Chapter 7 Transport Properties of Semiconductors

Lecture 4/5: Thermoelectric Effects

1. Seebeck Coefficient

N-type semiconductor

![Diagram of Seebeck Coefficient]

Temperature dependence of $E_\text{f}$: (a) low temperature $T<T_1$; (b) intermediate temperature $T_1<T<T_2$; and (c) high temperature $T>T_2$.

1) For high temperature $T>T_2$, 

$$E_f = E_i - k_B T \ln \frac{N_c}{N_D}$$

$$n = p = n_i = (N_c N_v)^{1/2} e^{-E_i / k_B T}$$

2) For low temperature $T<T_1$, 

$$E_f = \frac{E_c + E_D}{2} - \frac{k_B T}{2} \ln \frac{2N_c}{N_D}$$
\[
n = \left( \frac{N_c N_p}{2} \right)^{1/2} e^{-(E_c - E_f)/2k_B T} = N_D + p = N_D
\]

3) For intermediate temperature \( T_1 < T < T_2 \),

\[
E_f = E_c - k_B T \ln \frac{N_c}{N_D}
\]

\[
n = N_D + p \quad \text{and} \quad p = \frac{n_i^2}{N_D} = \frac{(N_c N_p)^{1/2}}{N_D} e^{-E_c/2k_B T}
\]

Thus, there are more electrons at higher temperature. The electron density gradient generates a diffusion of electrons from the hot side towards the cold side. And the electrons in the hot side have higher energy, or move faster. For an open circuit, electrons will accumulate at the cold end, which produces an electric field to counterbalance the diffusion until the net current is equal to zero.

Therefore, the electrostatic potential difference is attributed to both the electric field and the Fermi energy (\( E_c - E_f \)) change, as shown in the following figure, where

\[
qV_s = qV_b + \Delta(E_c - E_f) = -\mathcal{E} x \Delta x + d(E_c - E_f) \frac{dx}{dx} \Delta x
\]
Seebeck coefficients:

n-type: Negative!

\[
S_n = -\frac{k_B}{q} \left( \frac{5}{2} + s \right) \frac{E_c - E_f}{qT} = -\frac{1}{qT} \left[ \frac{5}{2} + s \right] k_B T + E_c - E_f
\]

p-type: Positive!

\[
S_p = \frac{k_B}{q} \left( \frac{5}{2} + s \right) + \frac{E_c - E_f}{qT} = \frac{1}{qT} \left[ \frac{5}{2} + s \right] k_B T + E_f - E_v
\]

For compensated semiconductors,

\[
S = \frac{S_n \sigma_n + S_p \sigma_p}{\sigma_n + \sigma_p}
\]

Seebeck coefficients of metals are much smaller than those of semiconductors, and are given by

\[
S = -\frac{\pi^2}{3} \frac{k_B^2 T}{qE_f}
\]

Phonon-drag effect
2. Peltier Effect

Heat is generated or absorbed when a current flows through a junction of two materials.

As shown in the above energy band diagram, electrons in the valence band have an average energy of \((s+5/2)k_B T\). The scattering factor \(s\) is \(-1/2\) for acoustic phonon scattering, 0 for neutral impurity scattering and \(3/2\) for ionized impurity scattering.

An energy equal to \(E_c-E_f+E_e\) will be absorbed if an electron flows from the metal to the n-type semiconductor. The same amount of energy will be emitted if an electron flows from the semiconductor to the metal.

\[
q\pi_{ab} = E_c - E_f + \frac{5}{2} + s k_B T
\]

or

\[
\pi_{ab} = \frac{E_c - E_f}{q} + \frac{\frac{5}{2} + s k_B T}{q}
\]

If \(a\) and \(b\) are both n-type with different doping densities \(n_a\) and \(n_b\) respectively, the Peltier coefficient can be written as

\[
\pi_{ab} = \frac{k_B T}{q} \ln \frac{n_a}{n_b}
\]

Similarly for p-type materials,

\[
\pi_{ab} = \frac{k_B T}{q} \ln \frac{p_b}{p_a}
\]
Thomson Effect

\[ \tau_s = T \frac{dS}{dT} \]

Thermal conductivity

\[ \kappa = \kappa_c + \kappa_p \]

Applications

1) Thermocouple

For example, chromel-alumel pair has \( S_{ab} \approx 40\mu V/K \) at 300K.

2) Electricity generator
3) Refrigerator