Department of Biomedical Engineering

VI Semester

CBM 370 - Wearable Devices

Unit- 2 Signal Processing and Energy Harvesting for Wearable Devices

2.6 Power Requirements- Solar cell, Vibration based, Thermal based

2.6.1 Power Requirement -Solar Cell:

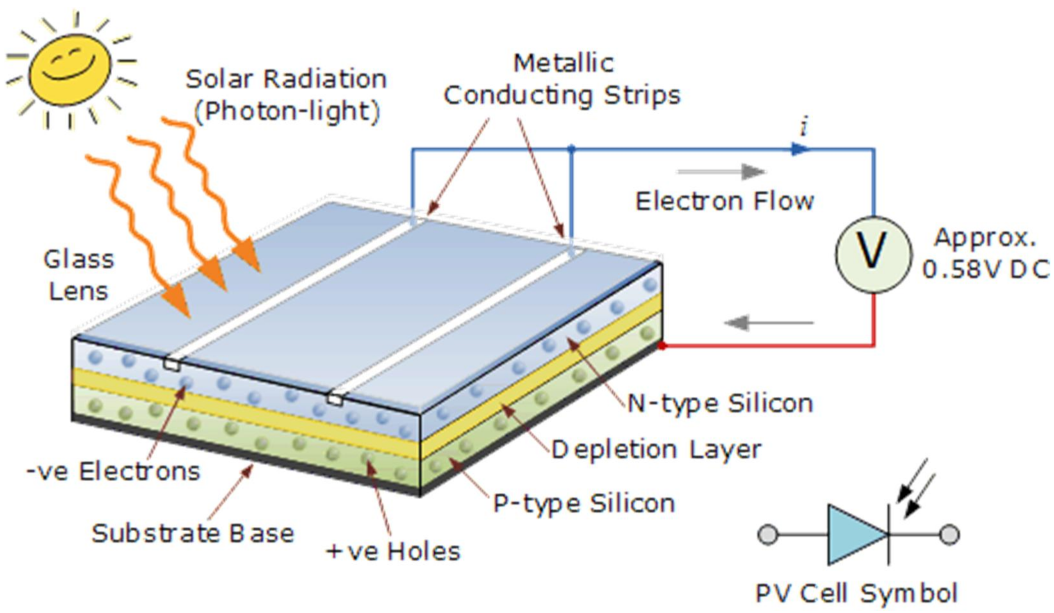


Fig. Basics behind a solar cell

- The most common photovoltaic cells are silicon-based.
- To create a solar cell, silicon layers will be doped to have more electrons, an n-type layer, in one (or some) layer(s) and others doped to have fewer, a p-

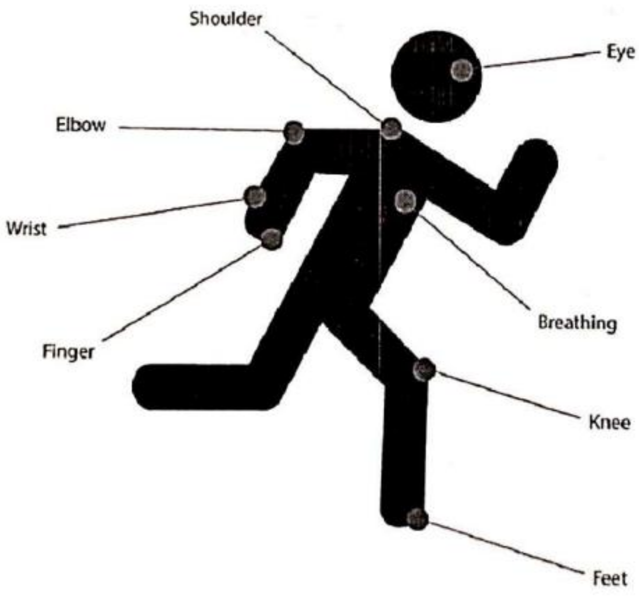
type layer. P-type layers have an excess of holes–effectively locations where electrons are missing.

- These types of doped materials are configured so a p-type layer will be next to an n-type layer. The excess electrons and holes flow between the layers.
- This flow of charge carriers and creation of ions induce an internal electric field.
- Photovoltaic cells have this type of structure. When sunlight hits a photovoltaic cell, absorption of sunlight will excite electrons, creating holes in their place.
- The flow of the electrons creates electricity which can then be harnessed.
- Silicon solar cells generally have an efficiency hovering somewhere around 25 percent.
- Solar cells are a promising solution for powering wearable devices, especially in environments with ample sunlight.
- The efficiency of solar cells typically ranges around 25%, and they can generate significant power under optimal conditions.
- For instance, a wearable device equipped with solar cells can produce between **27.8 mW** and **159.1 mW** depending on the intensity of sunlight received.
- **Operational Capacity**: Devices can remain operational if exposed to direct sunlight for approximately 6 hours daily, recharging their batteries during this time.
- **Battery Integration**: Solar energy harvested during the day can recharge batteries for use during periods without light, ensuring continuous operation.
- **Types:**
    - ✓ **Monocrystalline & Polycrystalline Silicon:** These are the most common type of solar cells, known for their efficiency. However, they can be rigid, making them less suitable for flexible wearables
    - ✓ **Thin-film Solar Cells** (e.g., perovskite, organic photovoltaics): These cells are made from thin layers of semiconductor materials, making them more flexible and lightweight.
    - ✓ **Organic Solar Cells:** These use organic polymers to convert light into electricity. They are highly flexible and can even be printed onto fabrics, making them ideal for integration into clothing.

- ***Garmin*** currently advertises a limited offering of solar-powered watches. These smartwatches have impressive battery lives. They list their Instinct Solar watches operating for 54 days on a single charge.

2.6.2 Power Requirement – Vibration based:

- Vibration-based systems utilize piezoelectric materials to convert mechanical energy from body movements into electrical energy. This method is particularly effective due to the ***constant motion associated with human activity***.
- **Energy Generation**: Vibration harvesting can produce sufficient power levels required for small wearable devices.
- **Advantages**: This approach can be effective even when the wearer is stationary, as it captures energy from minor movements or vibrations.
- **Examples:** Research is being done on integrating this into shoe insoles or clothing to power small sensors.



This diagram likely represents optimal locations for **wearable energy harvesting** or **biometric sensing**. Each point could correspond to different energy-harvesting techniques:

- ✓ **Eye** → Solar-powered smart glasses.
- ✓ **Shoulder & Elbow** → Piezoelectric/vibration-based sensors for motion energy.
- ✓ **Wrist & Finger** → Smartwatches/rings with solar or kinetic energy.
- ✓ **Breathing (Chest)** → Thermoelectric generators (TEGs) or respiratory motion sensors.
- ✓ **Knee & Feet** → Piezoelectric/triboelectric nanogenerators to capture walking energy.

- ❖ There are four different types of **materials** that can be used for piezoelectric energy harvesting: ceramics, single crystals, polymers, and composites.
- ❖ Of these, **ceramic** is the preferred material for this type of energy harvesting because of its low cost, effective piezoelectric properties and easy incorporation into energy harvesting devices.
- ❖ Piezoelectric vibration energy harvesting is the preferred method for use with wearable devices since it is the most capable of producing the power level needed for **small-scale devices**.
- ❖ There are ***two kinds of mechanical energy*** that can be scavenged from the human body.
- ❖ The first is related to ***continuous activity***, such as breathing and heart beating;
- ❖ while the other is related to **discontinuous movements**, such as walking and joint movements.
- ❖ Of these, the process of walking produces the largest amount of power compared with other body motions.
- ❖ It has been recorded that a **68kg** man is able to generate **67W** when walking at a speed of two steps per second. The easiest way to harvest this energy is through piezoelectric shoe inserts.
- ❖ ***Body joints*** are also attractive locations for harvesting energy due to their high motion amplitude, fast angular velocity, large impulse force, and high frequency of use in daily human activities.
- ❖ For example, the knee joint produces high biomechanical energy since it generates a larger torque in comparison to other human joints. Knee joint motions are often related to gait motion, where walking and running frequencies are normally in the range of ***0.5-5 Hz***.

- Even for relatively minor activities such as ***eye blinking***, piezoelectric transducers have effectively been used to convert motional energy into electricity. For example, a selfpowered sensor was developed for both energy harvesting and health rehabilitation monitoring, which was based on polymeric piezoelectric nano/microfibers.
- Furthermore, continuous energy can be harvested from the process of human ***breathing***. There are two kinds of energy that can be collected in this case. The first relies on scavenging energy due to the ***intake and release of air***, which can produce approximately ***1 W of power***. The other relies on ***chest expansion***, which requires a tight band fixed around the chest of the user to generate around ***0.83 W*** when breathing normally.

<u>Wearable Piezoelectric Applications:</u>

Piezoelectric components can be used for wearable technologies and other new technologies. Their use presents vast possibilities across many industries. Human comfort, convenience, health and safety have the potential to be greatly improved with the availability and use of products containing piezoelectric components. Many of these capabilities and products are already emerging in today's society. These include:

1. A **piezoelectric pacemaker** that is powered by the rhythm of a beating heart. This eliminates the need for invasive and dangerous surgery for battery replacement.
2. Footpath lighting powered by **footsteps striking energy**-absorbing tiles.
3. The ability to power monitoring and sensor devices in remote and **dangerous places** (bridges, pipelines, etc.). This eliminates the risk to humans that arises when batteries need charging or replacing.
4. A **vehicle driver's seat** that uses piezoelectric sensors to monitor and sense driver's heart rate and respiration. It uses vibration sensors to allow ventilation and massage features to be automatically activated in the seat when driver stress is detected.
5. Wearable devices that can be charged by **walking, running or other physical activity.**

Design Challenges in Wearables with Piezoelectric Technology:

1. **Material Choice:**

- ❒ Textiles that have a greater elasticity perform at a greater efficiency when harvesting piezoelectric energy.
- ❒ The greater elasticity of the material increases the stresses occurring in the garment and, consequently, increases the elongation of piezoelectric elements.
- ❒ In addition, the garment must be form fitting in order to increase the clothing pressure and increase the piezoelectricity efficiency by increasing the strain exerted on the harvester on the garment.

2. Durability:

- ❒ Energy harvesters are required to have high environmental durability and operational reliability.
- ❒ However, in the case of piezoelectric energy harvesters, the material properties may change during the manufacturing process, even if the piezoelectric effect is caused by intrinsic physical properties such as the crystal structure of the material. When a strain is repeatedly applied to a material, macroscopic cracks may occur resulting in a drop in the amount of power generated. Clarifying the mechanism behind the deterioration of materials that occurs during the conversion of kinetic energy into electric energy and taking countermeasures are challenges for piezoelectric technology.

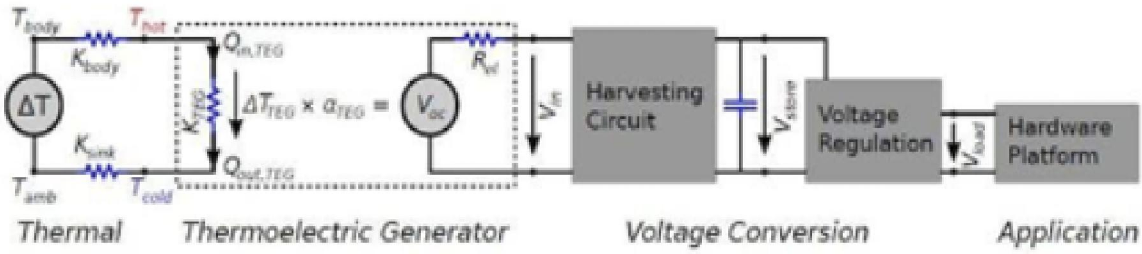
3. Operating Frequency:

- ❒ It is a well-known issue with piezoelectric energy harvesters that they do not harvest energy efficiency at varying frequencies. These devices operate at a high frequency whereas humans have an ultra-low frequency of around 1Hz.
- ❒ As the operating bandwidth of piezoelectric energy harvesters is quite high, this significantly limits their utility within real world applications in wearable devices.
- ❒ In addition, the motion range of humans is usually much higher than the predetermined device size and so resonant devices cannot render the advantage of powerful magnification.

- The operating excitation frequency must fall in the resonant frequency range of harvester so as to obtain the best results. Most commonly, the frequency up conversion technique is used to overcome this hurdle.
- Mostly, mechanical plucking mechanism by using ***piezoelectric bimorph*** was used for frequency-up conversion to power low-powered electronics. However, these devices showed some drawbacks such as reduced longevity due to direct contact between bimorph and plectra and noise.

2.6.3 Power Requirement – Thermal based:

- Thermal energy harvesting involves converting body heat into electrical energy using thermoelectric generators (TEGs).
- This method uses the temperature difference between the human body and the surrounding environment.
- Body heat applied to a thermoelectric generator plus energy harvesting to produce power for a wearable device achieves both minimization of power consumption.
- Another consideration in powering wearable devices is the necessity to impose weight and size constraints, particularly if you initially choose a battery as the source of power. To limit size and weight you should use energy harvesting instead of the battery.
- One can harvest energy from several environmental sources:
  - ✓ Light, using photovoltaics
  - ✓ Movement of the wearer
  - ✓ Radio frequency energy (RF)
  - ✓ Temperature differences using a thermoelectric generator (TEG)
- In one ***application*** a Thermoelectric Generator (TEG) on a ***human forehead*** powered a ***2-channel EEG system*** with a power consumption **of 0.8mW**. You can harvest up to ***30 μWcm-2*** before dc-dc conversion (Voltage Regulation in Fig. 1).



- ❒ A two-stage custom dc-dc converter design is used to convert the voltage produced by the TEG to 2.75V. Due to the large thermal harvester, the system has limited wearability.
- ❒ **Types:**
  - ✓ Bulk TEGs (e.g., Bi2Te3-based materials)
  - ✓ Flexible TEGs for wearable applications

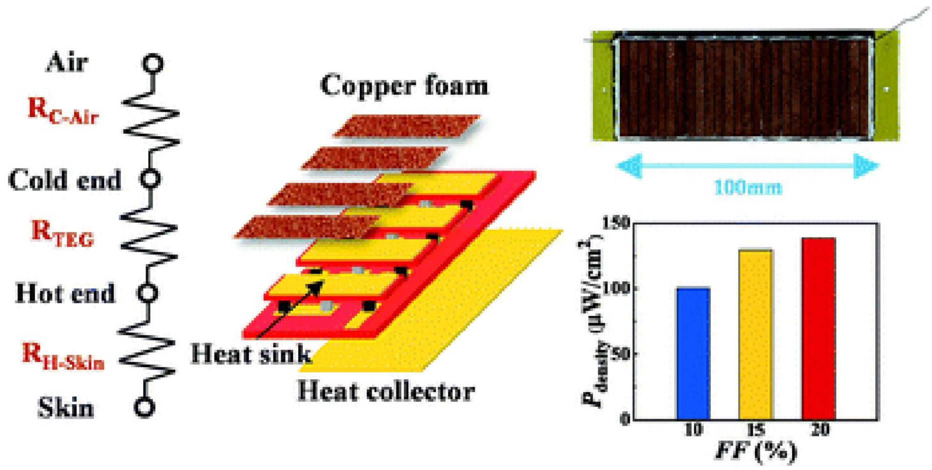


Illustration of a **Thermoelectric Generator (TEG) system** designed for wearable applications.

1. Circuit Representation (Left Side)

- Shows thermal resistances:
  - ❖ **R_C-Air:** Thermal resistance between the cold end and air.
  - ❖ **R_TEG:** Thermal resistance of the TEG module.
  - ❖ **R_H-Skin:** Thermal resistance between the hot end and skin.

- This suggests a **layered heat transfer system**, where body heat is used to generate electricity.

2. Structural Diagram (Middle)

- **Copper Foam:** Likely used to improve heat dissipation at the cold end.
- **Heat Sink & Heat Collector:** Enhances thermal gradient across the TEG, improving efficiency.
- The **hot end** is in contact with the skin, while the **cold end** interacts with air.

3. TEG Device (Top Right)

- A physical representation of the thermoelectric generator, with a **100mm width**, possibly for integration into wearables.

4. Power Density Graph (Bottom Right)

- Shows **P_density (μW/cm²)** vs. **Fill Factor (FF, %)**.
- Higher fill factor (FF = 20%) results in greater power density.
- Indicates that optimizing material coverage improves power generation efficiency.

<u>**Thermoelectric Generator (TEG):**</u>

❒ A single thermoelectric device is constructed from two solid-state devices that are usually made from bismuth telluride (Bi_2Te_3), as shown in Fig. 4.

❒ One of these pellets of semiconductor is doped with acceptor impurity to create a p-type component to have more positive charged carriers or holes, thus providing a positive Seebeck coefficient.

- The other is doped with donor impurity to produce an n-type component to have more negative charged carriers, thus providing a negative type of Seebeck coefficient.
- The two semiconductor components are then physically connected serially on one side, usually with a copper strip, and mounted between two ceramic outer plates that provide electric isolation and structural integrity.

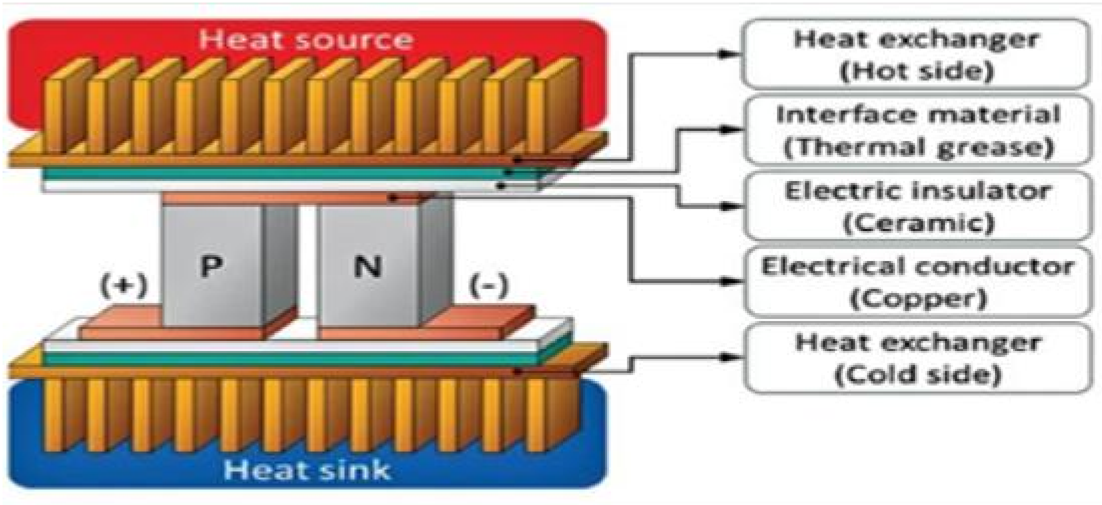


Fig. 4: Thermoelectric generator (TEG)

- The Seebeck effect is a direct energy conversion of heat into a voltage potential.
- It occurs due to the movement of charge carriers within the semiconductor.
- Charge carriers diffuse away from the hot side of the semiconductor. This diffusion leads to a build-up of charge carriers at one end. This build-up of charge creates a voltage potential that is directly proportional to the temperature difference across the semiconductor.
- The power generated in a TEG is single-phase DC that equals $I^2 R_L$, where I is the current and R_L is the load resistance.
- The output voltage and output power are increased either by increasing the temperature difference between the hot and cold ends or by connecting several TEGs in series, as shown in Fig. 5.

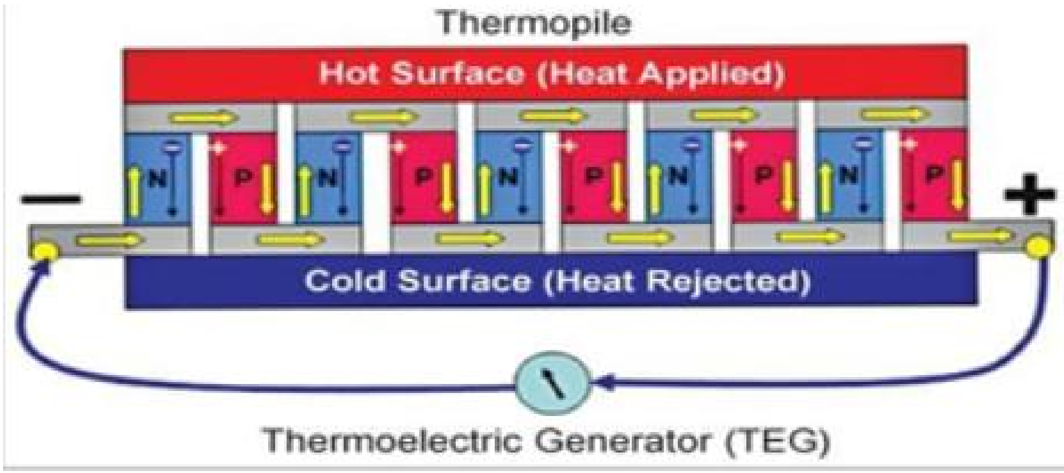


Fig.5 Series-connected thermoelectric generator

- The current flows as long as heat is applied to the hot junction. The process is reversible. If the hot and cold junctions are interchanged, the valence electrons flow in opposite direction and direction of the current changes.
- The thermoelectric effect allows converting waste heat into electric power.
- By combining thermoelectric and PV effects, higher solar electricity conversion efficiency is possible. PV absorbs about 58% of solar energy between 200nm and 800nm wavelengths.
- The rest of the solar energy from 800nm to 2500nm cannot be converted to electricity by PV. But this spectrum of solar radiation can generate electricity through thermoelectric effect by heating TEG.

There are three main types of thermoelectric materials used in thermoelectric generators:

1. **Bismuth telluride (Bi2Te3) alloy:**
   It is a semiconductor that has high electrical conductivity but is not good at transferring heat. The best working temperature of this class of material is below 450°C.
2. **Lead telluride (PbTe) alloy**: Lead telluride alloy is recognised as an excellent compound for power generation in the mid temperature range of 500-800°K.
3. **Silicon-germanium alloy**: It is a kind of semiconductor that is often used for thermoelectricity generation with a working temperature around 1300°C.

Why Bi_2Te_3 for Wearables?

Bi_2Te_3 is popular in thermoelectric generators (TEGs) due to the following properties:

- ✓ **High Thermoelectric Efficiency** – Exhibits a high Seebeck coefficient and low thermal conductivity, making it excellent for power conversion.
- ✓ **Lightweight & Compact** – Can be integrated into small and flexible wearables.
- ✓ **Operates at Body Temperature** – Works efficiently in temperature ranges suitable for human skin (~35°C).
- ✓ **Scalable Fabrication** – Available in thin films and nanostructured forms for flexibility.

****