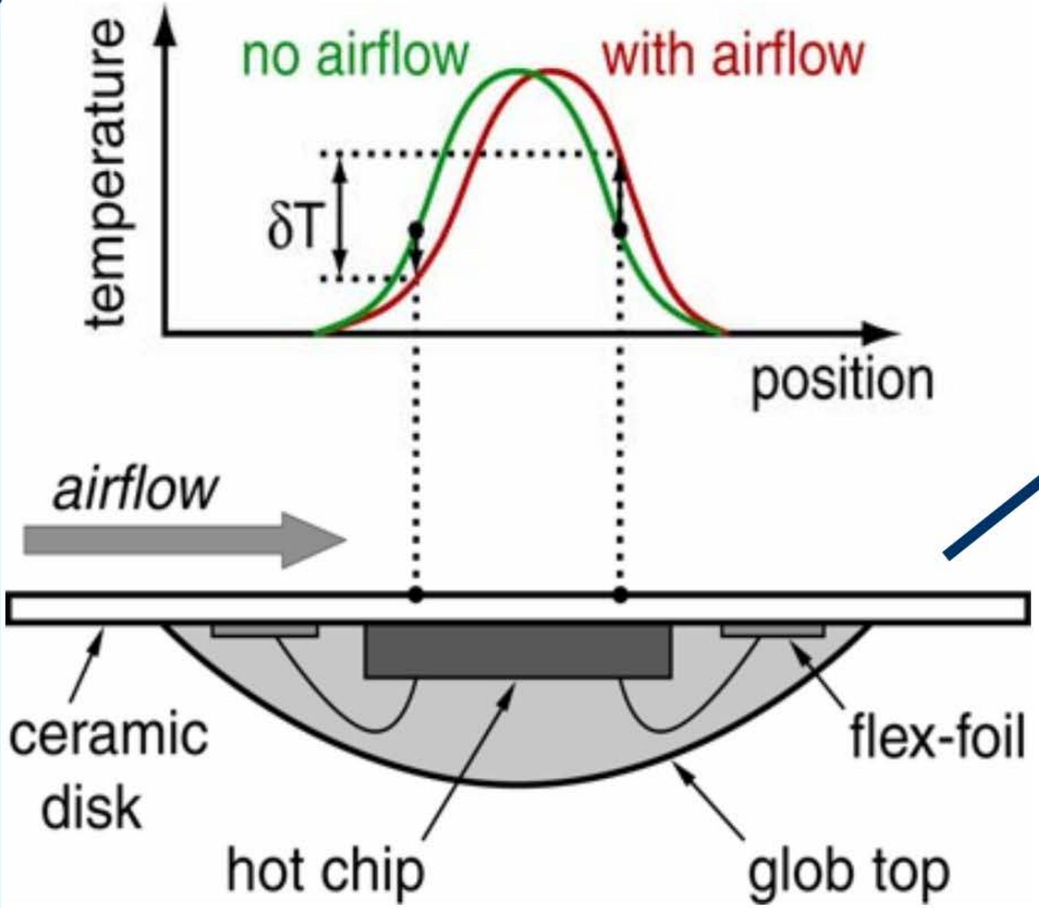
Problems:
- increased electrical resistance (noise)
- increased thermal conduction between cold and hot parts ⇒
  1. Increased source loading or
  2. More heat flux required to build up a temperature difference.

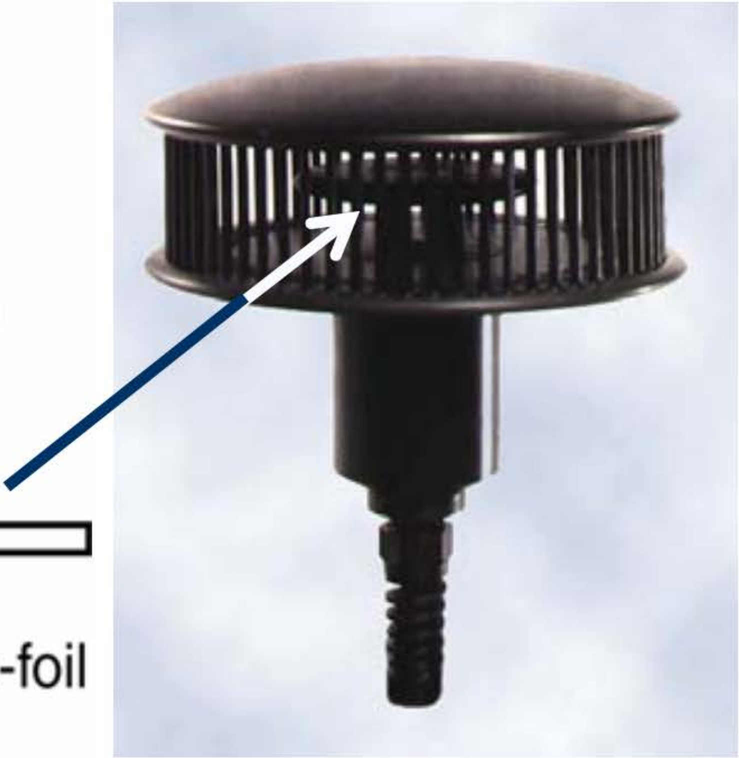
A Smart Wind Sensor!



Convective cooling ⇒ temperature gradient
⇒ wind speed <u>and</u> direction

Thermal Wind Sensor





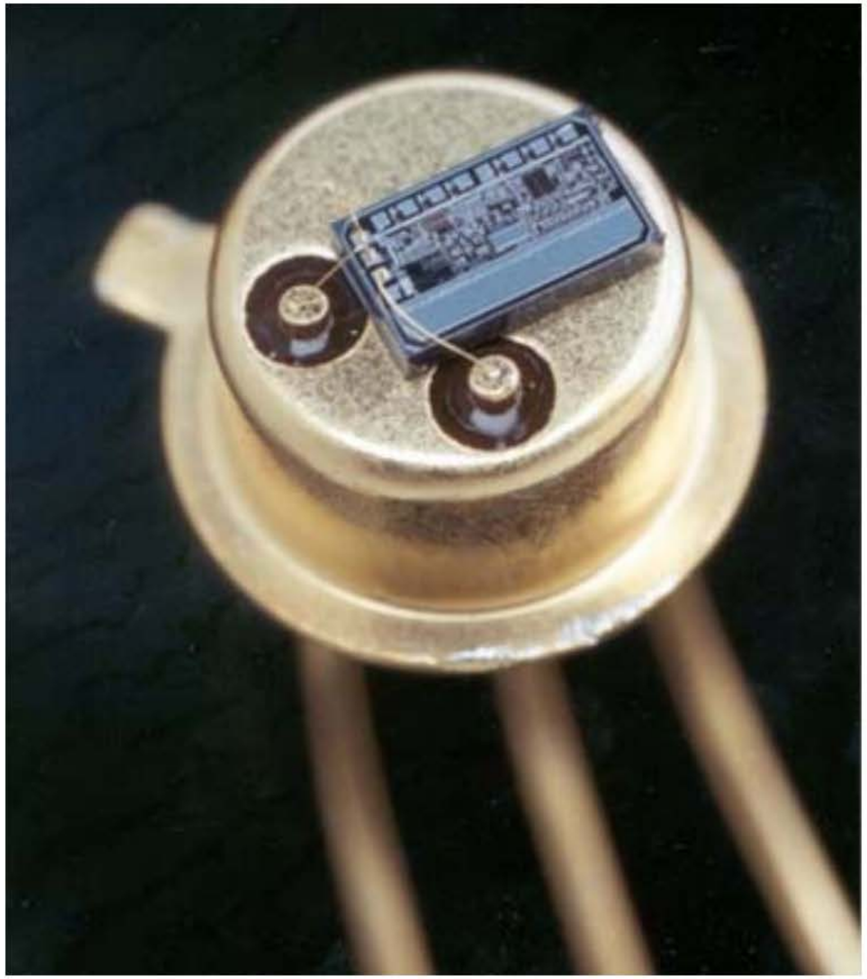
On-chip thermopiles measure temperature gradient

K. Makinwa et al., ISSCC ‘02

Smart Temperature Sensors

- Transistors are natural temperature sensors
- But manufacturing tolerances cause errors of up to 3°C

?



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BJT Characteristics: V_{BE}

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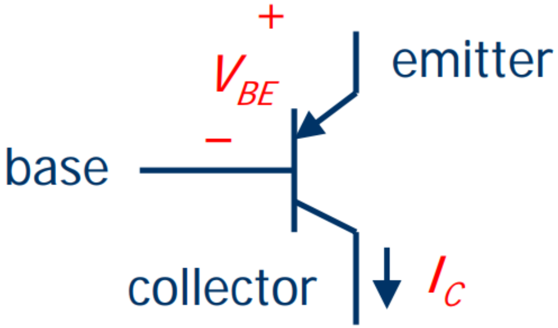
- For $I_C >> I_S$

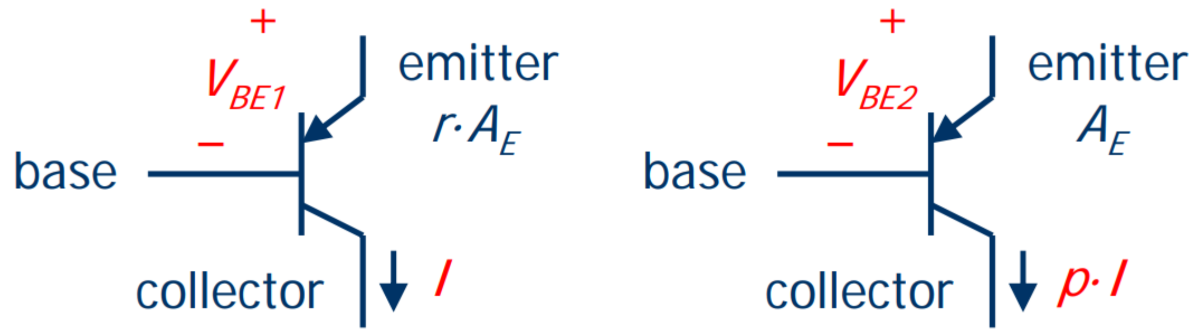


$$I_C \approx I_S \exp\left(\frac{qV_{BE}}{kT}\right)$$

$$\Rightarrow \quad V_{BE} = \frac{kT}{q} \ln \frac{I_C}{I_S}$$

- V_{BE} is a near-linear function of temperature
- With a **negative** temperature coefficient: ~ –2mV/°C
- But it is **process dependent** (via I_S and I_C)

BJT Characteristics: ΔV_{BE}



- By biasing two transistors at a fixed collector current ratio *p*, we can eliminate the process dependence:

$$\Delta V_{BE} = V_{BE2} - V_{BE1} = \frac{kT}{q} \ln(p \cdot r)$$

- ΔV_{BE} is a linear function of temperature
- With a **positive** tempco: ~ 180µV/°C (for $p \cdot r = 10$)

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A practical Bandgap temperature sensor

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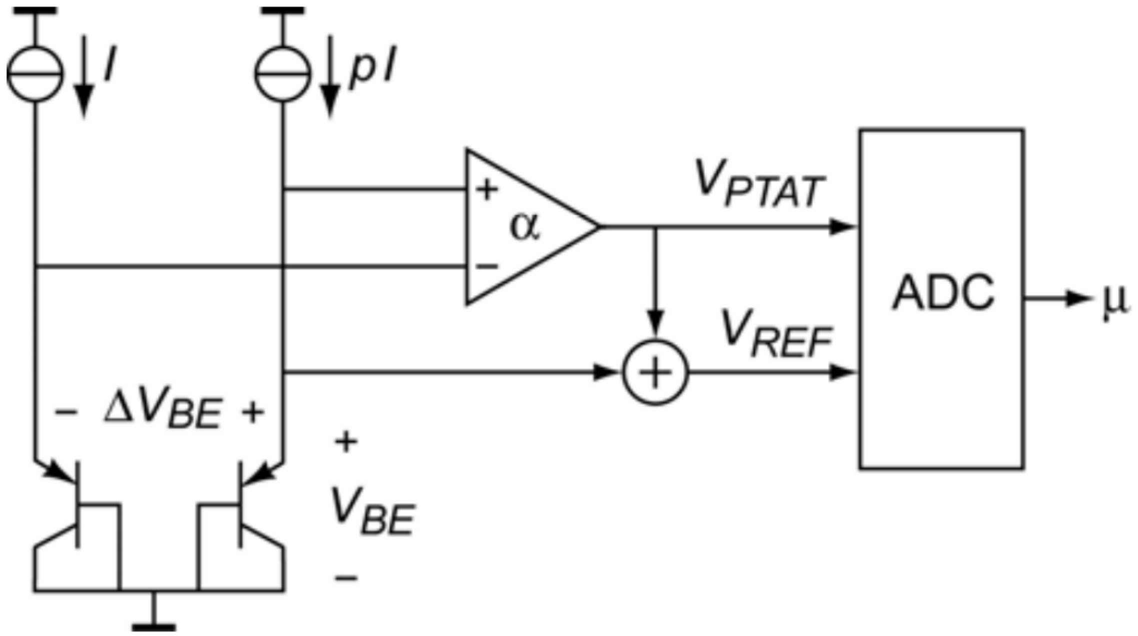
El. Instr.



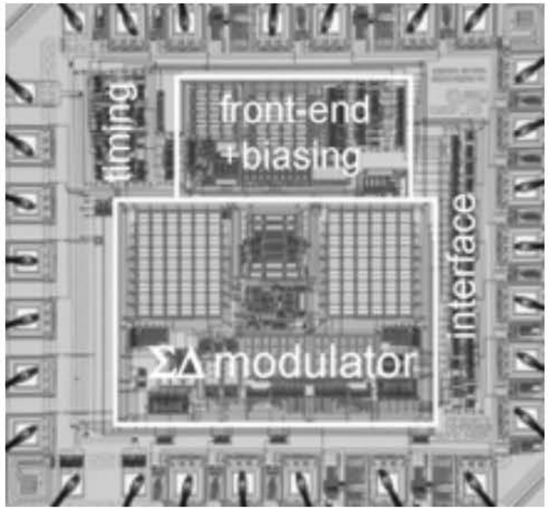
Current mirror ratio *p*, emitter area ratio *r* and amplifier gain α generate

$$V_{PTAT} = \alpha \frac{kT}{q} \ln(p \cdot r)$$

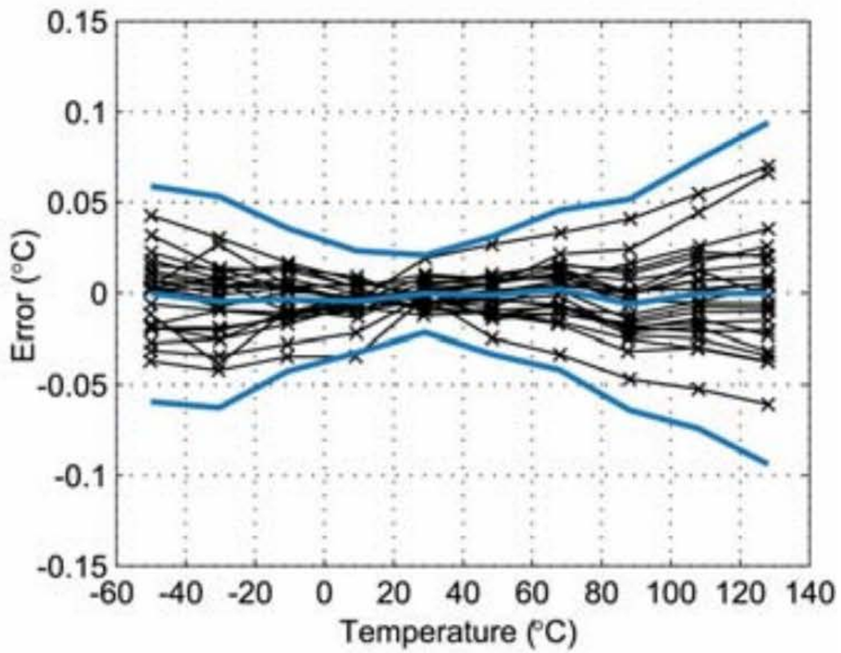
Current source I_{bias} generates V_{BE}
ADC then computes the ratio:

$$\mu = \frac{\alpha \cdot \Delta V_{BE}}{V_{BE} + \alpha \cdot \Delta V_{BE}} = \frac{V_{PTAT}}{V_{REF}}$$

State-of-the-Art



Pertijs et al., JSSC, Dec. ‘05



- CMOS ⇒ substrate PNPs
- I_S spread? ⇒ one room temperature trim
- Inaccuracy < ±0.1°C (3σ) from –55 to125°C