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Applied Physics

Lecture-19 & 20

Unit III-Thermal Properties of solids

Topics to be discussed in this lecture:

- **Thermoelectricity**
- **Seebeck Effect**
- **Peltier Effect**
- **Thomson Effect**

Thermoelectricity:

Turning temperature differences directly into electricity could be an efficient way of harnessing heat that is wasted in cars and power plants.

The **thermoelectric effect** is the direct conversion of temperature differences to electric voltage and vice versa via a thermocouple. Thermoelectric devices create a voltage when there is a different temperature on each side. Conversely, when a voltage is applied to it, heat is transferred from one side to the other, creating a temperature difference. At the atomic scale, an applied temperature gradient causes charge carriers in the material to diffuse from the hot side to the cold side.

This effect can be used to generate electricity, measure temperature or change the temperature of objects. Because the direction of heating and cooling is determined by the polarity of the applied voltage, thermoelectric devices can be used as temperature controllers.

The term "thermoelectric effect" encompasses three separately identified effects: the **Seebeck effect**, **Peltier effect**, and **Thomson effect**. The Seebeck and Peltier effects are different manifestations of the same physical process; textbooks may refer to this process as the **Peltier–Seebeck effect** (the separation derives from the independent discoveries by French physicist Jean Charles Athanase Peltier and Baltic German physicist Thomas Johann Seebeck). The Thomson effect is an extension of the Peltier–Seebeck model and is credited to Lord Kelvin.

Joule heating, the heat that is generated whenever a current is passed through a resistive material, is not generally termed a thermoelectric effect. The Peltier–Seebeck and Thomson effects are thermodynamically reversible, whereas Joule heating is not.

Seebeck Effect

The **Seebeck effect** is the build up of an electric potential across a temperature gradient. A thermocouple measures the difference in potential across a hot and cold end for two dissimilar materials. This potential difference is proportional to the temperature difference between the hot and cold ends. First discovered in 1794 by Italian scientist Alessandro Volta, it is named after the Baltic German physicist Thomas Johann Seebeck, who in 1821 independently rediscovered it. It was observed that a compass needle would be deflected by a closed loop formed by two different metals joined in two places, with an applied temperature difference between the joints. This was because the electron energy levels shifted differently in the different metals, creating a potential difference between the junctions which in turn created an electrical current through the wires, and therefore a magnetic field around the wires. Seebeck did not recognize that an electric current was involved, so he called the phenomenon "thermomagnetic effect". Danish physicist Hans Christian Ørsted rectified the oversight and coined the term "thermoelectricity".

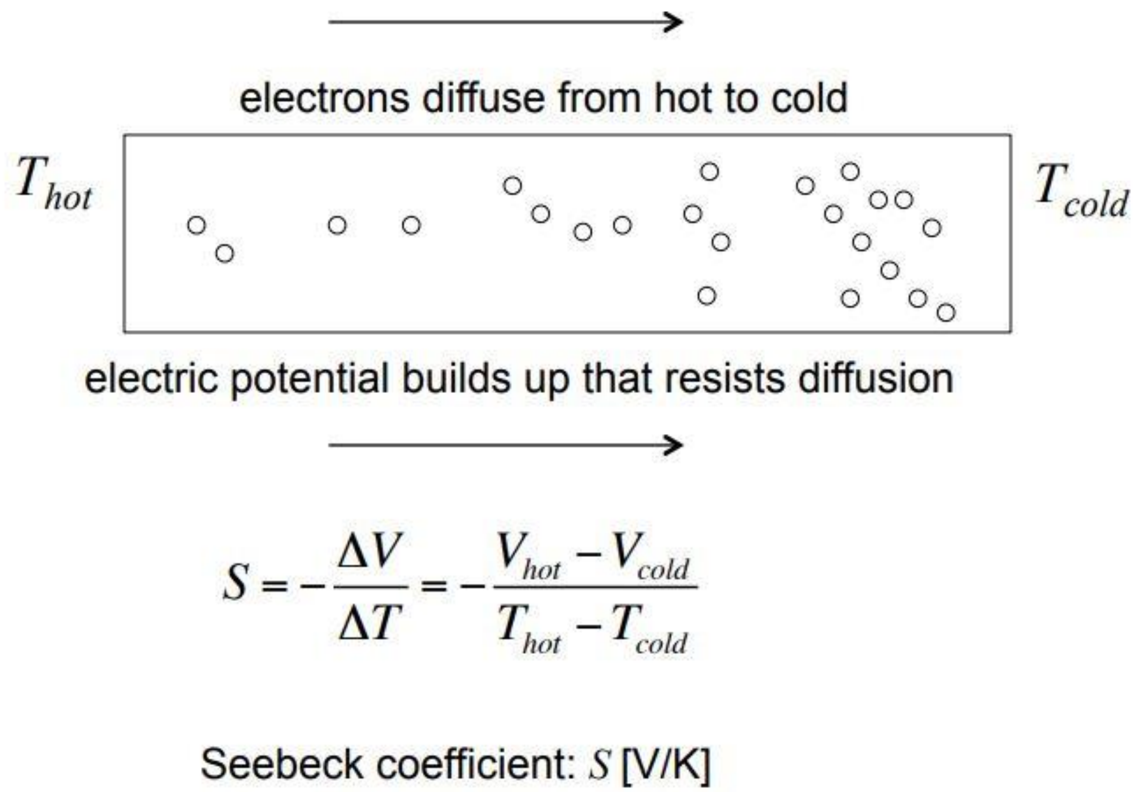


Fig.1 Seebeck Effect

The Seebeck effect is a classic example of an electromotive force (EMF) and leads to measurable currents or voltages in the same way as any other EMF. The local current density is given by

$$J = \sigma\left(-\nabla V + E_{emf}\right),$$

where V is the local voltage, and σ is the local conductivity. In general, the Seebeck effect is described locally by the creation of an electromotive field E_{emf}

$$E_{emf} = -S\Delta T$$

where S is the Seebeck coefficient (also known as thermopower), a property of the local material, and ΔT is the temperature gradient.

The Seebeck coefficients generally vary as function of temperature and depend strongly on the composition of the conductor. For ordinary materials at room temperature, the Seebeck coefficient may range in value from −100 μV/K to +1,000 μV/K.

If the system reaches a steady state, where J = 0, then the voltage gradient is given simply by the emf: $\Delta V = -S\Delta T$.This simple relationship, which does not depend on conductivity, is used in the thermocouple to measure a temperature difference; an absolute temperature may be found by performing the voltage measurement at a known reference temperature. A metal of unknown composition can be classified by its thermoelectric effect if a metallic probe of known composition is kept at a constant temperature and held in contact with the unknown sample that is locally heated to the probe temperature. It is used commercially to identify metal alloys. Thermocouples in series form a thermopile. Thermoelectric generators are used for creating power from heat differentials.

Peltier Effect

When an electric current is passed through a circuit of a thermocouple, heat is evolved at one junction and absorbed at the other junction. This is known as the Peltier Effect. The **Peltier effect** is the presence of heating or cooling at an electrified junction of two different conductors and is named after French physicist Jean Charles Athanase Peltier, who discovered it in 1834. When a current is made to flow through a junction between two conductors, A and B, heat may be generated or removed at the junction. The Peltier heat generated at the junction per unit time is,

$\dot{Q} = (\Pi_A - \Pi_B).I,$

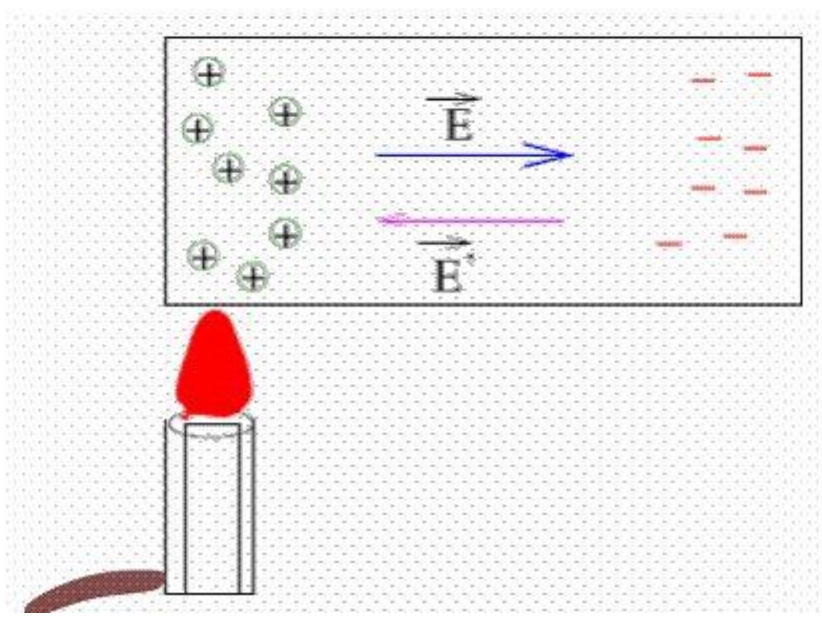
where Π_A and Π_B are the Peltier coefficients of conductors A and B, and I is the electric current (from A to B). The total heat generated is not determined by the Peltier effect alone; as it may also be influenced by Joule heating and thermal-gradient effects.

The Peltier coefficients represent how much heat is carried per unit charge. Since charge current must be continuous across a junction, the associated heat flow will develop a discontinuity if Π_A and Π_B are different. The Peltier effect can be considered as the back-action counterpart to the Seebeck effect (analogous to the back-EMF in magnetic induction): if a simple thermoelectric circuit is closed, then the Seebeck effect will drive a current, which in turn (by the Peltier effect) will always transfer heat from the hot to the cold junction.

A typical Peltier heat pump involves multiple junctions in series, through which a current is driven. Some of the junctions lose heat due to the Peltier effect, while others gain heat. Thermoelectric heat pumps exploit this phenomenon, as do thermoelectric cooling devices found in refrigerators.

Thomson Effect

William Thomson (later well known as Lord Kelvin) discovered a third thermoelectric effect which provides a link between Seebeck effect and Peltier effect. Thomson found that when a current is passed through an wire of single homogeneous material along which a temperature gradient exists, heat must be exchanged with the surrounding in order that the original temperature gradient may be maintained along the wire. (The exchange of heat is required at all places of the circuit where a temperature gradient exists.) Thomson effect may be understood by a simple picture. A conductor has free charge carriers, which are, electrons in metals, electrons and holes in semiconductors and ions in case of ionic conductors. Consider a section of such a conductor whose one end is hotter than the other end. Charge carriers at the hot end, being more energetic, will diffuse towards the colder end. The charge separation sets up an electric $\vec{E}$. Diffusion of carriers would stop when the attractive force on the carriers due to this field $\vec{E}$ is strong enough to retard the motion of the carriers due to thermal effect.



We can represent the effect of the thermal gradient responsible for the diffusive motion of the carriers by an effective field $\overrightarrow{E'}$.This effective field is proportional to the thermal gradient and can be written as

$$E' = \sigma.\frac{dT}{dx}$$

where σ is known as the Thomson coefficient for the material of the conductor. The $\in_{th}$Thomson electromotive force is given by

$$\in_{th} = \int E' dx = \int_{T1}^{T2} \sigma dT$$

where T1 and T2 are the temperatures at the two ends of the rod. Thomson effect is a manifestation of the Thomson emf described above. Clearly, one cannot demonstrate the existence of the emf by using it to drive a current in a close circuit. This is because if one uses a single metal with a temperature gradient, the integral σdT around a close loop is zero. For dis-similar metals, Peltier effect dominates over Thomson effect. When a current I is passed through a homogeneous conductor with a temperature gradient, the rate of heat production per unit volume is given by

$$\dot{Q} = \rho I^2 + \sigma I \frac{dT}{dx}$$

where ρ is the resistivity of the sample. The first term is the irreversible Joule heat. The second term is due to Thomson emf.

In metals such as copper and zinc, the hotter end is at a higher potential (as shown in the figure above). In such a situation if the current due to an external supply is in the same direction as the direction of decreasing potential, there is additional evolution of heat due to Thomson effect and the net heat produced is more than the Joule heat. If the direction of the current is reversed, heat energy is converted to electrical energy due to Thomson effect and the rate production of heat is reduced. This is known as **positive Thomson effect**.

An anomalous situation occurs in metals such as cobalt and iron. In these metals the hotter end is at a lower potential so that charge carriers move against the thermal gradient. The effect is opposite of what happens in case of positive Thomson effect. Such anomalous effect is known as **negative thomson effect**. Lead shows zero Thomson effect. The simple physical picture given above cannot explain the strange behavior.