Table 4.1 | Effective density of states function and effective mass values

	N_c (cm^{-3})	N_v (cm^{-3})	m_n^*/m_0	m_p^*/m_0
Silicon	2.8×10^{19}	1.04×10^{19}	1.08	0.56
Gallium arsenide	4.7×10^{17}	7.0×10^{18}	0.067	0.48
Germanium	1.04×10^{19}	6.0×10^{18}	0.55	0.37

Table 4.2 | Commonly accepted values of n_i at $T = 300$ K

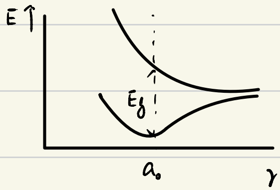
Silicon	$n_i = 1.5 \times 10^{10}$ cm^{-3}
Gallium arsenide	$n_i = 1.8 \times 10^{6}$ cm^{-3}
Germanium	$n_i = 2.4 \times 10^{13}$ cm^{-3}

4.1 Calculate the intrinsic carrier concentration, n_i, at $T = 200$, 400, and 600 K for (*a*) silicon, (*b*) germanium, and (*c*) gallium arsenide.

$$n_i^2 = n_o p_o$$

$$= N_c N_v \exp\left(\frac{-E_g}{kT}\right) \quad , \quad N_c = N_{co}\left(\frac{T}{300}\right)^{\frac{3}{2}}$$

$$= N_{co} N_{vo} \left(\frac{T}{300}\right)^3 \exp\left(\frac{-E_g}{kT}\right) \quad 300k, \ a_o, \ E_g = 1.12\ eV$$



4.7 Assume the Boltzmann approximation in a semiconductor is valid. Determine the ratio of $n(E) = g_C(E) f_F(E)$ at $E = E_c + 4kT$ to that at $E = E_c + kT/2$.

$$\frac{n(E_1)}{n(E_2)} = \frac{g_c(E_1)}{g_c(E_2)} \frac{\exp\left(\frac{E_1 - E_F}{kT}\right)}{\exp\left(\frac{E_2 - E_F}{kT}\right)}$$

$$= \frac{\frac{4\pi (2m_n^*)^{\frac{3}{2}}}{h^3} \sqrt{E_1 - E_c}}{\frac{4\pi (2m_n^*)^{\frac{3}{2}}}{h^3} \sqrt{E_2 - E_c}} \exp\left[\frac{(E_1 - E_F) - (E_2 - E_F)}{kT}\right)$$

$$= \frac{\sqrt{E_1 - E_c}}{\sqrt{E_2 - E_c}} \exp\left(\frac{E_1 - E_2}{kT}\right)$$

$$= \frac{\sqrt{4kT}}{\sqrt{\frac{kT}{2}}} \exp\left[-\left(4 - \frac{1}{2}\right)\right]$$

$$= 2\sqrt{2} \exp(-3.5) = 0.085$$

4.11 Calculate E_{Fi} with respect to the center of the bandgap in silicon for $T = 200$, 400, and 600 K.

$$n_0 = p_0$$

$$N_c \exp\left(\frac{-(E_c - E_{Fi})}{kT}\right) = N_v \exp\left(\frac{-(E_{Fi} - E_v)}{kT}\right)$$

$$\ln(N_c) - \frac{E_c - E_{Fi}}{kT} = \ln(N_v) - \frac{(E_{Fi} - E_v)}{kT}$$

$$kT \ln(N_c) - E_c + E_{Fi} = kT \ln(N_v) - E_{Fi} + E_v$$

$$2E_{Fi} - (E_c + E_v) = kT \ln\left(\frac{N_v}{N_c}\right)$$

$$E_{Fi} - \underbrace{\tfrac{1}{2}(E_c + E_v)}_{E_{midgap}} = \tfrac{1}{2} kT \ln\left(\frac{N_v}{N_c}\right)$$

4.17 Silicon at $T = 300$ K is doped with arsenic atoms such that the concentration of electrons is $n_0 = 7 \times 10^{15}$ cm^{-3}. (*a*) Find $E_c - E_F$. (*b*) Determine $E_F - E_v$. (*c*) Calculate p_0. (*d*) Which carrier is the minority carrier? (*e*) Find $E_F - E_{Fi}$.

(a) $n_0 = N_c \exp\left(\frac{-(E_c - E_F)}{kT}\right)$ $\qquad N_c = 2.8 \times 10^{19}$

$\ln(n_0) = \ln(N_c) - \frac{E_c - E_F}{kT}$ $\qquad N_v = 1.04 \times 10^{19}$

$$E_c - E_F = kT \ln\left(\frac{N_c}{n_0}\right)$$

$$= 0.0259 \cdot \ln\left(\frac{2.8 \times 10^{19}}{7 \times 10^{15}}\right)$$

$$= 0.2148 \text{ eV} \#$$

(b) $E_g - (E_c - E_F) = E_F - E_v$, $1.12 - 0.2148 = 0.9052$ eV

(c) $p_0 = N_v \exp\left(\frac{-(E_F - E_v)}{kT}\right)$

$$= 1.04 \times 10^{19} \exp\left(\frac{-0.9052}{0.0259}\right) = 6894.8534 \approx 6.9 \times 10^3$$

(d) Holes

(e) $n_0 = n_i \exp\left(\frac{E_F - E_{Fi}}{kT}\right) = \ln(n_0) = \ln(n_i) + \frac{E_F - E_{Fi}}{kT}$

$$\Rightarrow E_F - E_{Fi} = kT \ln\left(\frac{n_0}{n_i}\right) = 0.0259 \cdot \ln\left(\frac{7 \times 10^{15}}{1.5 \times 10^{10}}\right) = 0.338 \text{ eV}$$

4.20 (*a*) If $E_c - E_F = 0.28$ eV in gallium arsenide at $T = 375$ K, calculate the values of n_0 and p_0. (*b*) Assuming the value of n_0 in part (*a*) remains constant, determine $E_c - E_F$ and p_0 at $T = 300$ K.

(a) $n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$

$kT = (0.0259)\frac{375}{300} = 0.032375$

$N_{c0} = 4.7 \times 10^{17}$

$N_{v0} = 7 \times 10^{18}$

$N_c = 4.7 \times 10^{17}\left(\frac{375}{300}\right)^{\frac{3}{2}}$

$= 6.56 \times 10^{17}$

$N_v = 7 \times 10^{18}\left(\frac{375}{300}\right)^{\frac{3}{2}}$

$= 6.56 \times 10^{17} \exp\left(\frac{-0.28}{0.032375}\right)$

$= 1.15 \times 10^{14}$

p_0: $E_F - E_V = E_g - (E_n - E_F)$

$1.42 - 0.28 = 1.14$

$p_0 = N_v \exp\left(\frac{-1.14}{0.032375}\right) =$

(b) $E_c - E_F = kT \ln\left(\frac{N_c}{N_0}\right)$

$= 0.0259 \ln\left(\frac{4.7 \times 10^{17}}{1.15 \times 10^{14}}\right) = 0.2154\,\text{eV}$

$E_F - E_V = 1.42 - 0.2154 = 1.2046\,\text{eV}$

$p_0 = 7 \times 10^{18} \cdot \exp\frac{-1.2046}{0.0259} = 4.42 \times 10^{-2}\ \text{cm}^{-3}$

4.24 Silicon at $T = 300$ K is doped with boron atoms such that the concentration of holes is $p_0 = 5 \times 10^{15}$ cm^{-3}. (*a*) Find $E_F - E_v$. (*b*) Determine $E_c - E_F$. (*c*) Determine n_0. (*d*) Which carrier is the majority carrier? (*e*) Determine $E_{Fi} - E_F$.

(a) $E_F - E_v = kT \ln\left(\frac{N_v}{p_0}\right) = 0.0259 \cdot \ln\left(\frac{1.04 \times 10^{19}}{5 \times 10^{15}}\right) = 0.1979\,eV$

(b) $E_n - E_F = E_g - (E_F - E_v) = 1.12 - 0.1979 = 0.9221\,eV$

(c) $n_0 = N_c \exp\left(\frac{-(E_c - E_F)}{kT}\right) = 2.8 \times 10^{19} \cdot \exp\left(\frac{-0.922}{0.0259}\right) = 9.66 \times 10^{3}\ cm^{-3}$

(d) Holes

(e) $E_{Fi} - E_F = kT \ln\left(\frac{p_0}{n_i}\right)$

$= kT \ln\left(\frac{5 \times 10^{15}}{1.5 \times 10^{10}}\right) = 0.329\,eV$

4.27 Repeat Problem 4.26 for silicon.

4.28 (*a*) Assume that $E_F = E_c + kT/2$ at $T = 300$ K in silicon. Determine n_0. (*b*) Repeat part (*a*) for GaAs.

(a) $E_c - E_F < 3$ $\qquad \eta_F = \frac{E_c - E_F}{kT} = 0.5$

$n_0 = \frac{2}{\sqrt{\pi}} N_c F_{1/2}(\eta_F)$

$F_{1/2}(0.5) \simeq 1.0$ ，有考的話應該會給，沒給要算 $F_{1/2}$

$n_0 = \frac{2}{\sqrt{\pi}}\, 2.8 \times 10^{19} \cdot 1 = 3.16 \times 10^{19}\ cm^{-3}$

$F_{1/2} = \int_{E_c}^{\infty} \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$

沒辦法手算

(b)

4.30 (*a*) In silicon at $T = 300$ K, we find that $E_F - E_C = 4\,kT$. Determine the electron concentration. (*b*) Repeat part (*a*) for GaAs.

同 4.28

$\boxed{\textbf{4.36}}$ (*a*) Consider a germanium semiconductor at $T = 300$ K. Calculate the thermal equilibrium electron and hole concentrations for (i) $N_d = 2 \times 10^{15}$ cm^{-3}, $N_a = 0$, and (ii) $N_a = 10^{16}$ cm^{-3}, $N_d = 7 \times 10^{15}$ cm^{-3}. (*b*) Repeat part (*a*) for GaAs. (*c*) For the case of GaAs in part (*b*), the minority carrier concentrations are on the order of 10^{-3} cm^{-3}. What does this result mean physically?

Ge : $n_i = 2.4 \times 10^{13}$ cm^{-3}
300k. a.

$$(i) \quad n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

$$= \frac{2 \times 10^{15}}{2} + \sqrt{\left(\frac{2 \times 10^{15}}{2}\right)^2 + (2.4 \times 10^{13})^2}$$

$$= 2 \times 10^{15}$$

$$p_0 = \frac{n_i^2}{n_0} = \frac{(2.4 \times 10^{13})^2}{2 \times 10^{15}} = 2.88 \times 10^{11}$$

$$(ii) \quad p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

$$= \frac{3 \times 10^{15}}{2} + \sqrt{\left(\frac{3 \times 10^{15}}{2}\right)^2 \cancel{+ (2.4 \times 10^{13})^2}}$$

$$= 3 \times 10^{15}\ \text{cm}^{-3}$$

$$n_0 = \frac{n_i^2}{p_0} = 1.92 \times 10^{11}$$

4.39 A silicon semiconductor material at $T = 300$ K is doped with arsenic atoms to a concentration of 2×10^{15} cm^{-3} and with boron atoms to a concentration of 1.2×10^{15} cm^{-3}. (*a*) Is the material n type or p type? (*b*) Determine n_0 and p_0. (*c*) Additional boron atoms are to be added such that the hole concentration is 4×10^{15} cm^{-3}. What concentration of boron atoms must be added and what is the new value of n_0?

(a) $N_d > N_a$ n-type

(b)

$$n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

$$= 4\times10^{14} + \sqrt{(4\times10^{14})^2 + \cancel{(1.5\times10^{10})^2}}$$

$$= 8\times10^{14}\ \mathrm{cm^{-3}}$$

$$p_0 = \frac{n_i^2}{n_0} = \frac{(1.5\times10^{10})^2}{8\times10^{14}} = 2.81\times10^{5}\ \mathrm{cm^{-3}}$$

(c)

$$p_0 = 4\times10^{15} = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

$$4\times10^{15} = \frac{N_a - 2\times10^{15}}{2} + \sqrt{\left(\frac{N_a - 2\times10^{15}}{2}\right)^2 + \underbrace{\cancel{(1.5\times10^{10})^2}}_{\text{太小省略}}}$$

$$= N_{a\,new} - 2\times10^{15}$$

$$N_{a\,new} = 6\times10^{15}$$

$$N_{a\,add} = 4.8\times10^{15}\ \mathrm{cm^{-3}}$$

$$n_0 = \frac{n_i^2}{p_0} = 5.625\times10^{4}\ \mathrm{cm^{-3}}$$

4.47 In silicon at $T = 300$ K, it is found that $N_a = 7 \times 10^{15}$ cm^{-3} and $p_0 = 2 \times 10^4$ cm^{-3}. (*a*) Is the material n type or p type? (*b*) What are the majority and minority carrier concentrations? (*c*) What must be the concentration of donor impurities?

(a) n-type

(b) $n_0 = \dfrac{n_i^2}{p_0} = \dfrac{(1.5\times10^{10})^2}{2\times10^4} = 1.125\times10^{16}\ cm^{-3}$

$p_0 = 2\times10^4\ cm^{-3}$

(c) $n_0 \simeq N_d - N_a$

$1.125\times10^{16} = N_d - 7\times10^{15}$

$N_d = 1.825\times10^{16}$

4.49 Consider silicon at $T = 300$ K with donor concentrations of $N_d = 10^{14}$, 10^{15}, 10^{16}, and 10^{17}, cm^{-3}. Assume $N_a = 0$. (*a*) Calculate the position of the Fermi energy level with respect to the conduction band for these donor concentrations. (*b*) Determine the position of the Fermi energy level with respect to the intrinsic Fermi energy level for the donor concentrations given in part (*a*).

$$E_c - E_f = kT\left(\frac{N_c}{n_0}\right)$$

$$n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

$N_d \gg n_i$

$$n_0 \simeq N_d$$

$$E_c - E_f = kT\ln\left(\frac{N_c}{N_d}\right)$$

$N_c = 2.8 \times 10^{19}$ from Table 1

(a) $E_c - E_f = 0.0259 \ln\left(\frac{2.8\times10^{19}}{10^{14}}\right) = 0.3249\,eV$

$\vdots \qquad 10^{15} \qquad = 0.2652\,eV$

$\vdots \qquad 10^{16} \qquad = 0.2056\,eV$

$\vdots \qquad 10^{17} \qquad = 1.459\,eV$

(b)

$$E_F - E_{Fi} = kT\ln\left(\frac{N_d}{n_i}\right)$$

$$= 0.0259\ln\left(\frac{N_d}{1.5\times10^{10}}\right)$$

4.50 A silicon device is doped with donor impurity atoms at a concentration of 10^{15} cm^{-3}. For the device to operate properly, the intrinsic carriers must contribute no more than 5 percent to the total electron concentration. (*a*) What is the maximum temperature that the device may operate? (*b*) What is the change in $E_c - E_F$ from the $T = 300$ K value to the maximum temperature value determined in part (*a*). (*c*) Is the Fermi level closer or further from the intrinsic value at the higher temperature?

$$n_0 = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_i^2}$$

最多5%

$n_{0max} = 1.05 N_d$　　0.05 來自 n_i 貢獻

$$n_{0max} = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_{imax}^2}$$

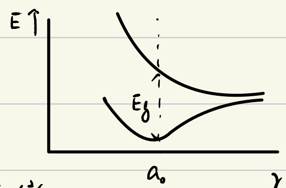
$$1.05 N_d = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 + n_{imax}^2}$$

$$0.55 N_d = \sqrt{\left(\frac{N_d}{2}\right)^2 + n_{imax}^2}$$

$$(0.55 N_d)^2 = \left(\frac{N_d}{2}\right)^2 + n_{imax}^2 \qquad N_d = 10^{15}$$

$$n_{imax}^2 = (0.55 N_d)^2 - \left(\frac{N_d}{2}\right)^2 = 5.25 \times 10^{28}$$

$$n_{imax} = N_c N_v \left(\frac{T}{300}\right)^3$$



$$n_i^2 = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$$

$$5.25 \times 10^{28} = 2.8 \times 10^{19} \times 1.04 \times 10^{19} \left[\frac{T}{300}\right]^3 e^{\frac{-12972.973}{T}}$$

E_g 也會隨溫度變化

a_0 會變化

$T = \ldots$

(b) $E_c - E_F = kT\left(\frac{N_c}{n_0}\right)$

$\Rightarrow n_{0max} = 1.5 n_0$ in 300K

簡單理解 熱脹冷縮 ?

(c) closer

這裡忽略