MODULE 2

SELF-GENERATING SENSORS

STRUCTURE:

➢ Thermoelectric Sensors

➢ Piezoelectric Sensors

➢ Pyroelectric Sensors

➢ Photovoltaic Sensors

➢ Electrochemical Sensors

Question 1: Describe self-generating sensors and their capabilities.

Answer:

1. **Self-Generating Sensors:**
    - Yield an electric signal from a measurand without needing an external electric supply.
    - Offer alternative methods for measuring common quantities like temperature, force, pressure, and acceleration.
2. **Capabilities:**
    - Based on reversible effects, allowing them to be used as actuators to obtain nonelectric outputs from electric signals.

Question 2: Explain thermoelectric sensors focusing on thermocouples, the reversible thermoelectric effects, and the Peltier and Thomson effects.

Answers:

1. Thermoelectric sensors utilize two reversible effects: the Peltier effect and the Thomson effect.
2. In a circuit with dissimilar metals A and B at different temperatures, an electric current is generated, converting thermal to electric energy.

Figure 6.3 Thomson effect: When there is a current along a conductor with non-homogeneous temperature, heat is absorbed or liberated.

3. Opening the circuit creates a thermoelectric electromotive force (emf) dependent on the metals and junction temperatures.
4. The Seebeck effect in a thermocouple results in either a current or a potential difference with differing temperatures at two metal junctions.
5. A thermocouple consists of a pair of different metals with a fixed junction, termed a thermocouple pair.
6. The Seebeck coefficient SAB defines the relationship between emf (EAB) and temperature difference (T) between junctions.

$$S_{AB} = \frac{dE_{AB}}{dT} = S_A - S_B$$

7. **The Peltier effect**, discovered by Jean C. A. Peltier in 1834, involves heating or cooling of a metal junction when an electric current flows through it.
8. Peltier effect is reversible; the direction of heat flow changes with the current direction.
9. Peltier coefficient (πAB) measures heat generated at the junction per unit of positive charge flowing from B to A.

$$dQ_P = \pm \pi_{AB} I \, dt \tag{6.2}$$

It can be shown [1] that for a junction at absolute temperature T we have

$$\pi_{AB}(T) = T \times (S_B - S_A) = -\pi_{BA}(T) \tag{6.3}$$

10. The Thomson effect, discovered by William Thomson, involves heat absorption or liberation in a conductor with nonhomogeneous temperature along it when a current flows.

Figure 6.3 Thomson effect: When there is a current along a conductor with non-homogeneous temperature, heat is absorbed or liberated.

The heat flux per unit volume q in a conductor of resistivity r with a longitudinal temperature gradient dT=dx, along which there is a current density i, is

$$q = i^2 r - i\sigma \frac{dT}{dx}$$

where σ is the Thomson coefficient. The first term on the right side describes the irreversible Joule effect, and the second term describes the reversible Thomson effect

$$\frac{dE_{AB}}{dT}\Delta T = \pi_{AB}(T+\Delta T) - \pi_{AB}(T) + (\sigma_B - \sigma_A) \times \Delta T \qquad (6.5)$$

By dividing both sides by ΔT and taking limits when ΔT goes to zero, we have

$$\frac{dE_{AB}}{dT} = \frac{d\pi_{AB}}{dT} + \sigma_B - \sigma_A \qquad (6.6)$$

11. Heat flux per unit volume (q) in a conductor with a temperature gradient and current density is described by the Thomson coefficient (σ).

12. The basic theorem for thermoelectricity states that the Seebeck effect arises from Peltier and Thomson effects.

13. Different junction types are available, including exposed junctions for static measurements or in noncorrosive gas flows, and grounded junctions suitable for measurements in flowing corrosive gases or liquids or under high pressures.

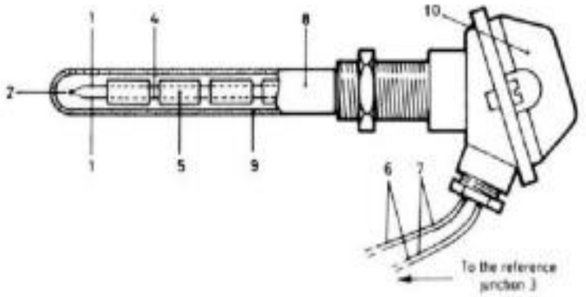

Figure 6.4 Industrial thermocouple with sheath. 1, conductors (different); 2, measurement junction; 3, reference junction; 4, bare thermocouple wires; 5, insulated thermocouple wires; 6, extension leads, of the same wire as that of the thermocouple; 7, compensation leads, different wire from that of the thermocouple but with small emf; 8, probe; 9, protection (external covering); 10, sheath head.

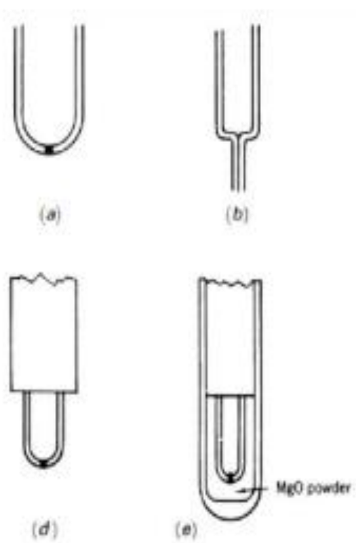

Figure 6.5 Different kinds of thermocouple junctions and their sheaths [4]: (*a*) butt-welded junction; (*b*) lap-welded junction; (*c*) twisted wire; (*d*) exposed thermocouple for fast response time; (*e*) enclosed thermocouple—electrical and ambient isolation; (*f*) grounded thermocouple soldered to the covering—ambient isolation.

Question 3: Explain the practical laws governing thermocouples focusing on the law of homogeneous circuits, the law of intermediate metals, and the law of successive or intermediate temperatures.

Answers:

1. **Law of Homogeneous Circuits:**
    - It's impossible to maintain a thermoelectric current in a circuit made of a single homogeneous metal solely by applying heat, even by altering the conductor's cross section.
    - Intermediate temperatures along a conductor don't affect the emf produced by a given temperature difference between junctions.

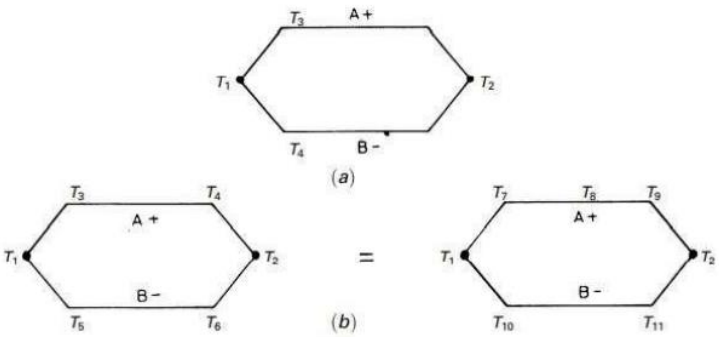

Figure 6.6 Homogeneous circuits law for thermocouples.

2. **Law of Intermediate Metals:**
    - The sum of all emfs in a circuit composed of various metals equals zero when the entire circuit is at a uniform temperature.
    - Addition of a meter into the circuit doesn't introduce errors if new junctions inserted are all at the same temperature.
    - Nichrome is used in wire wound resistors and strain gages, while CuO/Cu yields a large emf, necessitating clean electric contacts.
    - It's not necessary to calibrate all possible metal pairs; knowledge of their thermal relationship with a third material, typically platinum, suffices.

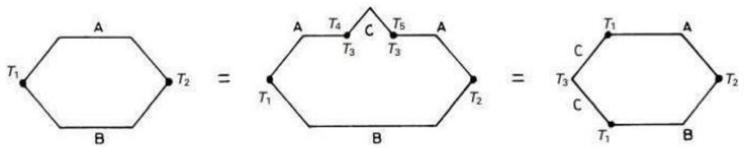

Figure 6.7 Intermediate metals law for thermocouple circuits.

3. **Law of Successive or Intermediate Temperatures:**
    - If two metals yield emf E1 at temperatures T1 and T2, and emf E2 at temperatures T2 and T3, then the emf at temperatures T1 and T3 will be E1 + E2.

- The reference junction need not be at 0°C; any reference temperature is acceptable.

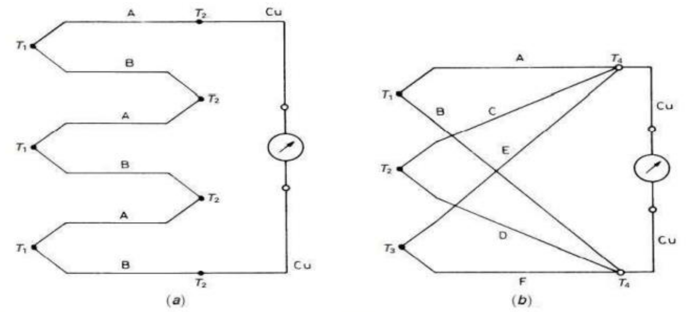

Figure 6.10 (*a*) Series (thermopile) and (*b*) parallel thermocouple connection.

These laws facilitate the analysis of thermocouple circuits, such as thermopiles and parallel connections, enhancing sensitivity and providing average temperature readings, respectively.

Question 4: Explain piezoelectric sensors, covering the piezoelectric effect, piezoelectric materials, and applications.

Answers:

1. **The Piezoelectric Effect:**

   - Piezoelectricity is the accumulation of electric charge in certain solid materials, like crystals, ceramics, and biological matter, when subjected to mechanical stress.
   - It's distinct from ferroelectricity, which involves a spontaneous or induced electric dipole moment, although all ferroelectric materials exhibit piezoelectricity.
   - Piezoelectricity relates to the crystalline structure, while ferromagnetism is linked to electron spin.
   - Piezoelectric equations describe the electric-mechanical relationship in piezoelectric materials.

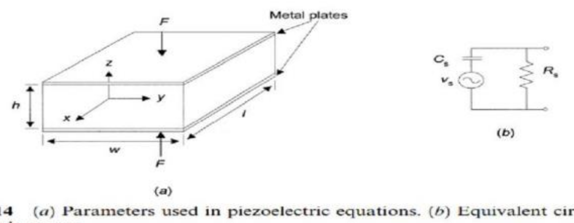

Figure 6.14 (*a*) Parameters used in piezoelectric equations. (*b*) Equivalent circuit for a piezoelectric sensor.

Hooke's law, in the elastic range is

$$S = sT \qquad (6.10)$$

where s is compliance, $1/s$ is Young's modulus, and T is the stress (F/A).

A potential difference applied between plates creates an electric field $\boldsymbol{E}$ and we have

$$\boldsymbol{D} = \epsilon \boldsymbol{E} = \epsilon_0 \boldsymbol{E} + \boldsymbol{P} \qquad (6.11)$$

2. **Piezoelectric Materials:**

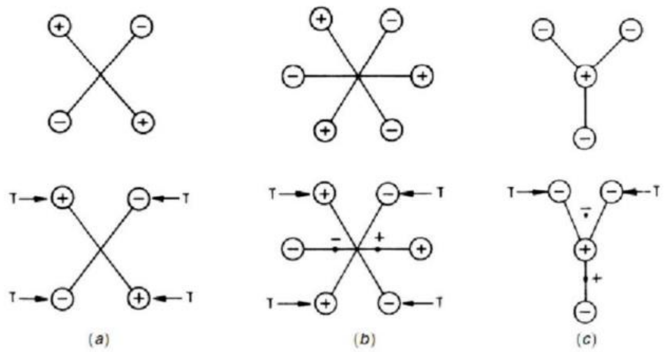

Figure 6.16 Effects of a mechanical stress on different molecules depending on their symmetry [5]: (*a*) When there is central symmetry, no electric polarization arises. (*b*) Polarization parallel to the effort. (*c*) Polarization perpendicular to the effort.

- Piezoelectric properties are found in 20 crystallographic classes, with only 10 displaying ferroelectric properties.
- All piezoelectric materials are anisotropic, with varying responses to force application.
- Common natural piezoelectric materials include quartz and tourmaline, while synthetic ceramics like lead zirconate titanate (PZT), barium titanate, and lead niobate are widely used.
- Piezoelectric ceramics offer high stability but are sensitive to temperature and aging near their Curie temperature.
- Polymers like polyvinylidene fluoride (PVF2 or PVDF) exhibit piezoelectric properties and are suitable for applications requiring unique shapes.
- Piezoelectric composite materials, composed of phases with at least one exhibiting piezoelectric properties, enhance mechanical properties for sensor applications.
- **Applications:**

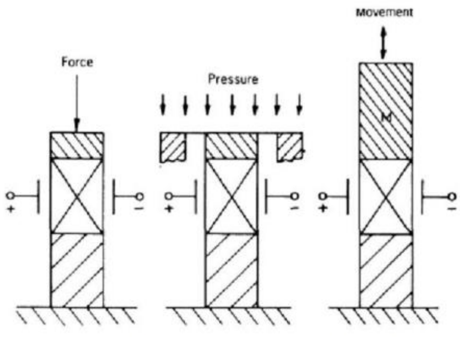

Figure 6.19 Force, pressure, and movement sensors based on piezoelectric elements (courtesy of PCB Piezotronics).

- **Sensor Design:**Piezoelectric sensors are sensitive to three quantities, necessitating special designs to minimize interference.
- **Pulse Measurement:**They are sensitive enough for pulse measurements and can be attached to the body with self-adhesive.
- **Stethoscopes:**Piezo sensors, due to their high sensitivity and robustness, are commonly used in stethoscopes.
- **Anesthesia Effectiveness:**Piezo sensors measure muscle response to electrical stimulation, aiding in assessing anesthesia effectiveness

Question: Explain pyroelectric sensors, covering the pyroelectric effect, pyroelectric materials, radiation laws, and applications.

Answers:

1. **The Pyroelectric Effect:**
    - Similar to the piezoelectric effect, the pyroelectric effect refers to a change in spontaneous polarization and resulting electric charge due to a change in temperature.

$$\Delta \boldsymbol{P} = \boldsymbol{p}\Delta T \tag{6.36}$$

where $\boldsymbol{P}$ is the spontaneous polarization.

This effect is mainly used for thermal radiation detection at ambient temperature (Section 6.3.3). Two metallic electrodes are deposited on faces perpendicular to the direction of the polarization, which yields a capacitor (C_d) acting as thermal sensor. When the detector absorbs radiation, its temperature and hence its polarization changes, thus resulting in a surface charge on the capacitor plates.

    - Pyroelectric coefficient, represented by the vector p, describes the effect when the change in temperature (ΔT) is uniform throughout the material.
2. **Pyroelectric Materials:**
    - Pyroelectricity, like piezoelectricity, is based on crystal anisotropy, with many piezoelectric materials also exhibiting pyroelectric properties.
    - Ten of the 21 non-centrosymmetric crystallographic classes display pyroelectric properties.
    - Pyroelectric materials are categorized as linear and ferroelectric, with polarization of linear materials unaffected by electric field inversion.
    - Examples include tourmaline, lithium sulfate, cadmium and selenium sulfides for linear materials, and lithium tantalate, strontium and barium niobate, lead

zirconate-titanate, triglycine sulfate (TGS), and polyvinylidene (PVF2 or PVDF) for ferroelectric materials.

- Pyroelectric properties vanish at the Curie temperature.

3. **Radiation Laws: Planck, Wien, and Stefan-Boltzmann:**

- Bodies above 0 K emit electromagnetic energy, with emitted radiation becoming visible above 500°C.
- A theoretical "blackbody" absorbs all incident energy and emits it as thermal radiation.
- Emissivity (E) represents the ratio of energy emitted by a body to that of a blackbody under similar conditions, with E = 1 for a blackbody.

$$W_\lambda = \frac{c_1}{\lambda^5[\exp(c_2/\lambda T) - 1]} \text{ W cm}^2/\mu\text{m} \qquad (6.44)$$

where

$c_1 = 2\pi c^2 h = 3.74 \times 10^4 \text{ W}\cdot\mu\text{m}^4/\text{cm}^2$
$c_2 = hc/k = 1.44 \text{ cm}\cdot\text{K}$
$h = 0.655 \times 10^{-33} \text{ W}\cdot\text{s}^2$ is Planck's constant

- Planck's law describes energy emitted by a blackbody at a given wavelength and temperature, with Wien's displacement law indicating a peak wavelength shifting towards shorter wavelengths with increasing temperatures.
- Stefan-Boltzmann law states that total radiant heat power emitted from a surface is proportional to the fourth power of its absolute temperature.

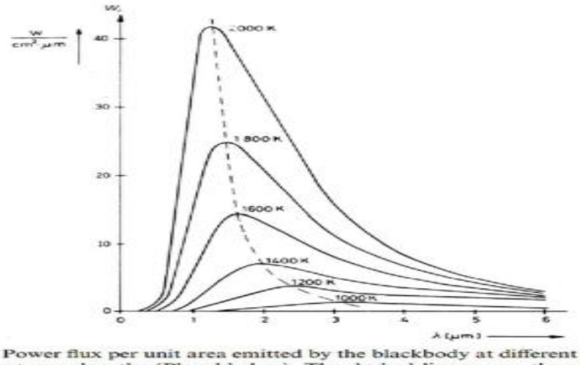

Figure 6.23 Power flux per unit area emitted by the blackbody at different temperatures and at different wavelengths (Planck's law). The dashed line passes through the maximums (Wien's law).

which is the equation for Wien's displacement law (to honor the man who discovered it before Planck's law was discovered). It indicates that the maximum is obtained at a wavelength that decreases for increasing temperatures.

The total flux power emitted by the blackbody per unit area is obtained by integrating (6.44) for all wavelengths. In a half-plane (solid angle 2π), the total emitted flux is

$$W = \sigma T^4 \qquad (6.47)$$

which shows a dependence on the fourth power of the absolute temperature. $\sigma = 5.67 \text{ pW/cm}^2\cdot\text{K}^4$ is the Stefan–Boltzmann constant.

4. **Applications:**
    - Pyroelectric sensors are commonly used for thermal radiation detection at ambient temperature, employed in pyrometers for non-contact temperature measurement in various industries.
    - Other applications include IR analyzers, intruder and position detection, automatic faucet control, fire detection, high-power laser pulse detection, and high-resolution thermometry.
    - Medical thermometers utilize pyroelectric sensors to measure ear temperature by detecting infrared radiation emitted by the eardrum and surrounding tissue.

Question: Explain photovoltaic sensors, focusing on the photovoltaic effect, photovoltaic materials, and applications.

Answers:

1. **The Photovoltaic Effect:**
    - In the internal photoelectric effect within a p-n junction, a voltage is generated based on incoming radiation intensity, known as the photovoltaic effect.
    - This effect occurs when radiation ionizes a region with a potential barrier, typically between a p-doped semiconductor (acceptors) and an n-doped semiconductor (donors) in thermal equilibrium.
    - Electrons from the n-region and holes from the p-region recombine, resulting in few free charge carriers at the contact surface and an opposing electric field due to fixed ions in the crystal structure, leading to equilibrium between diffusion and induced current.
    - External ohmic connections on each semiconductor balance the internal potential difference, yielding no detected voltage difference.

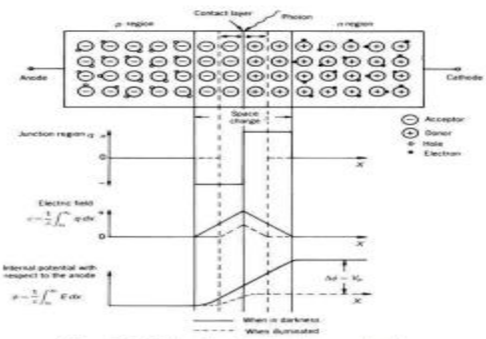

Figure 6.24 Photoelectric effect in a p–n junction.

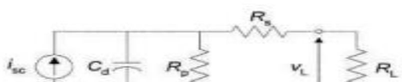

Figure 6.25 Equivalent simplified circuit for a photovoltaic detector. i_{sc} is the short-circuit current, R_p is the parallel resistance, R_s is the output series resistance, and C_d is the junction capacitance. R_L is the load resistance.

2. **Photovoltaic Materials & Applications:**
    - Besides p-n junctions, other methods can create potential barriers, but p-n junctions are most common.
    - Homojunctions occur between semiconductors of the same composition, while heterojunctions involve different compositions.
    - Material selection depends on the wavelength to be detected. Silicon and selenium are used for visible and near-infrared regions, often in homojunctions or heterojunctions.
    - Silicon may have an intrinsic region between p and n regions (p-i-n detectors) for a wider depletion region, improving efficiency, speed, and reducing noise and dark current.
    - Germanium, indium antimonide (SbIn), and indium arsenide (AsIn), among others, are used at different wavelengths.
    - Photovoltaic detectors offer better linearity, speed, and lower noise than photoconductors but require amplification, with linearity decreasing and response time increasing for large-load resistors.
    - Applications include flame photometers, colorimeters, infrared pyrometers, pulse laser monitors, smoke detectors, exposure meters in photography, and card readers.
    - Commercial models consist of matched emitter-detector pairs, some pre-connected to control relays.

Question: Explain electrochemical sensors, focusing on potentiometric and amperometric principles, selective electrodes, and applications.

Answers:

1. **Potentiometric Electrochemical Sensors:**
    - Yield an electric potential in response to a concentration change in a chemical sample.
    - Based on the voltage generated at the interface between phases with different concentrations, akin to voltaic cells.
    - Utilize a two-electrode arrangement where one electrode contains a selective membrane for the ion of interest, and the other is a reference electrode.
2. **Nernst Equation:**
    - Describes the potential difference when equilibrium is achieved between diffusion and electric potential due to ion concentration changes.

- Given by ΔE = (RT/zF) ln(Ci / Co), where Ci is the concentration of the ion species, fi is the activity coefficient, R is the gas constant, T is the temperature, z is the ion charge, and F is Faraday's constant.

$$E = \frac{RT}{zF} \ln \frac{a_{i,1}}{a_{i,2}} \qquad (6.48)$$

where $R = 8.31$ J/(mol·K) is the gas constant, T is the temperature in kelvins, z is the valence for the ion, $F = 96{,}500$ C is Faraday's constant, and a_i is the ion activity. For a liquid solution, activity is defined as

$$a_i = C_i f_i \qquad (6.49)$$

---

3. **Selective Electrodes:**
   - Primary electrodes may have single or crystalline membranes, which can be homogeneous or heterogeneous.
   - Examples include glass electrodes for pH and Na+ measurement and solid-state electrodes with deposited metal salts.
   - Other electrodes utilize membranes containing ion exchangers or neutral materials for ion transport, such as PVC membranes for K+ measurement.

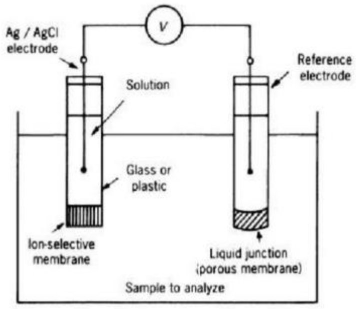

Figure 6.26 Measurement arrangement using an ion-selective electrode (ISE).

$$E = E_0 + \frac{RT}{zF} \ln a_i = E_0 + k \lg a_i$$

---

4. **Applications:**
   - Used for concentration measurement in various fields:
     - Agriculture: soil and fertilizer analysis.
     - Biomedical sciences: blood and urine analysis.

    - Chemical and food industries.
    - Environmental monitoring: ambient pollution measurement.

- Solid electrolyte oxygen sensors operate based on oxygen ions adsorbed by a metal oxide, affecting conductivity, commonly used to determine air-to-fuel ratio in internal combustion engines.
- Despite needing high temperatures and having low sensitivity to pressure changes, they offer wide operating ranges and find applications in automobiles, boilers, and furnaces.