Temperature Dependence of the Fermi Level

$$n = N_c Exp\left(\frac{E_F - E_C}{kT}\right) \qquad p = N_v Exp\left(\frac{E_V - E_F}{kT}\right)$$

$$E_F - E_C = kT * Ln\left(\frac{n}{N_C}\right) \qquad E_V - E_F = kT * Ln\left(\frac{p}{N_V}\right)$$

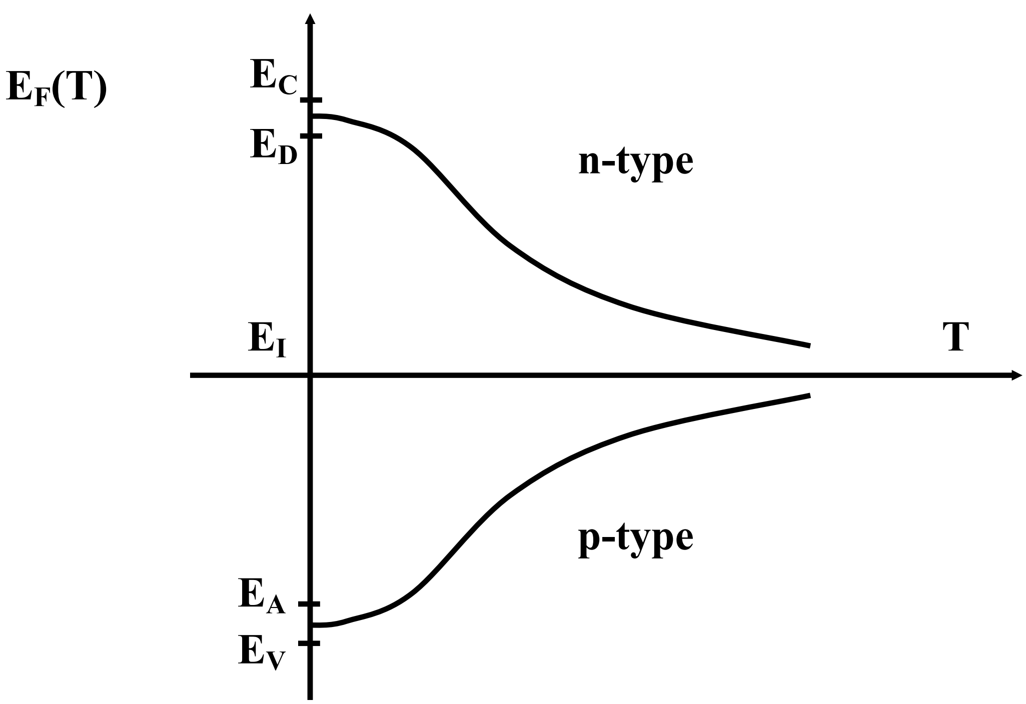
For an n-type semiconductor at room temperature, $n \approx N_D$

For an p-type semiconductor at room temperature, $p \approx N_A$

As T increases, the doping becomes less important than the thermal generation of carriers E_F tends to E_I

For an n-type, $\frac{\partial E_F}{\partial T} < 0$

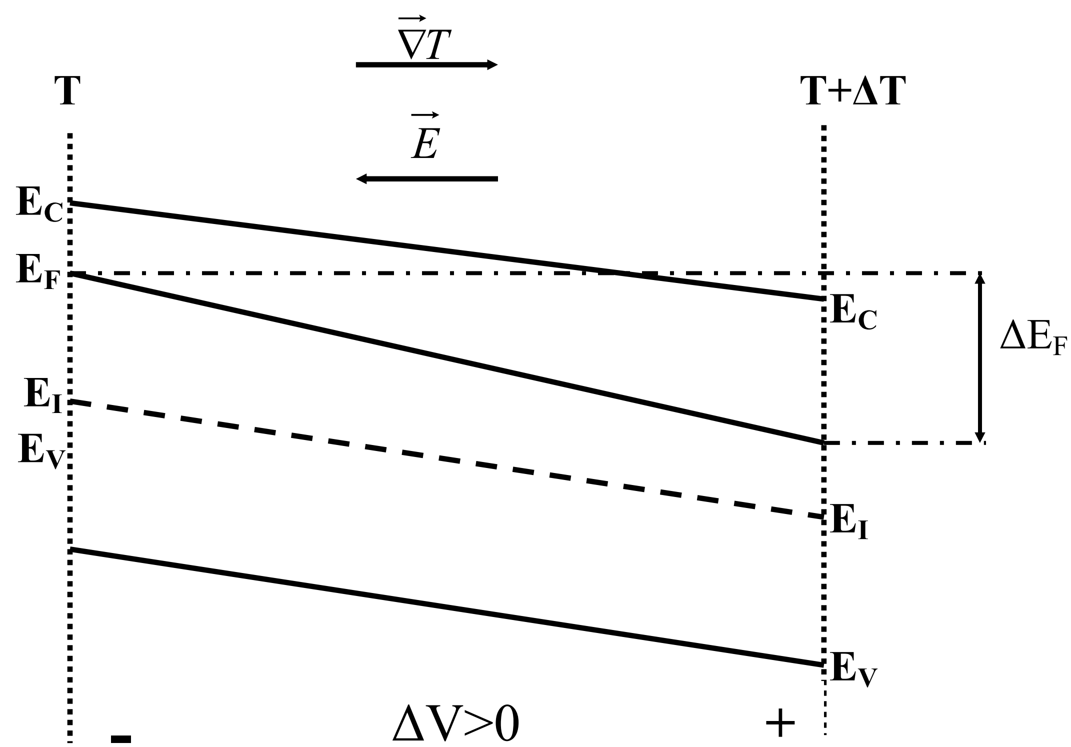
For an p-type, $\frac{\partial E_F}{\partial T} > 0$



Thermoelectric Effect

$E_F = E_F(T) \longrightarrow$ A temperature gradient induces a Fermi Level Gradient

N-type Semiconductor with a gradient of Temperature



$$-\Delta V = \frac{1}{q}\Delta E_F = \alpha \Delta T$$

α : Thermoelectric power, Seebeck Coefficient

For n-type, $\alpha < 0$, The induced electric field and the gradient of temperature are in the same direction.

For p-type, $\alpha > 0$, The induced electric field and the gradient of temperature are in opposite direction.

Seebeck Coefficient

For $\nabla T = 0$:

$$J_n = n\mu_n \frac{\partial E_F}{\partial x} = \sigma_n \frac{1}{q}\frac{\partial E_F}{\partial x}$$

For $\nabla T \neq 0$:

$$J_n = \sigma_n \left(\frac{1}{q}\frac{\partial E_F}{\partial x} - \alpha \frac{\partial T}{\partial x} \right)$$

$$\alpha_n = -\frac{(E_c - E_F) + 2kT}{qT} = -\frac{k}{q}\left(2 + Ln\left(\frac{N_C}{n} \right) \right) < 0$$

$$\alpha_p = \frac{(E_F - E_V) + 2kT}{qT} = \frac{k}{q}\left(2 + Ln\left(\frac{N_v}{p} \right) \right) > 0$$

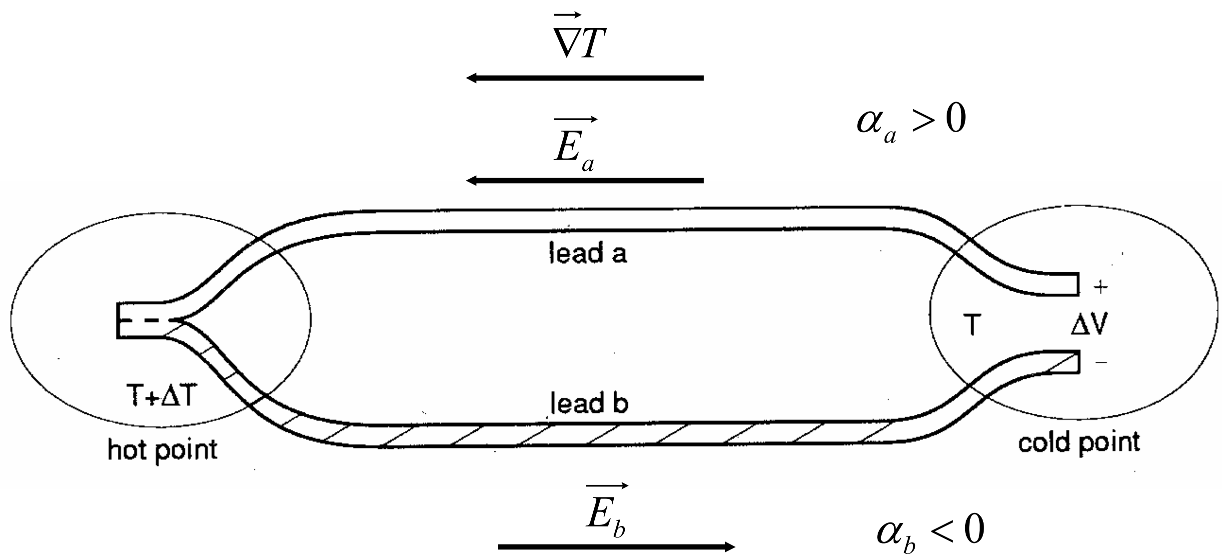
The Seebeck effect depends on carrier concentration and therefore depends on resistivity.

For pratical purposes,

$$|\alpha_{si}| \approx \frac{2.6k}{q} Ln\left(\frac{\rho}{5*10^{-6}\Omega m} \right)$$

Typically, for semiconductors, α is a few 100μV/K

Thermocouples



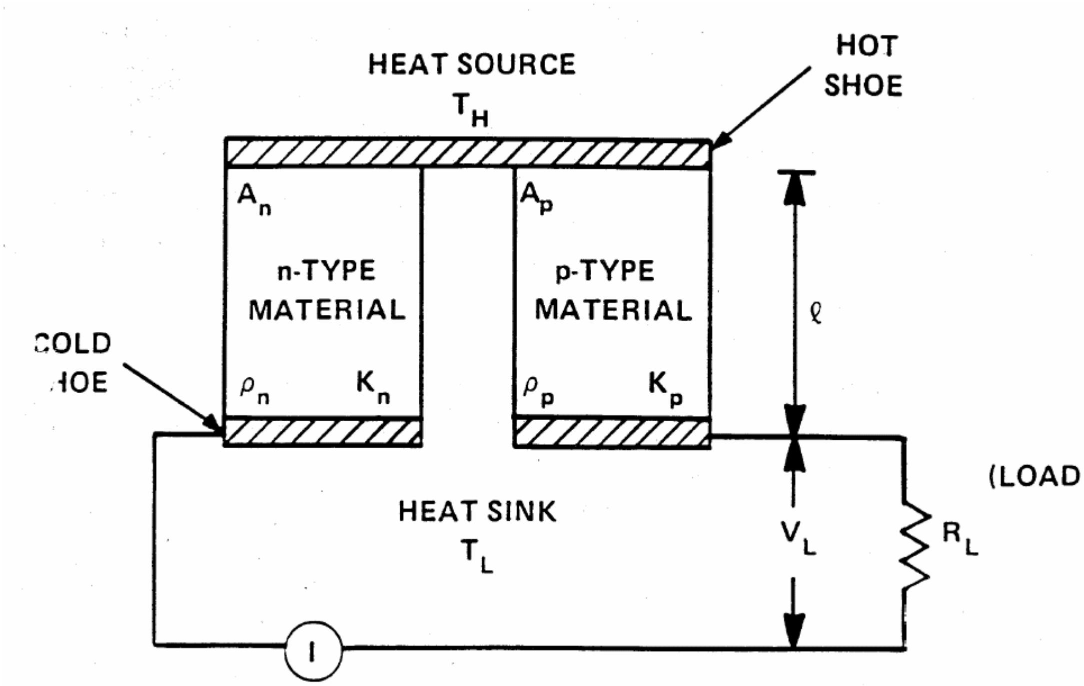
$$\Delta V = (\alpha_a - \alpha_b)\Delta T$$

TABLE 2 Seebeck Coefficient for Some Metals and Mono- and Poly-Silicon (in μV/K)

Material	273 K		300 K
p-type mono silicon (Si)			300 to 1000
Antimony (Sb)		43[a]	
Chrome (Cr)	18.8		17.3
Gold (Au)	1.79		1.94
Copper (Cu)	1.70		1.83
Aluminum (Al)			−1.7
Platinum (Pt)	−4.45		−5.28
Nickel (Ni)	−18.0		
Bismuth (Bi)		−79[a]	
n-type polysilicon (Si)			−200 to −500

[a]Averaged over 0 to 100 C.

Thermoelectric Generation



Efficiency:

$$\eta = \frac{R_L I^2}{Q_{in}}$$

Q_{in} : Thermal Power Input

The efficiency is a function of Z: Figure of merit for Thermoelectric Material:

$$Z = \frac{\alpha^2}{\rho\kappa}$$

ρ : Electrical resistivity

κ : Thermal Conductivity

Peltier Effect

Opposite to Seebeck effect: Applied Voltage induces heat flow
At a junction between two material A and B

$$Q_{ab} = \Pi_{ab} I$$

With Π_{ab} the Peltier coefficient

$$\Pi_{ab} = T\alpha_{ab}$$

$$Q_{ab} = \alpha_{ab} TI = (\alpha_a - \alpha_b) TI$$

Application: Thermoelectric coolers