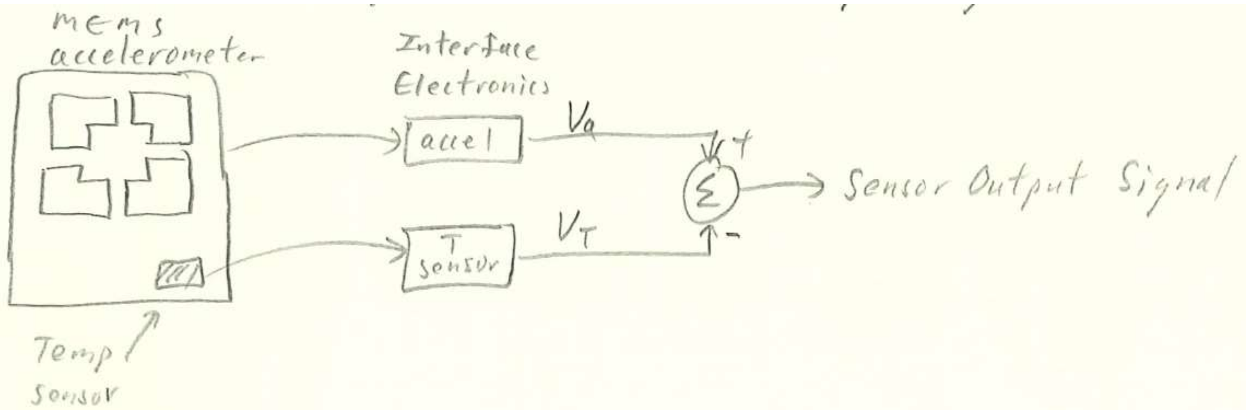
Lecture 11/16/22

Temperature Sensors

1) Background

Many microdevices (MEMS and electronics) are highly sensitive to temperature (internal and external).

Therefore, it is often desirable to measure temperature and compensate for the effects of temperature change on an output signal.



However, this approach requires knowledge of how the sensor's output varies with temperature.

2) Types of temperature sensors

a. Temperature dependent resistors

We discussed these earlier in the semester:

$\rho(T) = \rho_o(1 + \alpha_T T + \beta_T T^2) \approx \rho_o(1 + \alpha_T T)$ → for metals

ρ_o → resistivity at a reference temperature, T_o.

Example: for some $\rho_o \rightarrow R_o = 100\ \Omega$ at 0°C

$\alpha_T \rightarrow$ linear temperature coefficient of resistivity.

Example: platinum: $\alpha_T = 3.9\text{x}10^{-4}$ /°C

Platinum 100 (Pt100): a commonly used temperature measurement resistor (100 Ω at 0°C).

However, platinum is not a commonly used microfabrication material.

b. Thermistors

The thermoresistive characteristics of semiconductor materials often have the following relationship:

$$\rho(T) = \rho_{ref} e^{\left[B\left(1/_T - 1/_{T_{ref}}\right)\right]}$$

T_{ref} is often 25°C. However, the T and T_{ref} values in the equation are usually in the units of Kelvin.

B is the "B value", and is defined as $B_{T1/T2}$ where T1 and T2 define the temperature range over which the equation with this B value is valid. For example, $B_{25/100}$ defines a thermistor that is defined for temperatures between 25°C and 100°C. Typical B values might be between 3000 and 5000 over this temperature range.

ρ(T) has a large change over a small temperature range, but the effect is nonlinear.

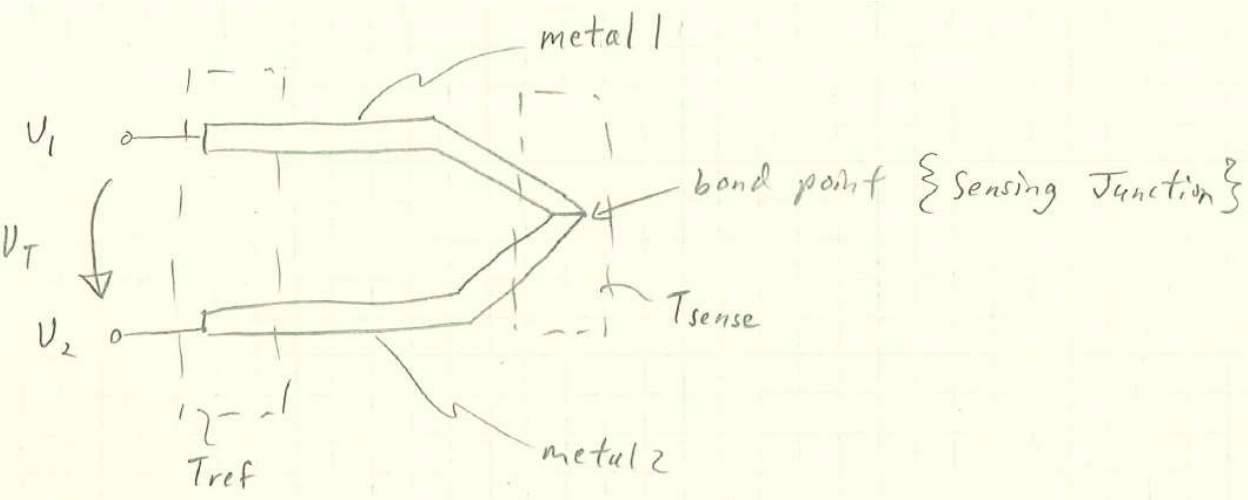
Thermistors can be very low cost and can be made out of semiconductor-based metal oxides. They are often used in electronic medical thermometers (very small temperature range).

A variety of common metal oxides are actually semiconductors. Examples:

Zinc oxide (ZnO) – used in sunscreen
Titanium dioxide (TiO2) – used as white food coloring
Indium tin oxide (ITO) – transparent conductor

c. Thermocouples (thermopiles)

We already discussed thermocouples earlier in the semester (9/26/22). They are based on the Seebeck effect with two dissimilar metals bonded at a sensing junction:



T_{sense} is the temperature being sensed, and T_{ref} is a reference temperature.

V_T is the open circuit voltage appearing on the left end.

$$V_T = V_2 - V_1 = (P_2 - P_1)\left(T_{sense} - T_{ref}\right) = (P_2 - P_1)\Delta T$$

P_1 and P_2 are the Seebeck coefficients for the two metals. This is a thermocouple.

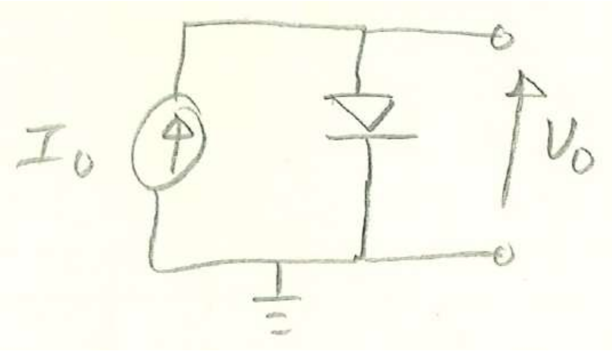
The theromocouple only produces a small current before the output voltage drops: it has a large output impedance. So, a high (very high) impedance voltage meter (amplifier) is needed to accurately read it.

Thermocouples can be made in macroscale or in microscale (on chip) technologies.

d. Thermodiodes and thermotransistors

(1) Thermodiode temperature sensing

Consider this thermodiode circuit:



$$I_o = I_s\left[e^{\lambda q V_o/k_B T} - 1\right]$$

Or: $V_o = \frac{k_B T}{q} ln\left(\frac{I_o}{I_s} - 1\right)$, for $\lambda = 1$

$\frac{k_B T}{q} = V_T$ is the thermal voltage

k_B is the Boltzmann's constant ($1.38\text{x}10^{-23}$ J/K)

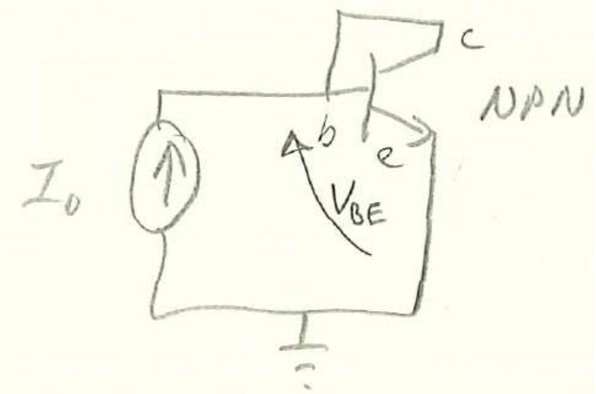
q is electronic charge ($1.60\text{x}10^{-19}$ C)

I_s is the diode reverse saturation current

For this circuit, set I_o to a constant current and then measure V_o to determine temperature.

(2) Thermotransistor temperature sensing

Consider this thermotransistor circuit:



$$V_{BE} = V_T ln\left(\frac{I_c}{I_{co}}\right)$$

$I_{co} = A_E J_S$ → saturation current (I_S)

A_E → emitter junction area

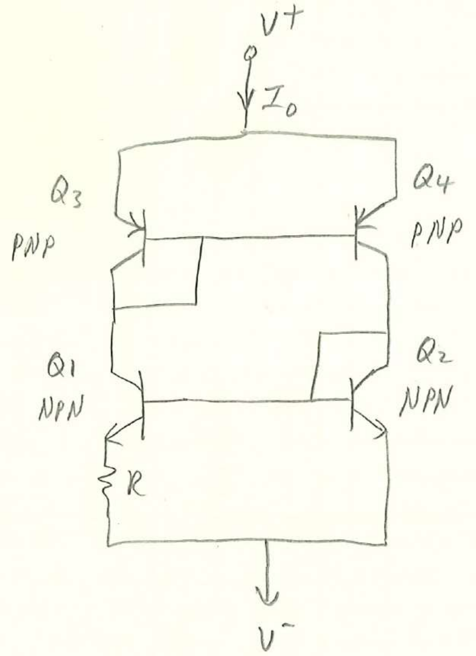
J_S → saturation current density

$\frac{k_B T}{q} = V_T$ → the thermal voltage, as before

However, the emitter junction area (A_E) can vary over the process tolerance range. Therefore, a better thermotransistor temperature measurement circuit is typically used.

(3) PTAT temperature measurement sensor

PTAT stands for “Proportional to Absolute Temperature.” It is a better thermotransistor circuit for measuring temperature:



$$I_o \approx \frac{2k_BT}{qR} ln\left(\frac{A_{E2}}{A_{E1}}\right)$$

Notice that the current is a function of the ratio of two emitter junction areas, which should track equally over the fabrication tolerance range. Therefore, error due to fabrication tolerances is largely eliminated.

Therefore, PTAT circuits are commonly used to measure temperature on microdevices.

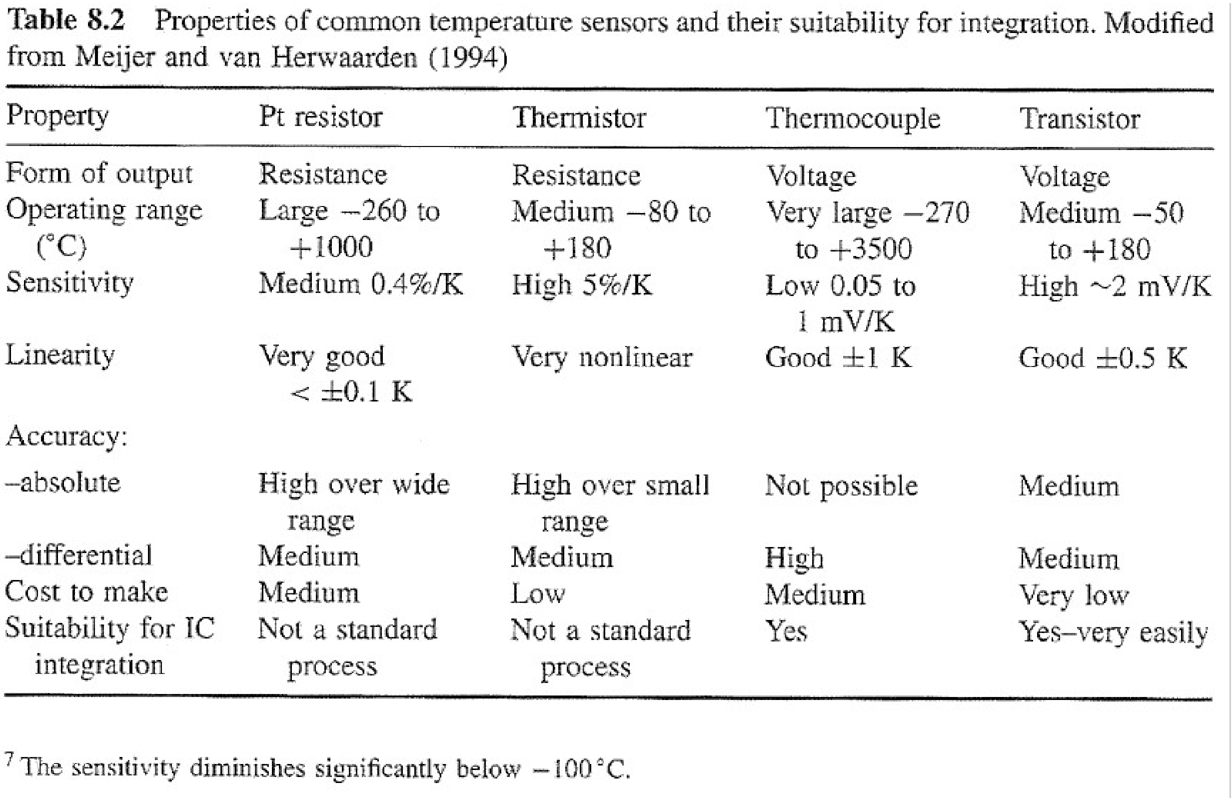


Table 8.2 Properties of common temperature sensors and their suitability for integration. Modified from Meijer and van Herwaarden (1994)

Property	Pt resistor	Thermistor	Thermocouple	Transistor
Form of output	Resistance	Resistance	Voltage	Voltage
Operating range (°C)	Large −260 to +1000	Medium −80 to +180	Very large −270 to +3500	Medium −50 to +180
Sensitivity	Medium 0.4%/K	High 5%/K	Low 0.05 to 1 mV/K	High ~2 mV/K
Linearity	Very good < ±0.1 K	Very nonlinear	Good ±1 K	Good ±0.5 K
Accuracy:				
–absolute	High over wide range	High over small range	Not possible	Medium
–differential	Medium	Medium	High	Medium
Cost to make	Medium	Low	Medium	Very low
Suitability for IC integration	Not a standard process	Not a standard process	Yes	Yes–very easily

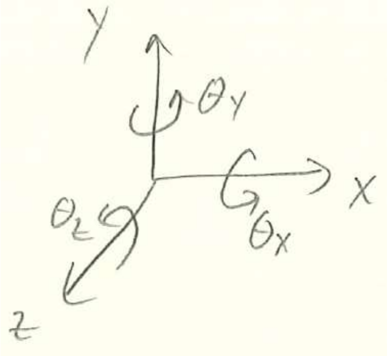
[7] The sensitivity diminishes significantly below −100 °C.

Chemical Sensors (Introduction)

1) The difficulty of chemical sensing

a. Consider inertial motion sensing

3 axes: 6 things to measure: 3 orthogonal translational accelerations and 3 orthogonal angular rates:



MEMS accelerometers → usually not affected by rotation.

MEMS gyroscopes → can be affected by large translational accelerations: can possibly use the accelerometers to compensate for this.

Temperature sensitivities → use an integrated temperature sensor (such as the PTAT) to compensate.

Drift errors over time → use a fixed reference to compensate (direction of gravity, earth's magnetic field, GPS, etc.).

Seal the unit in a hermetic package to isolate it from moisture, dust, etc. in the operating environment.

There are not many other possible environmental parameters that affect these sensors.

b. Consider a CO detector in your home

The atmospheric chemistry approximately consists of: 78% N_2, 21% O_2, 0.9% Ar, ~1% H_2O vapor, 0.03% CO_2, 0.018% Ne. 0.005% He, …

A quality CO sensor needs to not only respond to CO with high sensitivity, but to also be insensitive to all other gases present.

The sensor also needs to be insensitive to temperature, dust, vibration, light, biologicals, air pressure, liquids, etc. In other words, compared to inertial sensors, it requires substantially greater exposure to the environment, and therefore it must be much more highly selective in what it is sensitive to. This characteristic greatly complicates the realization of quality chemical sensors.