1. Prove the following relationship for intrinsic semiconductors;

$$E_F = E_g/2 + (3/4)k_BT\ln(m_h^*/m_e^*)$$

which represents that since k_BT is small at room temperature, and the effective masses of electrons and holes are not very much different, we can say that the Fermi level is roughly halfway between the valence and conduction bands.

1. In intrinsic semiconductor material, $N_e^* = N_h^*$.

where, $N_e^* = \frac{V}{4}\left(\frac{2m_e^* k_BT}{\pi\hbar^2}\right)^{3/2}\exp\left(-\frac{E_c-E_F}{k_BT}\right)$

$N_h^* = \frac{V}{4}\left(\frac{2m_h^* k_BT}{\pi\hbar^2}\right)^{3/2}\exp\left(-\frac{E_F-E_V}{k_BT}\right)$.

$N_e^* = N_h^*$,

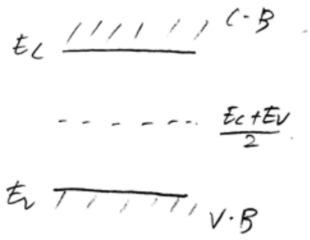
$$\frac{V}{4}\left(\frac{2m_e^* k_BT}{\pi\hbar^2}\right)^{3/2}\exp\left(-\frac{E_c-E_F}{k_BT}\right) = \frac{V}{4}\left(\frac{2m_h^* k_BT}{\pi\hbar^2}\right)^{3/2}\exp\left(-\frac{E_F-E_V}{k_BT}\right).$$

$\rightarrow \exp\left(\frac{2E_F-E_c-E_V}{k_BT}\right) = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$.

$\rightarrow 2E_F - E_c - E_V = k_BT\ln\left(\frac{m_h^*}{m_e^*}\right)^{3/2}$

$\rightarrow E_F = \frac{E_c+E_V}{2} + \frac{3}{4}k_BT\ln\left(\frac{m_h^*}{m_e^*}\right)$.

midgap energy.



2. In the figure below, σ is plotted as a function of the reciprocal temperature for an intrinsic semiconductor. Calculate the gap energy. (*Hint*: Use (8.14) and take the ln from the resulting equation.)

eq (8.14)

$$\sigma = 4.84 \times 10^{15} \left(\frac{m^*}{m_0}\right)^{3/2} T^{3/2} e(\mu_e + \mu_h) \exp\left[-\frac{E_g}{2k_0T}\right]$$

$$\ln\sigma = \text{const.} - \frac{3}{2}\ln\frac{1}{T} - \frac{E_g}{2k_0T}$$

주어진 그림에서 σ ($\log \sigma$) vs $1/T$ 그래프는 거의 직선을 나타낸다. 이는 기울기 $-E_g/2k_0$에 비해 $-\frac{3}{2}\ln\frac{1}{T}$ 이 주는 효과가 매우 작기 때문이다. 좀 더 엄밀하게 mobility 도 온도 의존성을 가지지만, 그 효과 역시 기울기에 영향을 주지 않는다 → 결국 그래프의 기울기를 구하면 된다

$$\frac{\ln 1 - \ln 100}{(0.8-0.6)\times 10^{-2}} = -2302.6\,(K) = -\frac{E_g}{2 \cdot k_0} \quad \therefore E_g = 0.397\,(eV)$$

3. Consider a silicon crystal containing 10^{12} phosphorous atoms per cubic centimeter. Is the conductivity increasing or decreasing when the temperature is raised from 300˚C to 350˚C? Explain by giving numerical values for the mechanisms involved.

300°C 이상의 온도는 donor (phosphorous) 에서 제공된 extra electron (10^{12} 개/cm^3) 이 대부분 conduction band 에 존재하게 한다 (350°C 에서도 동일한 효과)

intrinsic effect 를 알기 위해 각 온도에서의 자유 전자수를 고려.

$$N_e = 4.84 \times 10^{15} \left(\frac{m_e^*}{m_0}\right)^{3/2} T^{3/2} \exp\left[-\left(\frac{E_g}{2kT}\right)\right] \quad (m_e^*/m_0 = 1)$$

$$E_g(300°C) = E_{g0} - \frac{\xi \cdot 573^2}{573 + \theta_D} \quad \left(\begin{array}{l} \xi = 5\times 10^{-4}\ (eV/K) \\ \theta_D(Si) = 650\,K \end{array} \right.$$

$$= 1.17 - \frac{5\times 10^{-4} \times 573^2}{573 + 650} = 1.04\,(eV)$$

$$E_g(350°C) = 1.17 - \frac{5\times 10^{-4}\times 623^2}{623+650} = 1.02\,(eV)$$

$$\text{at } 300°C:\ N_e = 4.84\times 10^{15} \times 1 \times 573^{3/2} \cdot \exp\left(\frac{-1.04}{2\times 8.616\times 10^{-5}\times 573}\right) = 1.77\times 10^{15}\ (개/cm^3)$$

$$\text{at } 350°C:\ N_e = 4.84\times 10^{15} \times 1 \times 623^{3/2} \cdot \exp\left(\frac{-1.02}{2\times 8.616\times 10^{-5}\times 623}\right) = 5.63\times 10^{15}\ (개/cm^3)$$

$\sigma = N_e e \mu_e$ 에서, 온도가 300°C → 350°C 가 됨에 따라 intrinsic carrier 의 수가 늘어나므로 conductivity 는 증가한다. (mobility 에 의한 영향은 상대적으로 작음)

이 때의 conductivity 증가 (자유전자 수의 증가) 는 doping 의 효과 (extrinsic effect) 보다 intrinsic effect 에서 훨씬 더 많이 기인되었다

4. Consider a semiconductor with 10^{13} donors/cm^3 which has a binding energy of 10 meV.

(a) What is the concentration of extrinsic conduction electrons at 300 K ?

at 300K, band gap 1eV 가정, 300K 에서 $E_F \sim \frac{1}{2}E_g$ 가정.

$$\therefore N_{e,ex} = N_D \times \left(1 - \frac{1}{\frac{1}{2}e^{(E_D - E_F)/kT} + 1}\right) = 10^{13} \times \left(1 - \frac{1}{0.5 \cdot e^{(-0.01+0.5)/(8.616\times10^{-5} \cdot 300)} + 1}\right) \cong 10^{13} \text{(개/cm}^3\text{)}$$

(b) Assuming a gap energy of 1 eV (and m* = m_0), what is the concentration of intrinsic conduction electrons?

$$N_{e,in} = 4.84\times10^{15} \times (1) \times 300^{3/2} \exp\left(\frac{-1}{2\times 8.616\times10^{-5} \times 300}\right) = 9.99\times10^{10} \text{(개/cm}^3\text{)}$$

(c) Which contribution is larger?

$N_{e,extrinsic} > N_{e,intrinsic}$ 이므로

extrinsic effect 에 의한 conduction 이 전체 conduction 에 더 많이 기여한다.