Lecture 8: Thermal Sensors & Actuators

Thermal Sensors and Actuators Overview

- Example of Heat Rise Time in a Polysilicon Beam
- Thermal Expansion of Micro-devices
- Thermal Bimorph Principle
- Thermal Actuators
- Thermal Resistors
Example of Heat Flow in a Polysilicon Beam:

Consider the doped polysilicon beam, as shown below:

- Parameters Given:
  - Applied voltage, $V$: 0.5 V
  - Electric resistivity, $\rho$: 23 $\Omega$ um
  - Temp of Air, $T_\infty$: 21°C
  - Temp of Substrate, $T_\infty$: 21°C
  - Beam length, $L$: 100 um
  - Beam width, $b_w$: 4 um
  - Beam height, $b_h$: 4 um
  - Gap: 4 um

Questions:

(a) What is the thermal time constant, $\tau$, for the beam?

(b) What is the final steady state temperature, $T$, of the beam?

(c) How long will it take to heat the beam to 95% of its S.S. temp?
Example of Heat Flow in a Polysilicon Beam:

- **Step 1:** Find the heat input

- **Step 2:** Determine thermal capacitance, $C_{TH}$.

- **Step 3:** Determine thermal resistance, $R_{TH}$.
  
  Consider the possible heat flows, $q_1$, $q_2$, etc... out of the beam:
Example of Heat Flow in a Polysilicon Beam:

Step 3 (continued): Model system as a ‘thermal circuit’:

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Example of Heat Flow in a Polysilicon Beam:

Step 4: Having defined the system parameters, such as: heat input, $C_{TH}$ and $R_{TH}$ answer the problem questions:

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Nearly all materials undergo a change in volume or dimensions as their temperature changes.

For solids such as semiconductors, metals and dielectric materials, their volume increases as the temperature increases, as follows:

\[ \alpha = \frac{\Delta V}{V \Delta T} \]

where: \( \alpha = \) volumetric thermal expansion coefficient  
\( \Delta V = \) change in volume  
\( V = \) total volume  
\( \Delta T = \) change in temperature

Alternatively, we can define:

\[ \beta = \frac{\Delta L}{L \Delta T} \]

where: \( \beta = \) linear thermal expansion coefficient  
\( \Delta L = \) change in length along on dimension  
\( L = \) total length of that same dimension

Note the relation that exists between the two:

\[ \alpha = 3\beta \]

Note: Tables 5.2 and 5.3 in the textbook have common values listed for \( \beta \), for a number of common MEMS materials.
Liquids and gases typically have much greater thermal expansion, where:

\[ \alpha \text{ for water } = 400 \text{ ppm/K} \]

**note:** unit ppm → parts per million

For gases, we can use the ideal gas law:

\[ PV = nRT \]

where: 
- \( P \) = Pressure (absolute Pa)
- \( V \) = Volume (m³)
- \( n \) = # of moles
- \( R \) = 8,3145 \( \text{Joules/mol} \cdot \text{K} \)
- \( T \) = Temperature (absolute K)

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**Thermal Bi-morph Principle**

Two different materials, with different coefficients of thermal expansion, are joined together in such a way, that a temperature change will cause the entire structure to deform in a desired way.

Consider the following:

Fig. 5.3 Thermal Bimetalic bending, [Chang Liu]
The radius of curvature of the deformed structure can be expressed as (in terms of the variables of previous diagram):

\[
\frac{1}{r} = \frac{6w_1w_2E_1E_2t_1t_2(t_1 + t_2)(\alpha_1 - \alpha_2)\Delta T}{(w_1E_1t_1^2)^2 + (w_2E_2t_2^2)^2 + 2w_1w_2E_1E_2t_1t_2(2t_1^2 + 3t_1t_2 + 2t_2^2)}
\]

To find a value for deflection, consider the arc-angle \( \theta \):

\[
\delta = r - r\cos\theta \approx \frac{1}{2}r\theta^2
\]

Example Displacement of Bimorph Actuator

See Class Notes:
Thermal Actuators

Operate based on Ohmic heating of different cross-sectional areas.

We will attempt to estimate the deflection of this device, based on the following assumptions:

- Cold arm remains straight
- Hot arm will bend in an ‘arc’ shape
- Connection of cold arm and hot arm considered as a point

Deflection Estimation:

- δ-deflection
- ‘Arc’ is length of hot arm
- r-radius of curvature
- θ
Thermal Actuators

Deflection Estimation:

Some useful circle formulas:
\[ \theta = \frac{\text{arc length}}{r} \]
\[ r = h + d_o \]
\[ c = 2r \sin \left( \frac{1}{2} \theta \right) \]
\[ d_o = r \cos \left( \frac{1}{2} \theta \right) \]

For thermal actuators, we can assume:
\[ L_h \text{ (hot arm length)} = \text{arc length} = L(1 + \alpha \Delta T) \]
\[ L_c + L_f \text{ (cold arm + flexure length)} = \text{chord length} c \]

Therefore, based on this information, we can determine both, \( r \) and \( \theta \).

Then, we can use \( r \) and \( \theta \) to determine the tip deflection using:
\[ \delta = r - r \cos \theta = \frac{1}{2} r \theta^2 \]
Thermal Resistors

A thermal resistor is an electrical resistor with significant temperature sensitivity.

The resistance of a thermal resistor is defined as:

\[ R_T = R_o \left( 1 + \alpha_R (T - T_o) \right) \]

where: \( R_T \) = Electrical resistance at temperature \( T \)
\( R_o \) = Electrical resistance at temperature \( T_o \) (initial)
\( \alpha_R \) = Temperature coefficient of resistance (TCR)

A **Thermistor** is a semiconductor thermal resistor.

Example of Thermistor

Consider the following doped polysilicon beam:

If the TCR of the doped material is 200 ppm/°C, and the nominal (un-heated) resistance \( R_o \) is 1000 Ω, what is the resistance if the temperature increases by 300°C?

\[ R_T = 1000 \Omega \left( 1 + 0.0002 \cdot (300) \right) \]
\[ R_T = 1060 \Omega \]
Thermal Resistors

Note: When measuring resistance, care must be taken so as not to create a significant current $i$, during measurement.

Otherwise, a large current could cause further ohmic heating, and invalidate the measurement.

Case Study: Thermal Accelerometer
(with no moving mass)

It is possible to create an accelerometer, with no moving structures at all, using thermal phenomena.

Figure 5.13. Thermal Accelerometer, [Chang Liu]
Case Study: Hot-Wire Anemometer

Hot-wire anemometry (HWA) is a thermal-sensor based method used for the measurement of fluid velocity.

![Diagram of 'Conventional' HWA](image1)

Figure 5.14. Diagram of ‘Conventional’ HWA, [Chang Liu]

Conventional HWAs are: (1) difficult to assemble and fabricate and (2) difficult to arrange in an array to measure an entire fluid flow field distribution.

MEMS technology is ideally suited to overcome both of these limitations.

![MEMS based HWA](image2)

Figure 5.15. MEMS based HWA, [Chang Liu]
Case Study: Bimorph Artificial Cilia Actuator

Many micro-scale biological systems, can be mimicked using MEMS based devices.

This example shows how ‘cilia’ can be mimicked, and potentially used for handling and transporting micro-objects.

Figure 5.5. MEMS based Artificial Cilia for Micro-object Transport, [Chang Liu]

Thermal Sensors and Actuators

For Homework:

Review Example 5.1.

Read Case Studies:

5.3 Lateral Thermal Actuators

5.8-Bimetallic Structure for Infrared Sensing