Recapitulate

- Role of Bragg reflection.

$$\frac{2\pi}{\lambda} = \frac{n\pi}{a}$$

$$\Rightarrow 2a = n\lambda$$

- Discussed the electron transport in Kronig Penny model.

Recapitulate

- Filled Bands do not conduct.
- Transport a the bottom of band can be described in terms of electrons while at the top of the band in terms of holes.
- Difference between metals, insulators and semiconductors.

Conductivity

The electron and hole currents add and so does the conductivity

$$\sigma = ne\mu_n + pe\mu_p$$

$$\mu \equiv \left| \frac{e\tau}{m^*} \right|$$

Hall Effect

The electron and hole oppose each other in Hall effect as both the type of charge carriers get deflected to the same face.

$$R_H = \frac{1}{e}\frac{p\mu_p^{\,2} - n\mu_n^{\,2}}{\left(p\mu_p + n\mu_n\right)^2}$$

Electrons in CB per Unit Volume

$$n = \int_{\varepsilon_c}^{\varepsilon_{ct}} g(\varepsilon) f(\varepsilon) d\varepsilon$$

$$g(\varepsilon) = \frac{1}{2\pi^2} \left(\frac{2m_e^*}{\hbar^2} \right)^{3/2} (\varepsilon - \varepsilon_c)^{1/2}$$

$$f(\varepsilon) = \frac{1}{e^{(\varepsilon - \varepsilon_F)/kT} + 1}$$

Note

- It is per unit volume, so *V* is not therein the density of state expression.
- An effective mass (*d.o.s*) has been used rather than the actual mass of electron.
- The zero of the energy has been shifted to the bottom of conduction band.

Two Approximations

1. Put $\varepsilon_{ct} = \infty$.

2. Neglect 1 in the denominator of $f(\varepsilon)$.

After the Approximations

$$n = A\int_{\varepsilon_c}^{\infty}\left(\varepsilon - \varepsilon_c\right)^{1/2} e^{-(\varepsilon-\varepsilon_F)/kT} d\varepsilon$$

$$= Ae^{-(\varepsilon_c-\varepsilon_F)/kT}\int_{\varepsilon_c}^{\infty}\left(\varepsilon - \varepsilon_c\right)^{1/2} e^{-(\varepsilon-\varepsilon_c)/kT} d\varepsilon$$

$$A \equiv \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}$$

$$n = Ae^{-(\varepsilon_c - \varepsilon_F)/kT} \int_{\varepsilon_c}^{\infty} \left(\varepsilon - \varepsilon_c\right)^{1/2} e^{-(\varepsilon - \varepsilon_c)/kT} d\varepsilon$$

Put $(\varepsilon - \varepsilon_c) / kT = x; d\varepsilon = (kT)dx$

$$n = Ae^{-(\varepsilon_c - \varepsilon_F)/kT} \left(kT\right)^{3/2} \int_0^{\infty} x^{1/2} e^{-x} dx$$

$$= \frac{\sqrt{\pi}}{2} Ae^{-(\varepsilon_c - \varepsilon_F)/kT} \left(kT\right)^{3/2}$$

Final Expression

$$n = 2\left(\frac{m_e^* kT}{2\pi\hbar^2}\right)^{3/2} e^{-(\varepsilon_c - \varepsilon_F)/kT}$$

For $m_e^* = m_e$

$$n \approx 4.83 \times 10^{21} T^{3/2} e^{-(\varepsilon_c - \varepsilon_F)/kT} m^{-3}$$

Hole Statistics

$$f_h(\varepsilon) = 1 - f(\varepsilon)$$

$$= 1 - \frac{1}{e^{(\varepsilon - \varepsilon_F)/kT} + 1}$$

$$= \frac{e^{(\varepsilon - \varepsilon_F)/kT}}{e^{(\varepsilon - \varepsilon_F)/kT} + 1}$$

$$= \frac{1}{e^{(\varepsilon_F - \varepsilon)/kT} + 1}$$

Hole Density of States

$$g_h(\varepsilon) = \frac{1}{2\pi^2}\left(\frac{2m_h^*}{\hbar^2}\right)^{3/2}\left(\varepsilon_v - \varepsilon\right)^{1/2}$$

Holes in VB per Unit Volume

$$p = \int_{-\infty}^{\varepsilon_v} g_h(\varepsilon) f_h(\varepsilon) d\varepsilon$$

$$p = B \int_{-\infty}^{\varepsilon_v} \left(\varepsilon_v - \varepsilon\right)^{1/2} e^{-(\varepsilon_F - \varepsilon)/kT} d\varepsilon$$

$$B \equiv \frac{1}{2\pi^2} \left(\frac{2m_h^*}{\hbar^2} \right)^{3/2}$$

Final Expression

$$p = B\int_{-\infty}^{\varepsilon_v} \left(\varepsilon_v - \varepsilon\right)^{1/2} e^{-(\varepsilon_F - \varepsilon)/kT} d\varepsilon$$

Put $(\varepsilon_v - \varepsilon) / kT = x; d\varepsilon = -(kT)dx$

$$p = 2\left(\frac{m_h^* kT}{2\pi\hbar^2}\right)^{3/2} e^{-(\varepsilon_F - \varepsilon_v)/kT}$$

Fermi Energy

Charge Neutrality Condition

$$n = p$$

$$2\left(\frac{m_e^* kT}{2\pi\hbar^2}\right)^{3/2} e^{-(\varepsilon_c - \varepsilon_F)/kT}$$

$$= 2\left(\frac{m_h^* kT}{2\pi\hbar^2}\right)^{3/2} e^{-(\varepsilon_F - \varepsilon_v)/kT}$$

$$\left(m_e^*\right)^{3/2} e^{-(\varepsilon_c-\varepsilon_F)/kT}$$

$$=\left(m_h^*\right)^{3/2} e^{-(\varepsilon_F-\varepsilon_v)/kT}$$

$$\frac{3}{2}kT\ln\left(\frac{m_e^*}{m_h^*}\right)=(\varepsilon_c-\varepsilon_F+\varepsilon_v-\varepsilon_F)$$

$$\varepsilon_F=\frac{\varepsilon_c+\varepsilon_v}{2}-\frac{3}{4}kT\ln\left(\frac{m_e^*}{m_h^*}\right)$$

Note

- To a good approximation the Fermi energy is half way in the band gap.
- This justifies neglect of 1 in the denominator in F.D. Statistics.
- It also has a very weak temperature dependence.

Order of Number of *n* at 300 K

$$n = 2\left(\frac{m_e^* kT}{2\pi\hbar^2}\right)^{3/2} e^{-(\varepsilon_c - \varepsilon_F)/kT}$$

$$\approx 2.5 \times 10^{25} e^{-(\varepsilon_c - \varepsilon_F)/kT}; \text{for } m_e^* = m_e$$

At 300K

$$kT \approx 0.026eV$$

n for Si and Ge at 300 K

$$n \approx 2.5 \times 10^{25} e^{-(1.1/2\times 0.026)}$$

$$\approx 1.63 \times 10^{16} m^{-3} \text{ for Si}$$

$$n \approx 2.5 \times 10^{25} e^{-(0.72/2\times 0.026)}$$

$$\approx 2.42 \times 10^{19} m^{-3} \text{ for Ge}$$

Note

- There as an exponential dependence of n on temperature.
- Hence the conductivity increases with temperature, even though mobility may show decrease.

Extrinsic Semiconductor

- Doping of group 3 or group 5 elements.
- Group 3 doping creates electron states in the gap close to the top of valence band.
- Group 5 doping creates the same in the gap close to bottom of conduction band.

Donor Energy Levels

$$\varepsilon_c - \varepsilon_d$$

	P	As	Sb
Ge	0.012	0.0127	0.0096
Si	0.045	0.049	0.039

Acceptor Energy Levels

$$\varepsilon_a - \varepsilon_v$$

	B	Al	Ga
Ge	0.0104	0.0102	0.0108
Si	0.045	0.057	0.065

Charge Carriers for Doped SC

- The old expressions are valid. Only position of Fermi level changes.

- Fermi Level has a strong dependence on temperature.

Fermi Energy

General Charge Neutrality Condition

$$n + N_a^- = p + N_d^+$$

Two Approximations

1. All impurity atoms are ionized. Quite valid at R.T.

2. Minority carrier concentration is negligible. Valid for reasonable dopings.