Electronic Instrumentation

Lecturer: Kofi Makinwa

K.A.A.Makinwa@TUDelft.NL

015-27 86466
Room. HB13.270 EWI building

Also involved:
Saleh Heidary
(S.H.Shalmany@TUDelft.NL)

Content and Schedule

Monday Sept. 16:	Transduction of information (Chapter 2) - Sensitivity and cross-sensitivities - Resistive transducers - Capacitive transducers
Wednesday Sept. 18:	Submit Assignment 1 Detection limit due to offset

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What Is A Sensor?

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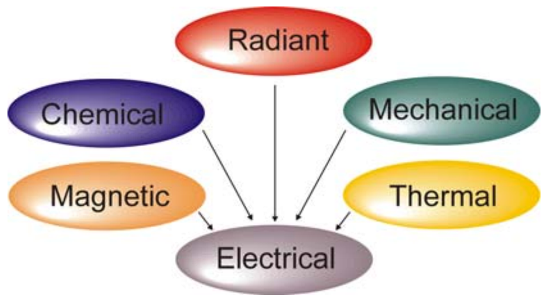

- A device that converts information from one energy domain into the **electrical** domain
- Where it can be easily (digitally) processed and stored

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The World Is Analog

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

Transduction

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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

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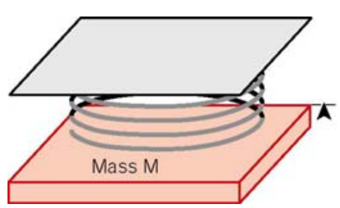
Transduction matrix:

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



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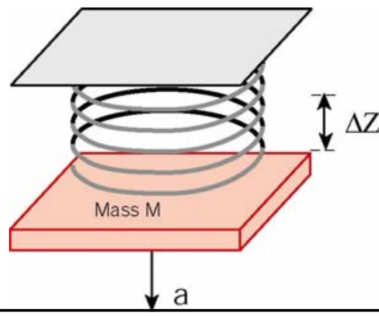

Acceleration to displ. = Transduction from mechanical to mechanical

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Transduction

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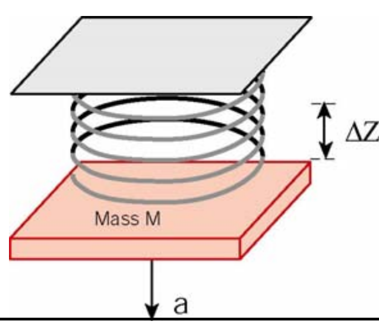
Transduction matrix (red text ⇒ non-zero coefs):

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



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Transduction

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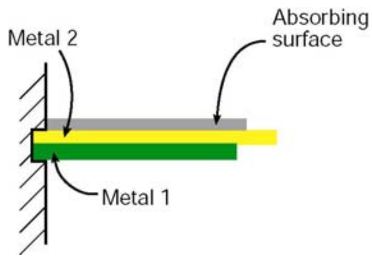

Transduction

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Transduction matrix:

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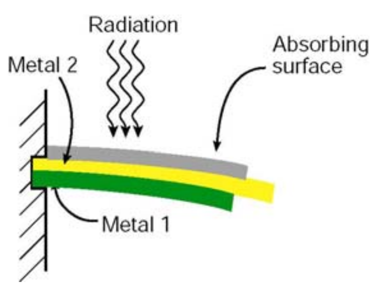

Transduction in two steps:
1. from optical to thermal, followed by
2. thermal to mechanical

= tandem transducer

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Transduction

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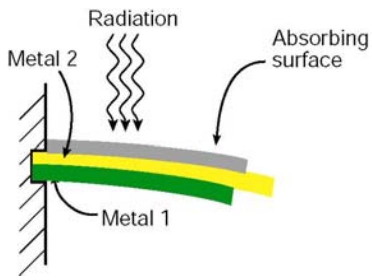
Tandem transduction:



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

= tandem transducer

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

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Transduction

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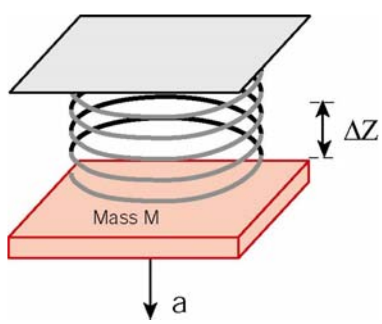
Tandem transduction requires an intermediate *non-electrical* domain:



So:

1. Acceleration to displacement (within mechanical domain),

followed by
2. displacement to capacitance (to the electrical domain)

⇒ not a tandem transducer

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Transduction

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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

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Transduction

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Transduction to the electrical domain:

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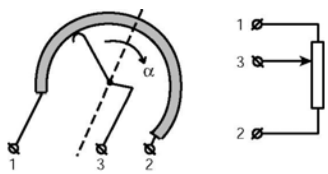
Two types of sensors:

- Self generating sensors
- Modulating sensors

Transduction

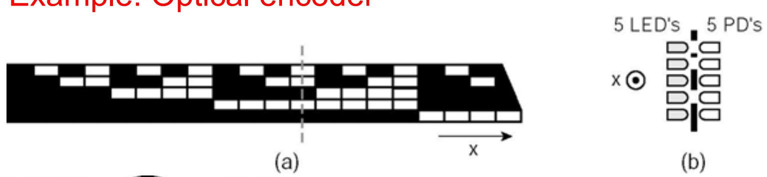
Self-generating sensors:
Example: Potentiometer

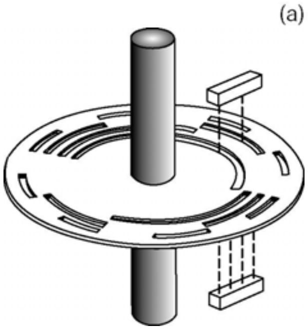


+ No additional sources of uncertainty
+ No external power supply
- Draws all its energy from the measurand (mechanical source loading)

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)

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Resistive sensors

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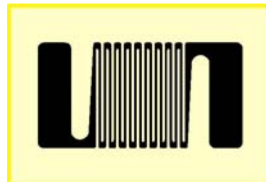
Force sensors using strain gauges

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:

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

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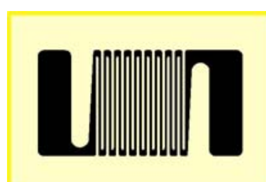
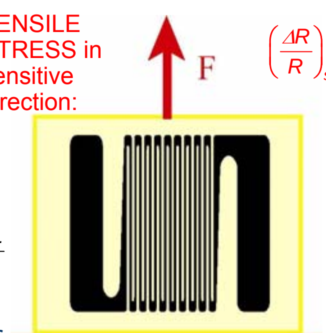


In case of strain (deformation) due to mechanical stress:

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

When assuming constant volume:

TENSILE STRESS in sensitive direction:



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

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

k= gauge factor

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Resistive sensors

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Force sensors using strain gauges

Resistance value is defined by specific resistivity and dimensions:

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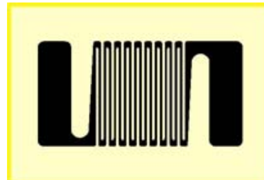

In case of strain (deformation) due to mechanical stress:

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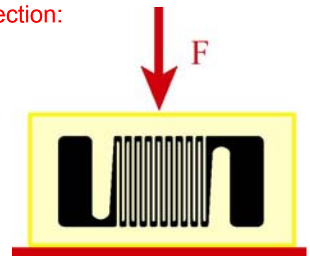
When assuming constant volume:

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

k= gauge factor

COMPRESSIVE STRESS in sensitive direction:

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



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Resistive sensors

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Force sensors using strain gauges

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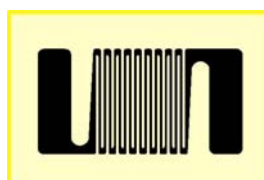

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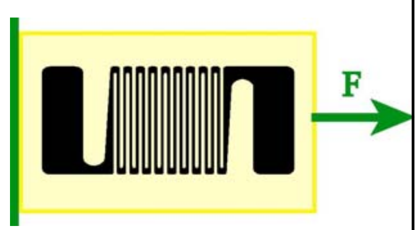
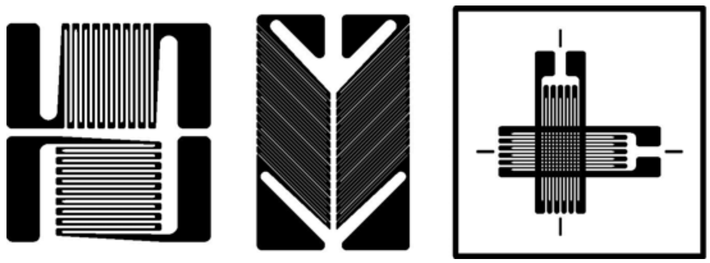
Applying load in insensitive direction:



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

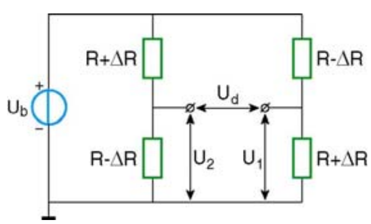
Resistive sensors

Measuring force in two dimensions



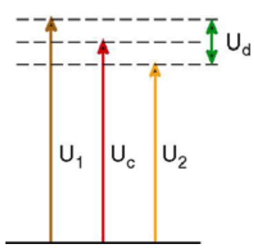
The Wheatstone bridge

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:

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

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Bridge configurations

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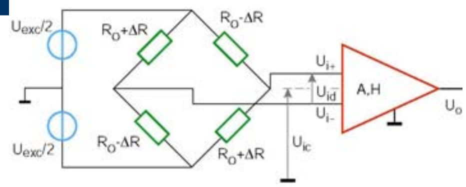
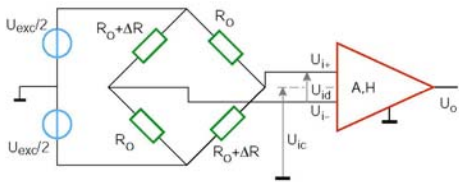
Full bridge



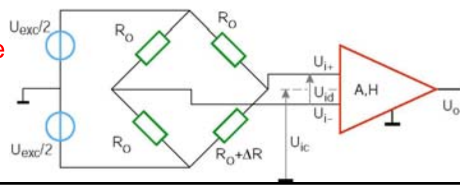
- Linear
- All elements on structure
- Increasing AND decreasing with measurand

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.

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Capacitive sensor readout

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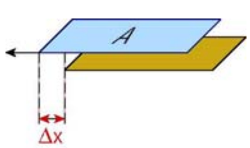
Very suitable for displacement measurements

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

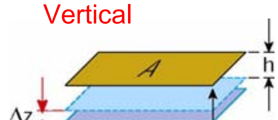
Lateral



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

Linear

Vertical



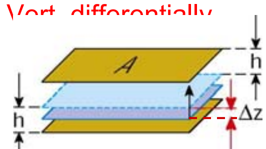
$$C = \varepsilon_o \frac{A}{h + \Delta z}$$

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

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

Non-linear

Vert. differentially



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

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

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

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

Non-linearity reduced by differential measurement

MEMS Microphone

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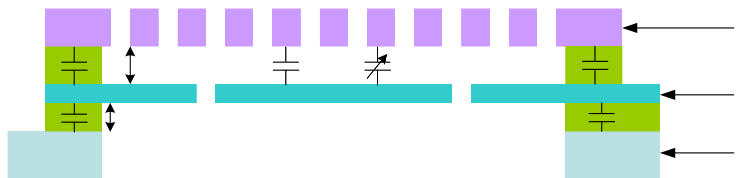
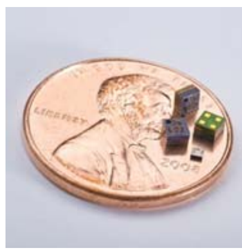
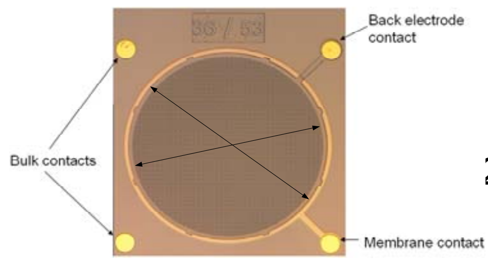
El. Instr.



- 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

2um

Cmic

hbox=500nm

Capacitive sensor readout

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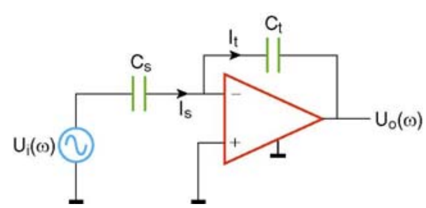
The charge amplifier (1)

For an “ideal” opamp:

(a) $U_- = U_+ = 0$
(b) $I_s(\omega) = j\omega C_s \cdot U_i(\omega)$
(c2) $I_t(\omega) = -j\omega C_t \cdot U_o(\omega)$, 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 ($U_o \propto 1/(1/d) = d$) .

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

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Capacitive sensor readout

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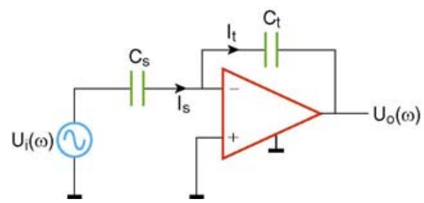
The charge amplifier (2)

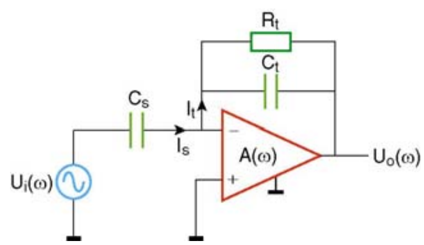
For an “ideal” opamp:

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



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

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



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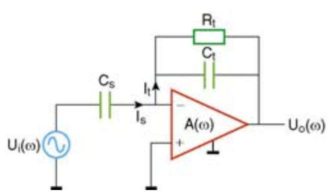
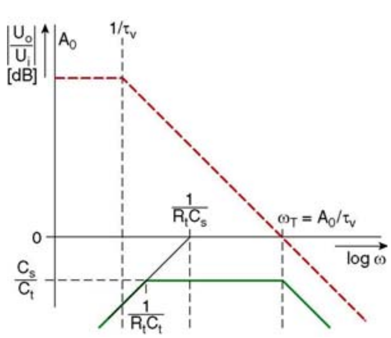
Modulus transfer of the charge amplifier



$$\frac{U_o}{U_i} = \frac{-j\omega R_t C_s}{\left(1 + j\omega\frac{\tau_v}{A_o}\right)(1 + j\omega R_t C_t)}$$



For sensor readout the charge amplifier typically attenuates the excitation voltage U_i ($C_s \ll C_t$).

Features:
1. Can be used for excitation voltage frequencies up to ω_T.

2. U_- is virtual ground and can be used for adding currents in a differential sensor structure.

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Capacitive sensor readout

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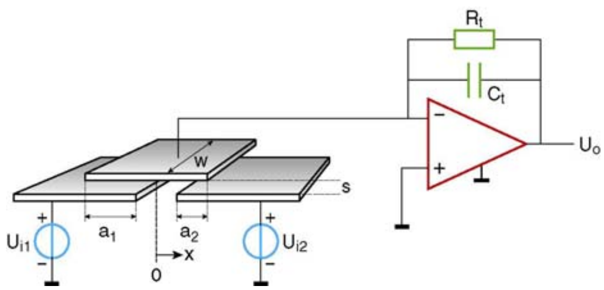
Application in differential sensor readout



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

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Piezo-electric force sensors

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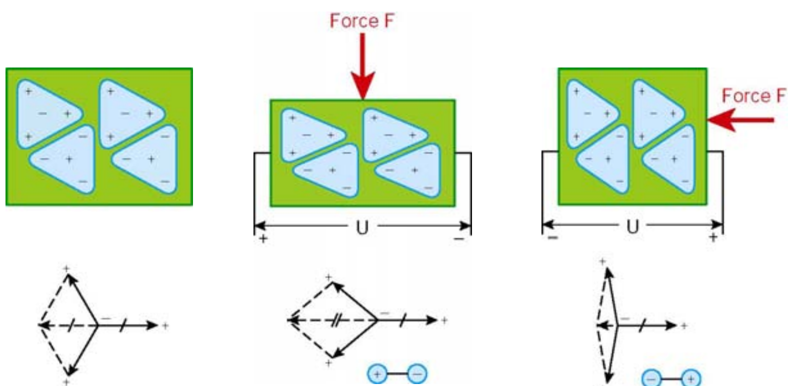
Piezo-electricity



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.

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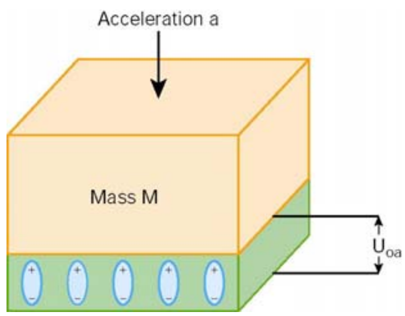
Piezo-electric force sensors

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

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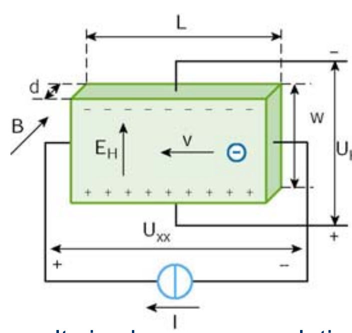
Magnetic field sensor using the Hall Effect

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.

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Magnetic field sensor using the Hall Effect

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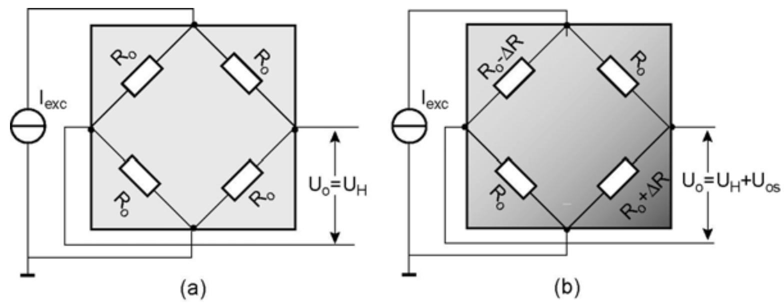
Stress in the conductive layer results in offset.



Wheatstone bridge not balanced at B= 0 T.

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The spinning current technique

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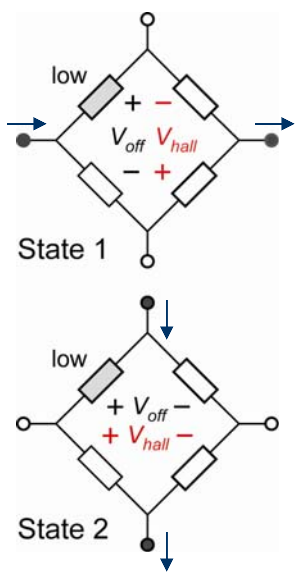

- Changing the **direction** of the bias current changes the **relative** polarity of V_{off} & V_{hall}
- So **averaging** the bridge output cancels V_{off}!

In practice

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

⇒ 3 current directions needed for optimal offset cancellation!

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Spinning-Current Hall Plate

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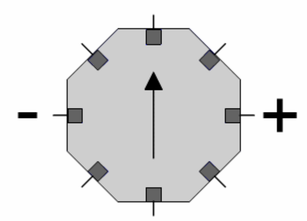

- 3 current directions
  ⇒ Octagonal Hall plate
- Bias current rotated, while Hall voltages are summed
- Cancels offset due to **static** bridge mismatch

⇒ 10 - 100μT offset

Earth's magnetic field ~ 50μT

So electronic compass applications are possible …

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Smart Hall Sensor

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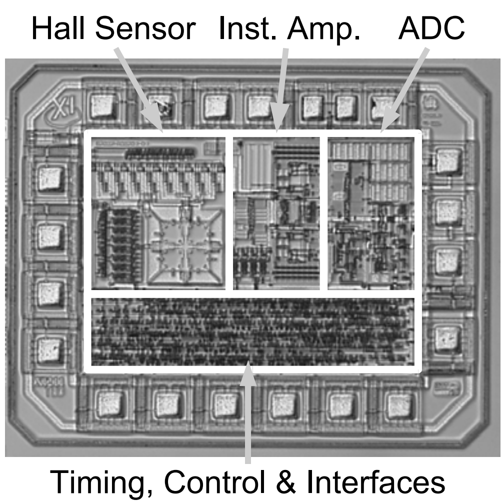
El. Instr.



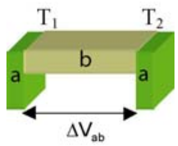
- Standard 0.5μm CMOS
- Spinning current technique + low-offset amplifier
  ⇒ 4μT offset
- State-of-the-art!

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

Temperature sensors

ET8.017
El. Instr.

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).

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

Temperature sensors

ET8.017
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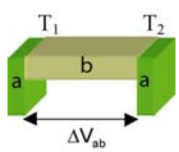
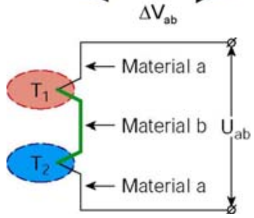


Practical use of the Seebeck effect:
a thermocouple with two different materials
and a temperature difference



$$U_{ab} = \left[\alpha_{a,T1} \cdot T_1 - \alpha_{b,T1} \cdot T_1\right] + \left[\alpha_{b,T2} \cdot T_2 - \alpha_{a,T2} \cdot T_2\right] \approx (\alpha_a - \alpha_b)(T_1 - T_2) = \alpha_{ab}(T_1 - T_2)$$

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.

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Temperature sensors

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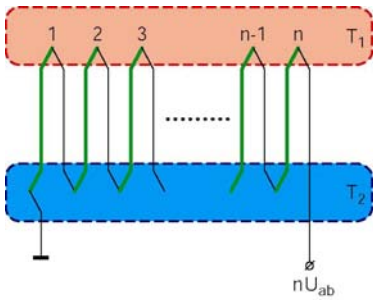
Problem: readout circuit has offset

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.

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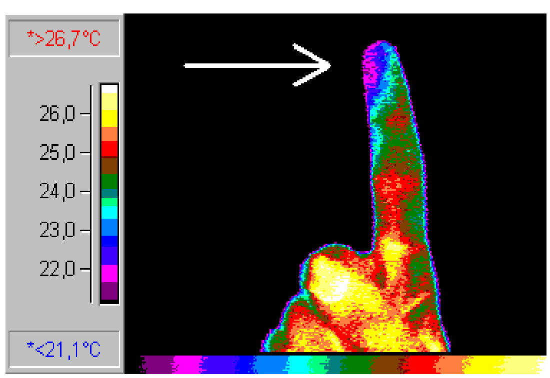
A Smart Wind Sensor!

ET8.017
El. Instr.



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

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Thermal Wind Sensor

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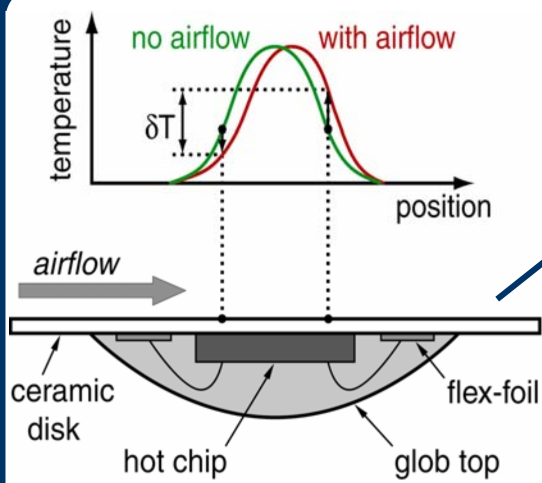
El. Instr.



On-chip thermopiles measure temperature gradient

K. Makinwa et al., ISSCC ‘02

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Smart Temperature Sensors

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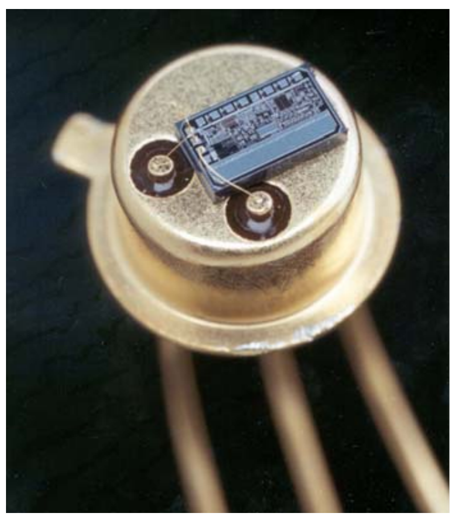
- Transistors are natural temperature sensors
- But manufacturing tolerances cause errors of up to 3°C

?



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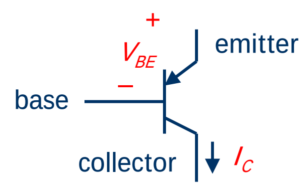
BJT Characteristics: V_{BE}

ET8.017 El. Instr.

- 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)

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BJT Characteristics: ΔV_{BE}

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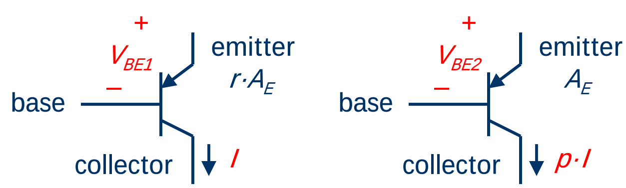

- By biasing two transistors at a fixed collector current ratio p, we can eliminate the process dependence:

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

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

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Operating Principles (1)

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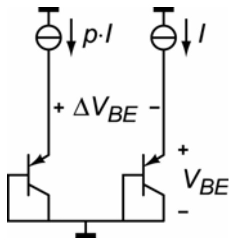

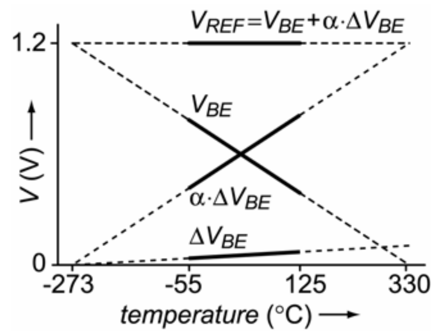

- Two bipolar transistors can generate:
  ΔV_{BE} proportional to absolute temperature (PTAT)
  V_{BE} complementary to absolute temperature (CTAT)

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Operating Principles (2)

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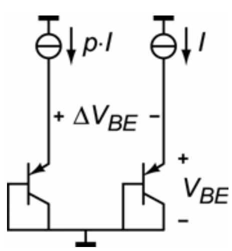
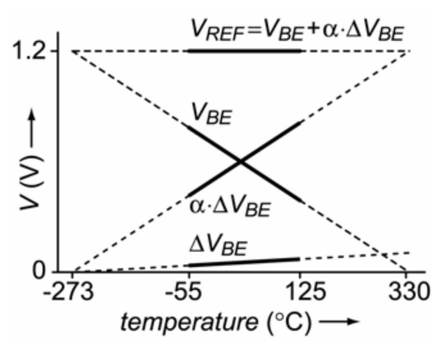
El. Instr.

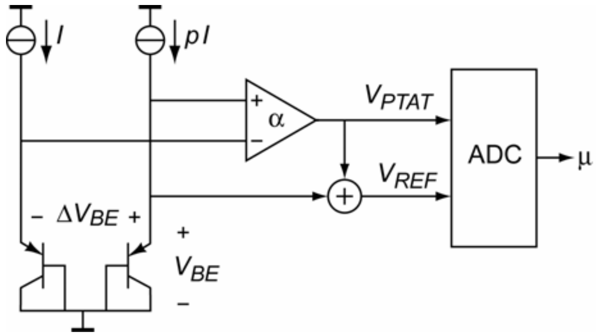




- These voltages can be combined to give:
  V_{REF} temperature independent (band-gap) voltage
  $\alpha \cdot \Delta V_{BE}$ temperature dependent voltage
- Their ratio is a measure of temp: $$\mu = \frac{\alpha \cdot \Delta V_{BE}}{V_{BE} + \alpha \cdot \Delta V_{BE}}$$

A practical Bandgap temperature sensor

ET8.017
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

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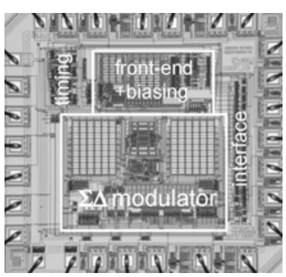
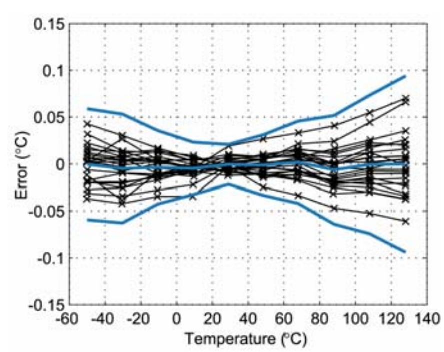


Pertijs et al., JSSC, Dec. ‘05



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

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Assignment 2a

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

- The accuracy of a bandgap temp sensor will be limited by the offset and gain error of the "α" amplifier
- Assuming p=1, r=16 and α = 8, what offset corresponds to 0.1°C error?
- Similarly what gain error corresponds to an error of less than 0.1°C over the military range -55°C to 125°C?
- Assume that the tempco of V_{BE} = -2mV/°C and that ideally, V_{REF} = 1.2V
- Please submit this before the class on Wed. 19 Sept.

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Assignment 2b

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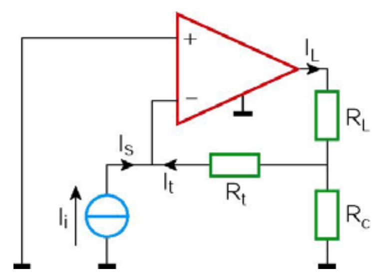
El. Instr.



- Derive an expression for the transfer function I_L/I_i of the circuit shown above.
- Assuming the opamp suffers from offset and bias current, calculate the corresponding detection limit
- Please submit this before the class on Wed. 19 Sept.