Temperature Sensors

1) Background

Many micro devices (MEMS & electronics) are highly dependent on temperature (external/internal)

- desirable to measure temperature and compensate for the effect of temperature in the output signal

\[ R(T) = R_0 \left( 1 + \alpha_T T + \beta T^2 \right) \]

\[ \approx R_0 \left( 1 + \alpha_T T \right) \]

\( R_0 = \) resistance at \( T_0 \)

ex: \( R_0 = 100 \Omega \) at \( 0^\circ C \)

\( \alpha_T = \) linear temperature coefficient of resistivity

ex: platinum: \( \alpha_T = 3.9 \times 10^{-4} / ^\circ C \)

Platinum-100: a commonly used temperature measurement resistor

However: Platinum is not a commonly used microfabrication material
b. Thermistors

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

\[ p(T) = \text{Pre} \times B \left( \frac{1}{T} - \frac{1}{T_{\text{ref}}} \right) \]

- \( T_{\text{ref}} \) is often 25°C
- \( p(T) \) has a large change over a small temperature range
- can be low cost
- often used in electronic medical thermometers over small temp. range

c. Thermocouples or Thermopiles

Metals possess a coefficient called the Seebeck coefficient, \( P \).

For 2 dissimilar metals, \( A \) and \( B \), \( P_A \neq P_B \).

Take 2 dissimilar metals and bond them at 1 point, where we want to measure the temperature. The other ends will be at a reference temperature, \( T_{\text{ref}} \):

\[ U_T = U_1 - U_2 = (P_1 - P_2)(T_{\text{sense}} - T_{\text{ref}}) = (P_1 - P_2) \Delta T \]
Thermocouples have a high output impedance. 

Model:

\[
\begin{align*}
U_T & \rightarrow V_0 \\
& \rightarrow R_{\text{load}}
\end{align*}
\]

For \( R_{\text{load}} \) large: \( V_0 \approx U_T \)

For \( R_{\text{load}} \) small (\( R_{\text{load}} \gg R_{\text{room}} \)): \( V_0 \approx 0 \)

Thermocouples need an interface circuit with a very large input impedance.

d. Thermodiodes and Thermo-transistors

Thermodiode circuit:

\[
I_0 = I_s \left[ e^{\frac{(k_B T \cdot V_0)}{k_B}} - 1 \right]
\]

or \( V_0 = \frac{k_B T}{q} \ln \left( \frac{I_0}{I_s} \right) - 1 \) for \( \lambda = 1 \)

\( \frac{k_B T}{q} \) = thermal voltage

\( k_B \) = Boltzmann's constant = \( 1.38 \times 10^{-23} \) J/K

\( q \) = electronic charge = \( 1.60 \times 10^{-19} \) C

\( I_s \) = diode reverse saturation current

Set \( I_0 = \text{constant} \), measure \( V_0 \) to determine temperature.
simple thermistor circuit

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

\[ I_{co} = A_e J_s = \text{saturation current} \]

\[ A_e = \text{emitter junction area} \]

\[ J_s = \text{saturation current density} \]

\[ V_T = \frac{k_B T}{q} \text{ as before} \]

0 A better thermistor circuit: PTAT (Proportional To Absolute Temperature)

\[ I_o \approx \frac{2 K_R T}{q R} \ln \left( \frac{A_{e2}}{A_{e1}} \right) \]

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)

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

7 The sensitivity diminishes significantly below −100 °C.