5.1 The concentration of donor impurity atoms in silicon is $N_d = 10^{15}$ cm^{-3}. Assume an electron mobility of $\mu_n = 1300$ cm^2/V-s and a hole mobility of $\mu_p = 450$ cm^2/V-s. (*a*) Calculate the resistivity of the material. (*b*) What is the conductivity of the material?

$$\sigma = e\mu_n n + e\mu_p p = 1.6\cdot 10^{-19}\cdot 1300\cdot 10^{15}$$

$$\rho = \frac{1}{\sigma}$$

5.5 A silicon sample is 2.5 cm long and has a cross-sectional area of 0.1 cm^2. The silicon is n type with a donor impurity concentration of $N_d = 2 \times 10^{15}$ cm^{-3}. The resistance of the sample is measured and found to be 70 Ω. What is the electron mobility?

$$R = \frac{\rho L}{A} = \frac{\rho\, 2.5}{0.1} = \frac{2.5}{\sigma\, 0.1}$$

$$= \frac{2.5}{e(\mu_n n + \cancel{\mu_p p})\, 0.1}$$

$$70 = \frac{25}{1.6\cdot 10^{-19}\cdot \mu_n \cdot 2\cdot 10^{15}}, \quad \mu_n = 1116\ \mathrm{cm^2/V\text{-}s}$$

5.10 (*a*) Three volts is applied across a 1-cm-long semiconductor bar. The average electron drift velocity is 10^4 cm/s. Find the electron mobility. (*b*) If the electron mobility in part (*a*) were 800 cm^2/V-s, what is the average electron drift velocity?

(a) $$E = \frac{V}{L} = \frac{3}{1} = 3$$

$$\underset{[\mathrm{cm/s}]}{v_{dn}} = \mu_n \underset{[\mathrm{V/cm}]}{E}, \quad \mu_n = \frac{10^4}{3} = 3333\ [\mathrm{cm^2/V\text{-}s}]$$ #

(b) $$v_{dn} = \mu_n E = 800\cdot 3 = 2.4\cdot 10^3\ [\mathrm{cm^2/V\text{-}s}]$$ #

5.14 In a particular semiconductor material, $\mu_n = 1000\ \text{cm}^2/\text{V-s}$, $\mu_p = 600\ \text{cm}^2/\text{V-s}$, and $N_C = N_V = 10^{19}\ \text{cm}^{-3}$. These parameters are independent of temperature. The measured conductivity of the intrinsic material is $\sigma = 10^{-6}\ (\Omega\text{-cm})^{-1}$ at $T = 300$ K. Find the conductivity at $T = 500$ K.

@ 300K ① $n = p = n_i$ ② $n_i^2 = n \cdot p$ (本質半導体條件)

1° $\sigma_i = e(n\mu_n + p\mu_p) = e n_i(\mu_n + \mu_p)$

$$10^{-6} = 1.6 \cdot 10^{-19}(1000+600)\, n_i \,,\quad n_i = 3.91 \cdot 10^{9}\ \text{cm}^{-3}$$

2° $n_i^2 = n \cdot p = N_c \cdot N_v \exp\left(\dfrac{-(\overbrace{E_c - E_v}^{=E_g})}{kT}\right)$

$$E_g = kT \ln\left(\frac{N_c N_v}{n_i^2}\right) = (0.0259) \ln\left(\frac{(10^{19})^2}{(3.91 \cdot 10^9)^2}\right), \quad \boxed{E_g = 1.122\text{eV}}$$

背

@ 500K

3° $n_i^2 = N_c N_v \exp\left(\dfrac{-\boxed{E_g}}{kT}\right)$

$$= (10^{19})^2 \exp\left(\frac{-1.122}{\underbrace{0.0259(500/300)}_{kT換算}}\right), \quad n_i = 2.27 \cdot 10^{13}\ \text{cm}^{-3}$$

4° $\sigma_i = e n_i(\mu_n + \mu_p) = (1.6 \cdot 10^{-19})(2.27 \cdot 10^{13})(1000+600)$

$$= 5.81 \cdot 10^{-13}\ [\Omega\text{-cm}]^{-1}$$

#

5.18 An n-type silicon resistor has a length $L = 150\ \mu\text{m}$, width $W = 7.5\ \mu\text{m}$, and thickness $T = 1\ \mu\text{m}$. A voltage of 2 V is applied across the length of the resistor. The donor impurity concentration varies linearly through the thickness of the resistor with $N_d = 2 \times 10^{16}\ \text{cm}^{-3}$ at the top surface and $N_d = 2 \times 10^{15}\ \text{cm}^{-3}$ at the bottom surface. Assume an average carrier mobility of $\mu_n = 750\ \text{cm}^2/\text{V-s}$. (*a*) What is the electric field in the resistor? (*b*) Determine the average conductivity of the silicon. (*c*) Calculate the current in the resistor. (*d*) Determine the current density near the top surface and the current density near the bottom surface.

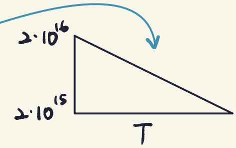
(a)

$$E = \frac{V}{L} = \frac{2}{150 \cdot 10^{-6}} = 133.3\ \text{V/cm}\ \#$$

(b)

$$\sigma_{avg} = e\,\mu_n N_d(x) \longrightarrow \text{上到下不均匀分佈}$$

$$= e\,\mu_n \frac{1}{T}\int_0^T \left(2\cdot 10^{16} - \frac{2\cdot 10^{16} - 2\cdot 10^{15}}{T}x\right)dx$$

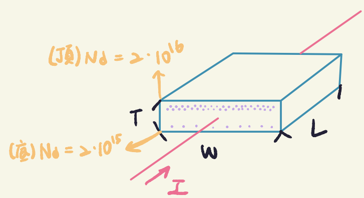


$$= e\,\mu_n \frac{1}{T}\int_0^T (2\cdot 10^{16})\left(1 - \frac{(2-0.2)\cancel{10^{16}}}{2\cdot\cancel{10^{16}}\,T}x\right)dx$$

可以上下同除0.9 $= \frac{0.9}{\frac{1}{0.9}T} = \frac{1}{1.111T}$，但沒必要

$$= e\,\mu_n \frac{1}{T}\int_0^T (2\cdot 10^{16})\left(1 - \frac{0.9}{T}x\right)dx$$

$$= e\,\mu_n \frac{1}{T}(2\cdot 10^{16})\left[\left(x - \frac{0.9}{T}\cdot\frac{1}{2}x^2\right)\right]_0^T$$



$$= e\,\mu_n \frac{1}{T}(2\cdot 10^{16})\left(T - \frac{0.9}{2}T\right)$$

$$= e\,\mu_n \cancel{\frac{1}{T}}(2\cdot 10^{16})\cancel{T}(1-0.45)$$

$$= 1.6\cdot 10^{-19}(750)(2\cdot 10^{16})(0.55)$$

$$= 1.32\ [\Omega\text{-cm}]^{-1}$$

(c)

$$I = \frac{V}{R} = \frac{A}{\rho L}V = \frac{\sigma A}{L}V = \frac{1.32(7.5\cdot 10^{-4})(10^{-4})}{150\cdot 10^{-4}}\cdot 2 = 1.32\cdot 10^{-5}\ \text{A}\ \#$$

(d) Top :

$$\sigma = e\,\mu_n n = 2.4\ [\Omega\text{-cm}]^{-1}$$

$$J = \sigma E = 2.4 \cdot 133.3 = 320\ [\text{A/cm}^2]\ \#$$

Bottom :

$$\sigma = e\,\mu_n n = 0.24\ [\Omega\text{-cm}]^{-1}$$

$$J = \sigma E = 0.24 \cdot 133.3 = 32\ [\text{A/cm}^2]\ \#$$

又不會考

5.21b 要分析解

5.21 Consider a semiconductor that is uniformly doped with $N_d = 10^{14}\ \text{cm}^{-3}$ and $N_a = 0$, with an applied electric field of $E = 100$ V/cm. Assume that $\mu_n = 1000\ \text{cm}^2/\text{V-s}$ and $\mu_p = 0$. Also assume the following parameters:

$$N_c = 2 \times 10^{19}\ (T/300)^{3/2}\ \text{cm}^{-3}$$
$$N_v = 1 \times 10^{19}\ (T/300)^{3/2}\ \text{cm}^{-3}$$
$$E_g = 1.10\ \text{eV}$$

(*a*) Calculate the electric-current density at $T = 300$ K. (*b*) At what temperature will this current increase by 5 percent? (Assume the mobilities are independent of temperature.)

(a) @ $T = 300\,k$

$$J = \sigma E = e(n\mu_n + \cancel{p\mu_p})E$$

$$n_i^2 = N_c N_v \exp\left(\frac{-E_g}{kT}\right) = 2 \cdot 10^{38} (300/300)^3 \exp\left(\frac{-1.1}{0.0259}\right) = 7.18 \cdot 10^{19}$$

$$n_i = 8.47 \cdot 10^9 \quad , \quad N_d = 10^{14}$$

$$N_d \gg n_i \Rightarrow n_0 \approx N_d \quad (\text{n-type})$$

$$\Rightarrow J = e n_0 \mu_n E = 1.6 \cdot 10^{-19} (10^{14})(1000)(100) = 1.6\ \text{A/cm}^2$$

(b)

$$n_0 + N_a = p_0 + N_d$$

$$n_0 + N_a = \frac{n_i^2}{n_0} + N_d$$

$$n_0^2 - (N_d - N_a) n_0 - n_i^2 = 0$$

$$n_0 = \frac{+(N_d - \cancel{N_a}) + \sqrt{(N_d - \cancel{N_a})^2 - 4n_i^2}}{2}$$

$$n_0 = \frac{N_d}{2} + \frac{1}{2}\sqrt{N_d^2 - 4n_i^2} = \frac{N_d}{2} + \sqrt{\left(\frac{N_d}{2}\right)^2 - n_i^2}$$

$$n_0 + N_a = p_0 + N_d$$
$$n_0 + N_a = \frac{n_i^2}{n_0} + N_d$$
$$n_0^2 - (N_d - N_a)n_0 - n_i^2 = 0$$
$$n_0 = ?$$

skip

5.24 Three scattering mechanisms are present in a particular semiconductor material. If only the first scattering mechanism were present, the mobility would be $\mu_1 = 2000$ cm²/V-s, if only the second mechanism were present, the mobility would be $\mu_2 = 1500$ cm²/V-s, and if only the third mechanism were present, the mobility would be $\mu_3 = 500$ cm²/V-s. What is the net mobility?

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_3}$$

＊見CH5, P.15

$$= \frac{1}{2000} + \frac{1}{1500} + \frac{1}{500} = 0.003167 , \quad \mu = 316 \text{ cm}^2/\text{V-s} \quad \#$$

✗ **5.28** (*a*) Assume that the electron mobility in an n-type semiconductor is given by

$$\mu_n = \frac{1350}{\left(1 + \dfrac{N_d}{5 \times 10^{16}}\right)^{1/2}} \text{ cm}^2/\text{V-s}$$

where N_d is the donor concentration in cm^{-3}. Assuming complete ionization, plot the conductivity as a function of N_d over the range $10^{15} \le N_d \le 10^{18}$ cm^{-3}. (*b*) Compare the results of part (*a*) to that if the mobility were assumed to be a constant equal to 1350 cm²/V-s. (*c*) If an electric field of $E = 10$ V/cm is applied to the semiconductor, plot the electron drift current density of parts (*a*) and (*b*).

畫圖題應該不会考

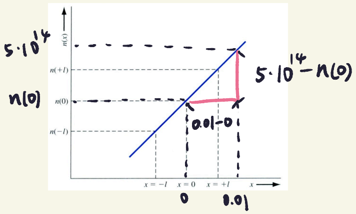
✗ **5.29** Consider a sample of silicon at $T = 300$ K. Assume that the electron concentration varies linearly with distance, as shown in Figure P5.29. The diffusion current density is found to be $J_n = 0.19$ A/cm². If the electron diffusion coefficient is $D_n = 25$ cm²/s, determine the electron concentration at $x = 0$. 求 X=0 時的 J

$$J_n = e D_n \frac{dn}{dx}$$

$$= e D_n \left(\frac{5 \cdot 10^{14} - n(0)}{0.01 - 0} \right)$$

$$0.19 = (1.6 \cdot 10^{-19})(25)\left(\frac{5 \cdot 10^{14} - n(0)}{0.01}\right)$$

$$n(0) = 0.25 \cdot 10^{14} \text{ cm}^{-3}$$



題目要改成這樣

- **Example 5.4** Assume that, in an n-type gallium arsenide semiconductor at T=300°K, the electron concentration varies linearly from 1×10^{18} to 7×10^{17} cm^{-3} over a distance of 0.10 cm. Calculate the diffusion current density if the electron diffusion coefficient is D_n = 225 cm²/s.

下題会考

5.31 The electron diffusion current density in a semiconductor is a constant and is given by $J_n = -2\ \text{A/cm}^2$. The electron concentration at $x = 0$ is $n(0) = 10^{15}\ \text{cm}^{-3}$. (*a*) Calculate the electron concentration at $x = 20\ \mu\text{m}$ if the material is silicon with $D_n = 30\ \text{cm}^2/\text{s}$. (*b*) Repeat part (*a*) if the material is GaAs with $D_n = 230\ \text{cm}^2/\text{s}$.

＊記得用cm算

$$J_n = e D_n \frac{dn}{dx}$$

$$-2 = (1.6\cdot10^{-19})\, 30 \left(\frac{n(x)-n(0)}{x-0}\right)$$

$$= (1.6\cdot10^{-19})\, 30 \left(\frac{n(x)-10^{15}}{20\cdot10^{-6}\times\underbrace{10^{2}}_{\text{m to cm}}}\right)$$

$$-2 = (1.6\cdot10^{-15})\,\frac{3}{2}\,(n(x)-10^{15})$$

$$\frac{-1}{1.2}10^{15} = n(x) - 10^{15}$$

$$n(x) = \left(1-\frac{1}{1.2}\right)10^{15} = 1.67\cdot10^{15}\ \text{cm}^{-3}\ \#$$

cm

＊載子濃度 n, p

＊擴散(不是常數)

$$\Rightarrow \begin{cases} J_n = e D_n \dfrac{dn}{dx} \\ J_p = -e D_p \dfrac{dp}{dx} \end{cases}$$

＊漂移(是常數)

$$\Rightarrow \begin{cases} J_n = e n \mu_n E \\ J_p = e p \mu_p E \end{cases}$$

5.33 In silicon, the electron concentration is given by $n(x) = 10^{15} e^{-x/L_n}\ \text{cm}^{-3}$ for $x \geq 0$ and the hole concentration is given by $p(x) = 5 \times 10^{15} e^{+x/L_P}\ \text{cm}^{-3}$ for $x \leq 0$. The parameter values are $L_n = 2 \times 10^{-3}$ cm and $L_P = 5 \times 10^{-4}$ cm. The electron and hole diffusion coefficients are $D_n = 25\ \text{cm}^2/\text{s}$ and $D_P = 10\ \text{cm}^2/\text{s}$, respectively. The total current density is defined as the sum of the electron and hole diffusion current densities at $x = 0$. Calculate the total current density.

$$J_{Total} = J_n + J_p$$

$$J_n = e D_n \frac{dn}{dx} = (1.6\cdot10^{-19})(25)(10^{15})\frac{d}{dx}e^{-x/L_n}$$

$$= 40\cdot10^{-4}\cdot\frac{-1}{L_n}\,\cancel{e^{-x/L_n}}\ 0$$

$$(e^{at})' = a e^{at}$$

$$(e^{-\frac{1}{a}t})' = -\frac{1}{a} e^{-\frac{1}{a}t}$$

when $x=0$ $$= \frac{-40\cdot10^{-4}}{2\cdot10^{-3}} = 20\cdot10^{-1} = 2$$

$$J_p = -e D_p \frac{dp}{dx} = -(1.6\cdot10^{-19})(10)(5\cdot10^{15})\frac{d}{dx}e^{+x/L_p}$$

$$= -(80\cdot10^{-4})\cdot\frac{1}{L_p}\,\cancel{e^{x/L_p}}\ 0$$

when $x=0$ $$= -\left(\frac{80\cdot10^{-4}}{5\cdot10^{-4}}\right) = -16$$

$$J_{Total} = J_n + J_p = -2 - 16 = -16\ [\text{A/cm}^2]$$

$J = \frac{I}{A}$ 用定義推單位

5.36 The total current in a semiconductor is constant and equal to $J = -10$ A/cm^2. The total current is composed of a hole drift current and electron diffusion current. Assume that the hole concentration is a constant and equal to 10^{16} cm^{-3} and assume that the electron concentration is given by $n(x) = 2 \times 10^{15} e^{-x/L}$ cm^{-3} where $L = 15$ μm. The electron diffusion coefficient is $D_n = 27$ cm^2/s and the hole mobility is $\mu_p = 420$ cm^2/V-s. Calculate (*a*) the electron diffusion current density for $x > 0$, (*b*) the hole drift current density for $x > 0$, and (*c*) the required electric field for $x > 0$.

(a) $J_n = e D_n \frac{dn}{dx} = (1.6\cdot10^{-19})(27)\frac{d}{dx}(2\cdot10^{15}e^{-x/L})$

$= (1.6\cdot10^{-19})(27)(2\cdot10^{15})\left(\frac{-1}{15\cdot10^{-6}\cdot10^{2}}\right)e^{-x/L}$

$= 3.2\cdot\cancel{10^{-4}}\cdot27\cdot\frac{-1}{15\cdot\cancel{10^{-4}}}e^{-x/L}$

$= -5.76\,e^{-x/L}$

(b) $J_{total} = J_p + J_n$

$J_p = J_{total} - J_n = -10-(-5.76e^{-x/L}) = 5.76e^{-x/L} - 10$ [A/cm^2]

(c) $J_p = \sigma E = e\mu_p p E$

$5.76e^{-x/L} - 10 = (1.6\cdot10^{-19})(420)(10^{16})E$

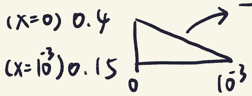
$E = 8.57e^{-x/L} - 14.88$ [V/cm] #

***5.38** In n-type silicon, the Fermi energy level varies linearly with distance over a short range. At $x = 0$, $E_F - E_{Fi} = 0.4$ eV and, at $x = 10^{-3}$ cm, $E_F - E_{Fi} = 0.15$ eV. (*a*) Write the expression for the electron concentration over the distance. (*b*) If the electron diffusion coefficient is $D_n = 25$ cm²/s, calculate the electron diffusion current density at (*i*) $x = 0$ and (*ii*) $x = 5 \times 10^{-4}$ cm.

(a)

$$E_F - E_{Fi} = \frac{0.15 - 0.4}{10^{-3}} x + 0.4$$

$$= -2.5 \cdot 10^{2} x + 0.4$$



$$\frac{0.15 - 0.4}{10^{-3} - 0}$$

$$n = n_i \exp\left(\frac{-2.5 \cdot 10^{2} x + 0.4}{kT}\right)$$

(b)

$$J_n = e D_n \frac{dn}{dx}$$

$$= e D_n n_i \frac{d}{dx} \exp\left(\frac{-2.5 \cdot 10^{2} x + 0.4}{kT}\right)$$

- chain rule

$$\left(e^{at+b}\right)' = \exp(at+b)$$

$$= a \exp(at+b) \cdot (at+b)'$$

$$= e D_n n_i \frac{d}{dx} \exp\left(\frac{-2.5 \cdot 10^{2}}{kT} x + \frac{0.4}{kT}\right)$$

$$= e D_n n_i \left(\frac{-2.5 \cdot 10^{2}}{kT}\right) \exp\left(\frac{-2.5 \cdot 10^{2}}{kT} x + \frac{0.4}{kT}\right) \cdot \left(\frac{-2.5 \cdot 10^{2}}{kT}\right)$$

$$= \frac{-(1.6 \cdot 10^{-19})(25)(1.5 \cdot 10^{10})(2.5 \cdot 10^{2})}{0.0259} \times \exp\left(\frac{0.4 - 2.5 \cdot 10^{2} x}{0.0259}\right)$$

$$= -5.79 \cdot 10^{-4} \exp\left(\frac{0.4 - 2.5 \cdot 10^{2} x}{0.0259}\right)$$

(i) when $x = 0$, $J_n = -2.95 \cdot 10^{3}$ [A/cm²]

(ii) when $x = 5\mu m$, $J_n = -23.1$ [A/cm²]

5.40 Consider an n-type semiconductor at $T = 300$ K in thermal equilibrium (no current). Assume that the donor concentration varies as $N_d(x) = N_{d0}e^{-x/L}$ over the range $0 \le x \le L$ where $N_{d0} = 10^{16}$ cm^{-3} and $L = 10$ μm. (*a*) Determine the electric field as a function of x for $0 \le x \le L$. (*b*) Calculate the potential difference between $x = 0$ and $x = L$ (with the potential at $x = 0$ being positive with respect to that at $x = L$).

(a) $$E_x = -\left(\frac{kT}{e}\right)\frac{1}{N_d(x)}\frac{dN_d(x)}{dx}$$

$$= \frac{-(0.0259)}{N_{do}\,e^{-x/L}}\cdot\frac{d}{dx}\left(N_{do}\,e^{-x/L}\right)$$

$$= \frac{-(0.0259)}{N_{do}\,e^{-x/L}}\cdot\frac{-1}{L}\left(N_{do}\,e^{-x/L}\right)$$

$$= \frac{0.0259}{L} = \frac{0.0259}{10\cdot10^{-4}}\quad,\quad E_x = 25.9\ [V/cm]\ \#$$

(b)

$$\phi = -\int_0^L E_x\,dx = -(25.9)(L-0)$$

$$= -(25.9)(10\cdot10^{-4}) = -0.0259\,V = -25.9\,mV\ \#$$

***5.43** In GaAs, the donor impurity concentration varies as $N_{d0} \exp(-x/L)$ for $0 \le x \le L$, where $L = 0.1\ \mu$m and $N_{d0} = 5 \times 10^{16}$ cm^{-3}. Assume $\mu_n = 6000$ cm^2/V-s and $T = 300$ K. (*a*) Derive the expression for the electron diffusion current density versus distance over the given range of x. (*b*) Determine the induced electric field that generates a drift current density that compensates the diffusion current density.

(a)

$$J_{diff} = e D_n \frac{dn}{dx} = e D_n \exp \frac{d}{dx} N_{d0} \exp\left(\frac{-x}{L}\right)$$

$$= e D_n \left(\frac{1}{-L}\right) N_{d0} \exp\left(\frac{-x}{L}\right)$$

$$D_n = \mu_n \left(\frac{kT}{e}\right) = 6000 \cdot 0.0259 = 155.4$$

背

我也不知道 e 跑去哪

$$J_{diff} = -\left(\frac{(1.6 \cdot 10^{-19})(155.4)(5 \cdot 10^{16})}{0.1 \cdot 10^{-4}}\right) \exp\left(\frac{-x}{L}\right)$$

$$= -1.243 \cdot 10^{5} \exp\left(\frac{-x}{L}\right) \quad [A/cm^2]$$ #

(b)

$0 = J_{drf} + J_{diff}$ (電場 E 的 J_{drf} 会補償(抵消) J_{diff})
使 $J_{Total} = 0$

$$J_{drf} = e \mu_n n E$$

$$= (1.6 \cdot 10^{-19})(6000)(5 \cdot 10^{16}) \exp\left(\frac{-x}{L}\right) E = 48 \exp\left(\frac{-x}{L}\right) E$$

$$J_{drf} = -J_{diff}$$

$$48 \exp\left(\frac{-x}{L}\right) E = -\left(-1.243 \cdot 10^{5} \exp\left(\frac{-x}{L}\right)\right)$$

$$E = \frac{1.243 \cdot 10^{5} \cancel{\exp\left(\frac{-x}{L}\right)}}{48 \cancel{\exp\left(\frac{-x}{L}\right)}} = 2.59 \cdot 10^{3} \ [V/cm]$$ #

5.45 Consider a semiconductor at $T = 300$ K. (*a*) (*i*) Determine the electron diffusion coefficient if the electron mobility is $\mu_n = 1150\ \text{cm}^2/\text{V-s}$. (*ii*) Repeat (*i*) of part (*a*) if the electron mobility is $\mu_n = 6200\ \text{cm}^2/\text{V-s}$. (*b*) (*i*) Determine the hole mobility if the hole diffusion coefficient is $D_p = 8\ \text{cm}^2/\text{s}$. (*ii*) Repeat (*i*) of part (*b*) if the hole diffusion coefficient is $D_p = 35\ \text{cm}^2/\text{s}$.

(a) $D_n = \mu_n \left(\frac{kT}{e}\right) = 0.0259 \cdot 1150 = 29.8\ [\text{cm}^2/\text{s}]$ #

$D_n = \mu_n \left(\frac{kT}{e}\right) = 0.0259 \cdot 6200 = 160.6\ [\text{cm}^2/\text{s}]$ #

(b)

$D_p = \mu_p \left(\frac{kT}{e}\right)$

$\mu_p = D_p \left(\frac{e}{kT}\right) = \frac{8}{0.0259} = 308.9\ [\text{cm}^2/\text{V-s}]$ #

$\mu_p = D_p \left(\frac{e}{kT}\right) = \frac{35}{0.0259} = 1351\ [\text{cm}^2/\text{V-s}]$ #