# CHAPTER 2

**2.1**

Based upon Table 2.1, a resistivity of 2.83 µΩ-cm < 1 mΩ-cm, and aluminum is a conductor.

**2.2**

Based upon Table 2.1, a resistivity of $10^{15}$ Ω-cm > $10^5$ Ω-cm, and silicon dioxide is an insulator.

**2.3**

$$I_{max} = \left(10^7 \frac{A}{cm^2}\right)(5\mu m)(1\mu m)\left(\frac{10^{-8} cm^2}{\mu m^2}\right) = 500 \ mA$$

**2.4**

$$(a) \ R = \rho\frac{L}{A} = \left(2.82x10^{-6}\Omega - cm\right)\frac{2\sqrt{2} \ cm}{\left(5x10^{-4}cm\right)\left(1x10^{-4}cm\right)} = 160 \ \Omega$$

$$(b) \ R = \rho\frac{L}{A} = \left(2.82x10^{-6}\Omega - cm\right)\frac{2\sqrt{2} \ cm}{\left(5x10^{-4}cm\right)\left(0.5x10^{-4}cm\right)} = 319 \ \Omega$$

**2.5**

$$(a) \ R = \rho\frac{L}{A} = \left(1.66x10^{-6}\Omega - cm\right)\frac{2\sqrt{2} \ cm}{\left(5x10^{-4}cm\right)\left(1x10^{-4}cm\right)} = 93.9 \ \Omega$$

$$(b) \ R = \rho\frac{L}{A} = \left(1.66x10^{-6}\Omega - cm\right)\frac{2\sqrt{2} \ cm}{\left(5x10^{-4}cm\right)\left(0.5x10^{-4}cm\right)} = 188 \ \Omega$$

**2.6**

$$n_i = \sqrt{BT^3 \exp\left(-\frac{E_G}{8.62x10^{-5}T}\right)}$$

For silicon, B = 1.08 x $10^{31}$ and $E_G$ = 1.12 eV:

$n_i$ = 5.07 x$10^{-19}$/cm$^3$          6.73 x$10^9$/cm$^3$          8.36 x $10^{13}$/cm$^3$.

For germanium, B = 2.31 x $10^{30}$ and $E_G$ = 0.66 eV:

$n_i$ = 2.63 x$10^{-4}$/cm$^3$          2.27 x$10^{13}$/cm$^3$          8.04 x $10^{15}$/cm$^3$.

**2.7**

Define an M-File:

function f=temp(T)
ni=1E14;
f=ni^2-1.08e31*T^3*exp(-1.12/(8.62e-5*T));

$n_i = 10^{13}/cm^3$  for T = 436 K      $n_i = 10^{15}/cm^3$  for T = 602 K

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**2.8**

$$n_i = \sqrt{BT^3 \exp\left(-\frac{E_G}{8.62x10^{-5}T}\right)} \quad \text{with} \quad B = 1.27x10^{29}\,K^{-3}cm^{-6}$$

T = 300 K and $E_G$ = 1.42 eV:  $n_i = 2.21\ x10^6/cm^3$
T = 100 K:  $n_i = 6.03\ x\ 10^{-19}/cm^3$      T = 450 K: $n_i = 3.82\ x10^{10}/cm^3$

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**2.9**

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \quad B = 1.08x10^{31}$$

$$\left(10^{10}\right)^2 = 1.08x10^{31}T^3 \exp\left(-\frac{1.12}{8.62x10^{-5}T}\right)$$

Using a spreadsheet, solver, or MATLAB yields T = 305.22K

Define an M-File:

        function f=temp(T)
        f=1e20-1.08e31*T^3*exp(-1.12/(8.62e-5*T));

Then:  fzero('temp',300)    |    ans = 305.226 K

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**2.10**

$$v_n = -\mu_n E = \left(-700\frac{cm^2}{V-s}\right)\left(2500\frac{V}{cm}\right) = -1.75x10^6\frac{cm}{s}$$

$$v_p = +\mu_p E = \left(+250\frac{cm^2}{V-s}\right)\left(2500\frac{V}{cm}\right) = +6.25x10^5\frac{cm}{s}$$

$$j_n = -qnv_n = \left(-1.60x10^{-19}C\right)\left(10^{17}\frac{1}{cm^3}\right)\left(-1.75x10^6\frac{cm}{s}\right) = 2.80x10^4\frac{A}{cm^2}$$

$$j_p = qnv_p = \left(1.60x10^{-19}C\right)\left(10^3\frac{1}{cm^3}\right)\left(6.25x10^5\frac{cm}{s}\right) = 1.00x10^{-10}\frac{A}{cm^2}$$

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**2.11**

$$\left|j_n\right| = qnv_n = \left(1.60x10^{-19}C\right)\left(10^{18}\frac{1}{cm^3}\right)\left(10^7\frac{cm}{s}\right) = 1.60x10^6\frac{A}{cm^2} = 1.60\frac{MA}{cm^2}$$

$$\left|j_p\right| = qnv_p = \left(1.60x10^{-19}C\right)\left(10^2\frac{1}{cm^3}\right)\left(10^7\frac{cm}{s}\right) = 1.60x10^{-10}\frac{A}{cm^2}$$

**2.12**

$$v = \frac{j}{Q} = \frac{-2000A/cm^2}{0.01C/cm^2} = -2x10^5\frac{cm}{s}$$

**2.13**

$$j = Qv = \left(0.4\frac{C}{cm^3}\right)\left(10^7\frac{cm}{sec}\right) = 4x10^6\frac{A}{cm^2} = 4\frac{MA}{cm^2}$$

**2.14**

$$v_n = -\mu_n E = \left(-1000\frac{cm^2}{V-s}\right)\left(-2000\frac{V}{cm}\right) = +2.00x10^6\frac{cm}{s}$$

$$v_p = +\mu_p E = \left(+400\frac{cm^2}{V-s}\right)\left(-2000\frac{V}{cm}\right) = -8.00x10^5\frac{cm}{s}$$

$$j_n = -qnv_n = \left(-1.60x10^{-19}C\right)\left(10^3\frac{1}{cm^3}\right)\left(+2.00x10^6\frac{cm}{s}\right) = -3.20x10^{-10}\frac{A}{cm^2}$$

$$j_p = qnv_p = \left(1.60x10^{-19}C\right)\left(10^{17}\frac{1}{cm^3}\right)\left(-8.00x10^5\frac{cm}{s}\right) = -1.28x10^4\frac{A}{cm^2}$$

**2.15**

$$(a)\ \ E = \frac{5V}{10x10^{-4}cm} = 5000\frac{V}{cm}\qquad (b)\ \ V = \left(10^5\frac{V}{cm}\right)\left(10x10^{-4}cm\right) = 100\ V$$

**2.16**

$$j_p = qpv_p = \left(1.60x10^{-19}C\right)\left(\frac{10^{19}}{cm^3}\right)\left(10^7\frac{cm}{s}\right) = 1.60x10^7\frac{A}{cm^2}$$

$$i_p = j_p A = \left(1.60x10^7\frac{A}{cm^2}\right)\left(1x10^{-4}cm\right)\left(25x10^{-4}cm\right) = 4.00\ A$$

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**2.17**

For intrinsic silicon, $\sigma = q(\mu_n n_i + \mu_p n_i) = q n_i (\mu_n + \mu_p)$

$\sigma \leq 10^{-5} (\Omega - cm)^{-1}$ for an insulator

$$n_i = \frac{\sigma}{q(\mu_n + \mu_p)} \leq \frac{10^{-5}(\Omega - cm)^{-1}}{(1.602x10^{-19}C)(2000 + 750)\frac{cm^2}{v-\sec}} = \frac{2.270x10^{10}}{cm^3}$$

$$n_i^2 = \frac{5.152x10^{20}}{cm^6} = BT^3 \exp\left(-\frac{E_G}{kT}\right) \text{ with}$$

$B = 1.08x10^{31} K^{-3}cm^{-6}$, k = 8.62x10$^{-5}$eV/K and $E_G = 1.12eV$

Using MATLAB as in Problem 2.5 yields T $\leq$ 316.6 K.

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**2.18**

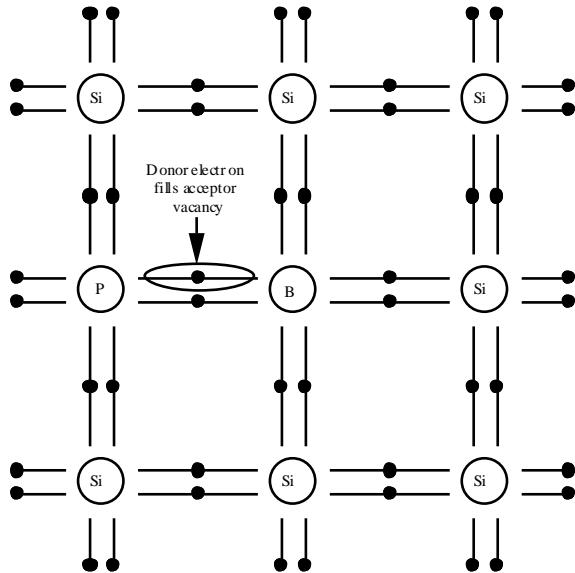For intrinsic silicon, $\sigma = q(\mu_n n_i + \mu_p n_i) = q n_i (\mu_n + \mu_p)$

$\sigma \geq 1000 (\Omega - cm)^{-1}$ for a conductor

$$n_i = \frac{\sigma}{q(\mu_n + \mu_p)} \geq \frac{1000(\Omega - cm)^{-1}}{1.602x10^{-19}C(100 + 50)\frac{cm^2}{v-\sec}} = \frac{4.16x10^{19}}{cm^3}$$

$$n_i^2 = \frac{1.73x10^{39}}{cm^6} = BT^3 \exp\left(-\frac{E_G}{kT}\right) \text{ with}$$

$B = 1.08x10^{31} K^{-3}cm^{-6}$, k = 8.62x10$^{-5}$eV/K and $E_G = 1.12eV$

This is a transcendental equation and must be solved numerically by iteration. Using the HP solver routine or a spread sheet yields T $\geq$ 2701 K. Note that this temperature is far above the melting temperature of silicon.

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**2.19**



No free electrons or holes (except those corresponding to $n_i$).

**2.20**

Since Ge is from column IV, acceptors come from column III and donors come from column V. (a) Acceptors: B, Al, Ga, In, Tl  (b) Donors: N, P, As, Sb, Bi

**2.21**

(a) Gallium is from column 3 and silicon is from column 4. Thus silicon has an extra electron and will act as a donor impurity.

(b) Arsenic is from column 5 and silicon is from column 4. Thus silicon is deficient in one electron and will act as an acceptor impurity.

**2.22**

(a) Germanium is from column IV and indium is from column III. Thus germanium has one extra electron and will act as a donor impurity.

(b) Germanium is from column IV and phosphorus is from column V. Thus germanium has one less electron and will act as an acceptor impurity.

**2.23**

$$E = \frac{j}{\sigma} = j\rho = \left(10000 \frac{A}{cm^2}\right)(0.02\Omega - cm) = 200 \frac{V}{cm}, \text{ a small electric field.}$$

**2.24**

$$\left|j_n^{drift}\right| = \left|qn\mu_n E\right| = \left|qnv_n\right| = \left(1.602x10^{-19}\right)\left(10^{17}\right)\left(\frac{C}{cm^3}\right)\left(10^7 \frac{cm}{s}\right) = 160 \frac{kA}{cm^2}$$

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**2.25**

$$N = \left( \frac{10^{16} \, atoms}{cm^3} \right) (0.5 \mu m)(5 \mu m)(0.5 \mu m) \left( \frac{10^{-4} \, cm}{\mu m} \right)^3 = 12,500 \, atoms$$

**2.26**

(a) Since arsenic is a donor, $N_D = 3 \times 10^{17}/cm^3$. Assume $N_A = 0$, since it is not specified. The material is n-type.

(b) At room temperature, $n_i = 10^{10}/cm^3$ and $N_D - N_A = 3x10^{17}/cm^3 \gg 2n_i$

So $n = 3x10^{17}/cm^3$ and $p = \frac{n_i^2}{n} = \frac{10^{20}/cm^6}{3x10^{17}/cm^3} = 333/cm^3$

(c) At 250K, $n_i^2 = 1.08x10^{31}(250)^3 \exp\left(-\frac{1.12}{8.62x10^{-5}(250)}\right) = 4.53x10^{15}/cm^6$

$n_i = 6.73x10^7/cm^3 \quad N_D - N_A \gg 2n_i$, so $n = 3x10^{17}/cm^3$ and $n = \frac{4.53x10^{15}}{3x10^{17}} = 0.0151/cm^3$

**2.27**

(a) Since boron is an acceptor, $N_A = 6 \times 10^{18}/cm^3$. Assume $N_D = 0$, since it is not specified. The material is p-type.

(b) At room temperature, $n_i = 10^{10}/cm^3$ and $N_A - N_D = 6x10^{18}/cm^3 \gg 2n_i$

So $p = 6x10^{18}/cm^3$ and $n = \frac{n_i^2}{p} = \frac{10^{20}/cm^6}{6x10^{18}/cm^3} = 16.7/cm^3$

(c) At 200K, $n_i^2 = 1.08x10^{31}(200)^3 \exp\left(-\frac{1.12}{8.62x10^{-5}(200)}\right) = 5.28x10^9/cm^6$

$n_i = 7.27x10^4/cm^3 \quad N_A - N_D \gg 2n_i$, so $p = 6x10^{18}/cm^3$ and $n = \frac{5.28x10^9}{6x10^{18}} = 8.80x10^{-10}/cm^3$

**2.28**

(a) Arsenic is a donor, and boron is an acceptor. $N_D = 2 \times 10^{18}/cm^3$, and $N_A = 8 \times 10^{18}/cm^3$. Since $N_A > N_D$, the material is p-type.

(b) At room temperature, $n_i = 10^{10}/cm^3$ and $N_A - N_D = 6x10^{18}/cm^3 \gg 2n_i$

So $p = 6x10^{18}/cm^3$ and $n = \frac{n_i^2}{p} = \frac{10^{20}/cm^6}{6x10^{18}/cm^3} = 16.7/cm^3$

**2.29**

(a) Phosphorus is a donor, and boron is an acceptor. $N_D = 2 \times 10^{17}/cm^3$, and $N_A = 5 \times 10^{17}/cm^3$. Since $N_A > N_D$, the material is p-type.

(b) At room temperature, $n_i = 10^{10}/cm^3$ and $N_A - N_D = 3x10^{17}/cm^3 \gg 2n_i$

So $p = 3x10^{17}/cm^3$ and $n = \frac{n_i^2}{p} = \frac{10^{20}/cm^6}{3x10^{17}/cm^3} = 333/cm^3$

**2.30**

$N_A > N_D: N_A - N_D = 5x10^{16} - 10^{16} = 4x10^{16}/cm^3 >> 2n_i = 2x10^{11}/cm^3$

$p = N_A - N_D = 4x10^{16}/cm^3 \ / \ n = \dfrac{n_i^2}{p} = \dfrac{10^{22}}{4x10^{16}} = 2.50x10^5/cm^3$

The material is p - type.

**2.31**

$N_A > N_D$: The material is p - type. $N_A - N_D = 10^{15} - 10^{14} = 9x10^{14}/cm^3$

If we assume $N_A - N_D >> 2n_i = 10^{14}/cm^3$ :

$p = N_A - N_D = 9x10^{14}/cm^3 \ / \ n = \dfrac{n_i^2}{p} = \dfrac{2510^{26}}{9x10^{14}} = 2.78x10^{12}/cm^3$

$If$ we use Eq. 2.12: $p = \dfrac{9x10^{14} + \sqrt{\left(9x10^{14}\right)^2 + 4\left(5x10^{13}\right)^2}}{2} = 9.03x10^{14}$

and $n = 2.77x10^{12}/cm^3$. The answers are essentially the same.

**2.32**

$N_D > N_A$: The material is n - type. $N_D - N_A = 3x10^{17} - 2x10^{17} = 1x10^{17}/cm^3$

$2n_i = 2x10^{17}/cm^3$; Need to use Eq. (2.11)

$n = \dfrac{10^{17} + \sqrt{\left(10^{17}\right)^2 + 4\left(10^{17}\right)^2}}{2} = 1.62x10^{17}/cm^3$

$p = \dfrac{n_i^2}{n} = \dfrac{10^{34}}{1.62x10^{17}} = 6.18x10^{16}/cm^3$

**2.33**

$N_D = 5 \times 10^{16}/cm^3$. Assume $N_A = 0$, since it is not specified.

$N_D > N_A$ : The material is n - type. $| \ N_D - N_A = 5x10^{16}/cm^3 >> 2n_i = 2x10^{10}/cm^3$

$n = 5x10^{16}/cm^3 \ | \ p = \dfrac{n_i^2}{n} = \dfrac{10^{20}}{5x10^{16}} = 2x10^3/cm^3$

$N_D + N_A = 5x10^{16}/cm^3 \ | \$ Using Fig. 2.8, $\mu_n = 960\dfrac{cm^2}{V-s}$ and $\mu_p = 280\dfrac{cm^2}{V-s}$

$\rho = \dfrac{1}{q\mu_n n} = \dfrac{1}{\left(1.602x10^{-19}C\right)960\dfrac{cm^2}{V-s}\left(\dfrac{5x10^{16}}{cm^3}\right)} = 0.130 \ \Omega - cm$

**2.34**

$N_A = 2.5 \times 10^{18}/cm^3$.  Assume $N_D = 0$, since it is not specified.

$N_A > N_D$ :  The material is p - type.  |  $N_A - N_D = 2.5 \times 10^{18}/cm^3 >> 2n_i = 2 \times 10^{10}/cm^3$

$p = 2.5 \times 10^{18}/cm^3$   |   $n = \dfrac{n_i^2}{p} = \dfrac{10^{20}}{2.5 \times 10^{18}} = 40/cm^3$

$N_D + N_A = 2.5 \times 10^{18}/cm^3$  |  Using Fig. 2.8,  $\mu_n = 170\dfrac{cm^2}{V-s}$  and  $\mu_p = 80\dfrac{cm^2}{V-s}$

$\rho = \dfrac{1}{q\mu_p p} = \dfrac{1}{1.602 \times 10^{-19}C\left(80\dfrac{cm^2}{V-s}\right)\left(\dfrac{2.5 \times 10^{18}}{cm^3}\right)} = 31.2 \ \text{m}\Omega - cm$

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**2.35**

Indium is from column 3 and is an acceptor.  $N_A = 8 \times 10^{19}/cm^3$.  Assume $N_D = 0$, since it is not specified.

$N_A > N_D$ :  material is p - type  |  $N_A - N_D = 8 \times 10^{19}/cm^3 >> 2n_i = 2 \times 10^{10}/cm^3$

$p = 8 \times 10^{19}/cm^3$   /   $n = \dfrac{n_i^2}{p} = \dfrac{10^{20}}{8 \times 10^{19}} = 1.25/cm^3$

$N_D + N_A = 7 \times 10^{19}/cm^3$  |  Using Fig. 2.8,  $\mu_n = 100\dfrac{cm^2}{V-s}$  and  $\mu_p = 50\dfrac{cm^2}{V-s}$

$\rho = \dfrac{1}{q\mu_p p} = \dfrac{1}{1.602 \times 10^{-19}C\left(50\dfrac{cm^2}{V-s}\right)\left(\dfrac{8 \times 10^{19}}{cm^3}\right)} = 1.56 \ \text{m}\Omega - cm$

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**2.36**

Phosphorus is a donor:  $N_D = 4.5 \times 10^{16}/cm^3$  |  Boron is an acceptor:  $N_A = 5.5 \times 10^{16}/cm^3$

$N_A > N_D$ :  The material is p - type.   |    $N_A - N_D = 10^{16}/cm^3 >> 2n_i = 2 \times 10^{10}/cm^3$

$p = 10^{16}/cm^3$  /  $n = \dfrac{n_i^2}{p} = \dfrac{10^{20}}{10^{16}} = 10^4/cm^3$

$N_D + N_A = 10^{17}/cm^3$   |  Using Fig. 2.8,  $\mu_n = 800\dfrac{cm^2}{V-s}$  and  $\mu_p = 220\dfrac{cm^2}{V-s}$

$\rho = \dfrac{1}{q\mu_n n} = \dfrac{1}{1.602 \times 10^{-19}C\left(220\dfrac{cm^2}{V-s}\right)\left(\dfrac{10^{16}}{cm^3}\right)} = 2.84 \ \Omega - cm$

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**2.37**

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p = \frac{1}{(1.602x10^{-19}C)(0.054\Omega-cm)} = \frac{1.16x10^{20}}{V-cm-s}$$

An iterative solution is required.  Using Fig. 2.8:

| $N_A$ | $\mu_p$ | $\mu_p$ p |
|---|---|---|
| $10^{18}$ | 100 | $1.0 \times 10^{20}$ |
| $1.1 \times 10^{18}$ | 100 | $1.1 \times 10^{20}$ |
| $1.2 \times 10^{17}$ | 95 | $1.14 \times 10^{20}$ |
| **$1.3 \times 10^{19}$** | **90** | **$1.17 \times 10^{20}$** |

**2.38**

$$\rho = \frac{1}{q\mu_n n} \quad | \quad \mu_n n = \frac{1}{(1.602x10^{-19}C)(0.054\Omega-cm)} = \frac{1.16x10^{20}}{V-cm-s}$$

An iterative solution is required.  Using the equations in Fig. 2.8:

| $N_D$ | $\mu_n$ | $\mu_n$ n |
|---|---|---|
| $10^{16}$ | 1250 | $1.25 \times 10^{19}$ |
| $10^{18}$ | 264 | $2.64 \times 10^{20}$ |
| $10^{17}$ | 802 | $8.02 \times 10^{19}$ |
| $1.2x10^{17}$ | 604 | $1.21 \times 10^{20}$ |
| **$1.85 \times 10^{19}$** | **626** | **$1.16 \times 10^{20}$** |

**2.39**

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p = \frac{1}{(1.602x10^{-19}C)(0.054\Omega-cm)} = \frac{1.16x10^{20}}{V-cm-s}$$

An iterative solution is required.  Using the equations in Fig. 2.8:

| $N_A$ | $\mu_p$ | $\mu_p$ p |
|---|---|---|
| $10^{18}$ | 96.7 | $9.67 \times 10^{20}$ |
| $1.1 \times 10^{18}$ | 93.7 | $1.03 \times 10^{20}$ |
| $1.2 \times 10^{17}$ | 91.0 | $1.09 \times 10^{20}$ |
| **$1.3 \times 10^{19}$** | **88.7** | **$1.15 \times 10^{20}$** |

**2.40**

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p = \frac{1}{(1.602x10^{-19}C)(0.5\Omega-cm)} = \frac{1.25x10^{19}}{V-cm-s}$$

An iterative solution is required. Using the equations in Fig. 2.8:

| $N_A$ | $\mu_p$ | $\mu_p\,p$ |
|---|---|---|
| $10^{16}$ | 406 | $4.06 \times 10^{18}$ |
| $2 \times 10^{16}$ | 363 | $7.26 \times 10^{18}$ |
| $3 \times 10^{16}$ | 333 | $9.99 \times 10^{18}$ |
| **$4 \times 10^{16}$** | **310** | **$1.24 \times 10^{19}$** |

**2.41**

Yes, by adding equal amounts of donor and acceptor impurities the mobilities are reduced, but the hole and electron concentrations remain unchanged. See Problem 2.44 for example. However, it is physically impossible to add exactly equal amounts of the two impurities.

**2.42**

$$\rho = \frac{1}{q\mu_n n} \quad | \quad \mu_n n \approx \mu_n N_D = \frac{1}{(1.602x10^{-19}C)(3\Omega-cm)} = \frac{2.08x10^{18}}{V-cm-s}$$

An iterative solution is required. Using the equations in Fig. 2.8:

| $N_D$ | $\mu_n$ | $\mu_n n$ |
|---|---|---|
| $10^{15}$ | 1350 | $1.35 \times 10^{18}$ |
| $1.5 \times 10^{15}$ | 1340 | $2.01 \times 10^{18}$ |
| $1.6 \times 10^{15}$ | 1340 | $2.14 \times 10^{18}$ |
| **$1.55 \times 10^{15}$** | **1340** | **$2.08 \times 10^{18}$** |

**2.43 (a)**

$$\rho = \frac{1}{q\mu_n n} \quad | \quad \mu_n n \approx \mu_n N_D = \frac{1}{\left(1.602x10^{-19}C\right)\left(0.001\Omega - cm\right)} = \frac{6.24x10^{21}}{V - cm - s}$$

An iterative solution is required.  Using the equations in Fig. 2.8:

| $N_D$ | $\mu_n$ | $\mu_n n$ |
|---|---|---|
| $10^{19}$ | 116 | $1.16 \times 10^{21}$ |
| $7 \times 10^{19}$ | 96.1 | $6.73 \times 10^{21}$ |
| **$6.5 \times 10^{19}$** | **96.4** | **$6.27 \times 10^{21}$** |

**(b)**

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p \approx \mu_p N_A = \frac{1}{\left(1.602x10^{-19}C\right)\left(0.001\Omega - cm\right)} = \frac{6.24x10^{21}}{V - cm - s}$$

An iterative solution is required using the equations in Fig. 2.8:

| $N_A$ | $\mu_p$ | $\mu_p p$ |
|---|---|---|
| $1 \times 10^{20}$ | 49.6 | $4.96 \times 10^{21}$ |
| $1.2 \times 10^{20}$ | 49.4 | $5.93 \times 10^{21}$ |
| $1.25 \times 10^{20}$ | 49.4 | $6.17 \times 10^{21}$ |
| **$1.26 \times 10^{20}$** | **49.4** | **$6.22 \times 10^{21}$** |

**2.44**

Based upon the value of its resistivity, the material is an insulator.  However, it is not intrinsic because it contains impurities.  Addition of the impurities has increased the resistivity.

Since $N_D - N_A = 0$, $n = p = n_i$, and $\sigma = q\left(\mu_n n_i + \mu_p n_i\right) = qn_i\left(\mu_n + \mu_p\right)$

$N_A + N_D = 10^{20}/cm^3$ which yields $\mu_p = 49.6$ and $\mu_n = 95.0$ using the

equations from Fig. 2.8.

$$\sigma = \frac{1}{qn_i\left(\mu_n + \mu_p\right)} \leq \frac{1}{\left(1.602x10^{-19}C\right)\left(10^{10}cm^{-3}\right)\left(95.0 + 49.6\right)\left(\dfrac{cm^2}{v - sec}\right)} = 4.32x10^6 \ \Omega - cm$$

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**2.45**

(a) For the 1 ohm-cm starting material:

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p \approx \mu_p N_A = \frac{1}{\left(1.602x10^{-19}C\right)\left(1\Omega - cm\right)} = \frac{6.25x10^{18}}{V - cm - s}$$

An iterative solution is required.  Using the equations in Fig. 2.8:

| $N_A$ | $\mu_p$ | $\mu_p$ p |
|---|---|---|
| $10^{16}$ | 406 | 4.1 x $10^{18}$ |
| 1.5 x $10^{16}$ | 383 | 5.7 x $10^{18}$ |
| **1.7 x $10^{16}$** | **374** | **6.4 x $10^{19}$** |

To change the resistivity to 0.25 ohm-cm:

$$\rho = \frac{1}{q\mu_p p} \quad | \quad \mu_p p \approx \mu_p N_A = \frac{1}{\left(1.602x10^{-19}C\right)\left(0.25\Omega - cm\right)} = \frac{2.5x10^{19}}{V - cm - s}$$

| $N_A$ | $\mu_p$ | $\mu_p$ p |
|---|---|---|
| 6 x $10^{16}$ | 276 | 1.7 x $10^{19}$ |
| 8 x $10^{16}$ | 233 | 2.3 x $10^{19}$ |
| **1.1 x $10^{17}$** | **225** | **2.5 x $10^{19}$** |

Additional acceptor concentration = $1.1x10^{17}$- $1.7x10^{16}$ = 9.3 x $10^{16}$/cm$^3$

(b) If donors are added:

| $N_D$ | $N_D + N_A$ | $\mu_n$ | $N_D - N_A$ | $\mu_n$n |
|---|---|---|---|---|
| 2 x $10^{16}$ | 3.7 x $10^{16}$ | 1060 | 3 x $10^{15}$ | 3.2 x $10^{18}$ |
| 1 x $10^{17}$ | 1.2 x $10^{17}$ | 757 | 8.3 x $10^{16}$ | 6.3 x $10^{19}$ |
| 8 x $10^{16}$ | 9.7 x $10^{16}$ | 811 | 6.3 x $10^{16}$ | 5.1 x $10^{19}$ |
| **4.1 x $10^{16}$** | **5.8 x $10^{16}$** | **950** | **2.4 x $10^{16}$** | **2.3 x $10^{19}$** |

So $N_D$ = 4.1 x $10^{16}$/cm$^3$ must be added to change achieve a resistivity of 0.25 ohm-cm.  The silicon is converted to n-type material.

**2.46**

Phosphorus is a donor: $N_D = 10^{16}/cm^3$ and $\mu_n = 1250$ cm$^2$/V-s from Fig. 2.8.

$$\sigma = q\mu_n n \approx q\mu_n N_D = \left(1.602x10^{-19}C\right)\left(1250\right)\left(10^{16}\right) = \frac{2.00}{\Omega - cm}$$

Now we add acceptors until $\sigma = 5.0$ ($\Omega$-cm)$^{-1}$:

$$\sigma = q\mu_p p \quad | \quad \mu_p p \approx \mu_p\left(N_A - N_D\right) = \frac{4\left(\Omega - cm\right)^{-1}}{1.602x10^{-19}C} = \frac{2.50x10^{19}}{V - cm - s}$$

| $N_A$ | $N_D + N_A$ | $\mu_p$ | $N_A - N_D$ | $\mu_p\, p$ |
|---|---|---|---|---|
| 1.00E+17 | 1.10E+17 | 2.25E+02 | 9.00E+16 | 2.02E+19 |
| 2.00E+17 | 2.10E+17 | 1.76E+02 | 1.90E+17 | 3.34E+19 |
| 1.50E+17 | 1.60E+17 | 1.95E+02 | 1.40E+17 | 2.74E+19 |
| 1.40E+17 | 1.50E+17 | 2.00E+02 | 1.30E+17 | 2.60E+19 |
| 1.30E+17 | 1.40E+17 | 2.06E+02 | 1.20E+17 | 2.47E+19 |
| **1.32E+17** | **1.42E+17** | **2.05E+02** | **1.22E+17** | **2.50E+19** |

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**2.47**

Boron is an acceptor: $N_A = 10^{16}/cm^3$ and $\mu_p = 405$ cm$^2$/V-s from Fig. 2.8.

$$\sigma = q\mu_p p \approx q\mu_p N_A = \left(1.602x10^{-19}C\right)\left(405\right)\left(10^{16}\right) = \frac{0.649}{\Omega - cm}$$

Now we add donors until $\sigma = 5.5$ ($\Omega$-cm)$^{-1}$:

$$\sigma = q\mu_n n \quad | \quad \mu_n n \approx \mu_n\left(N_D - N_A\right) = \frac{5.5\left(\Omega - cm\right)^{-1}}{1.602x10^{-19}C} = \frac{3.43x10^{19}}{V - cm - s}$$

| $N_D$ | $N_D + N_A$ | $\mu_n$ | $N_D - N_A$ | $\mu_p\, p$ |
|---|---|---|---|---|
| 8 x 10$^{16}$ | 9 x 10$^{16}$ | 832 | 7 x 10$^{16}$ | 5.8 x 10$^{19}$ |
| 6 x 10$^{16}$ | 7 x 10$^{16}$ | 901 | 5 x 10$^{16}$ | 4.5 x 10$^{19}$ |
| **4.5 x 10$^{16}$** | **5.5 x 10$^{16}$** | **964** | **3.5 x 10$^{16}$** | **3.4 x 10$^{19}$** |

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**2.48**

$$V_T = \frac{kT}{q} = \frac{1.38x10^{-23}T}{1.602x10^{-19}} = 8.62x10^{-5}T$$

| T (K) | 50 | 75 | 100 | 150 | 200 | 250 | 300 | 350 | 400 |
|---|---|---|---|---|---|---|---|---|---|
| $V_T$ (mV) | 4.31 | 6.46 | 8.61 | 12.9 | 17.2 | 21.5 | 25.8 | 30.1 | 34.5 |

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**2.49**

$$j = -qD_n\left(-\frac{dn}{dx}\right) = qV_T\mu_n\frac{dn}{dx}$$

$$j = \left(1.602x10^{-19}C\right)\left(0.025V\right)\left(350\frac{cm^2}{V-s}\right)\left(\frac{10^{18}-0}{0-0.5x10^{-4}}\right)\frac{1}{cm^4} = -28.0\frac{kA}{cm^2}$$

---

**2.50**

$$j = -qD_p\frac{dp}{dx} = \left(-1.602x10^{-19}C\right)\left(15\frac{cm^2}{s}\right)\left(-\frac{10^{19}/cm^3}{2x10^{-4}cm}\right)\exp\left(-\frac{x}{2x10^{-4}cm}\right)$$

$$j = 1.20x10^5\exp\left(-5000\frac{x}{cm}\right)\frac{A}{cm^2}$$

$$I(0) = j(0)A = \left(1.20x10^5\frac{A}{cm^2}\right)\left(10\mu m^2\right)\left(\frac{10^{-8}cm^2}{\mu m^2}\right) = 12.0\ mA$$

---

**2.51**

$$j_p = q\mu_p pE - qD_p\frac{dp}{dx} = q\mu_p p\left(E - V_T\frac{1}{p}\frac{dp}{dx}\right) = 0 \rightarrow E = V_T\frac{1}{p}\frac{dp}{dx}$$

$$E \approx V_T\frac{1}{N_A}\frac{dN_A}{dx} = 0.025\frac{-10^{22}\exp\left(-10^4 x\right)}{10^{14}+10^{18}\exp\left(-10^4 x\right)}$$

$$E(0) = -0.025\frac{10^{22}}{10^{14}+10^{18}} = -250\frac{V}{cm}$$

$$E\left(5x10^{-4}cm\right) = -0.025\frac{10^{22}\exp(-5)}{10^{14}+10^{18}\exp(-5)} = -246\frac{V}{cm}$$

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**2.52**

At x = 0:

$$j_n^{drift} = q\mu_n nE = \left(1.60x10^{-19}C\right)\left(350\frac{cm^2}{V-s}\right)\left(\frac{10^{16}}{cm^3}\right)\left(-20\frac{V}{cm}\right) = -11.2\frac{A}{cm^2}$$

$$j_p^{drift} = q\mu_p pE = \left(1.60x10^{-19}C\right)\left(150\frac{cm^2}{V-s}\right)\left(\frac{1.01x10^{18}}{cm^3}\right)\left(-20\frac{V}{cm}\right) = -484\frac{A}{cm^2}$$

$$j_n^{diff} = qD_n\frac{dn}{dx} = \left(1.60x10^{-19}C\right)\left(350\cdot0.025\frac{cm^2}{s}\right)\left(\frac{10^4-10^{16}}{2x10^{-4}cm^4}\right) = -70.0\frac{A}{cm^2}$$

$$j_p^{diff} = -qD_p\frac{dp}{dx} = \left(-1.60x10^{-19}C\right)\left(150\cdot0.025\frac{cm^2}{s}\right)\left(\frac{10^{18}-1.01x10^{18}}{2x10^{-4}cm^4}\right) = 30.0\frac{A}{cm^2}$$

$$j_T = -11.2 - 484 - 70.0 + 30.0 = -535\frac{A}{cm^2}$$

At $x = 1 \ \mu m$ assuming linear distributions :

$p(1\mu m) = 1.005x10^{18}/cm^3$, $n(1\mu m) = 5x10^{15}/cm^3$

$$j_n^{drift} = q\mu_n nE = \left(1.60x10^{-19}C\right)\left(350\frac{cm^2}{V-s}\right)\left(\frac{5x10^{15}}{cm^3}\right)\left(-20\frac{V}{cm}\right) = -5.61\frac{A}{cm^2}$$
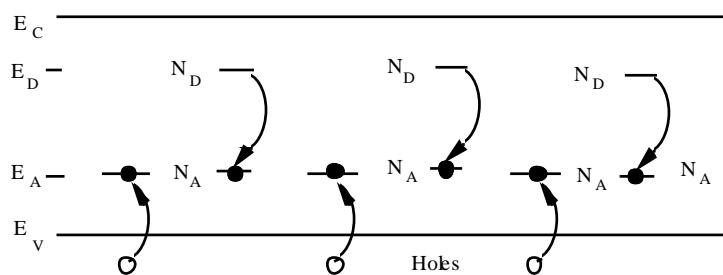
$$j_p^{drift} = q\mu_p pE = \left(1.60x10^{-19}C\right)\left(150\frac{cm^2}{V-s}\right)\left(\frac{1.005x10^{18}}{cm^3}\right)\left(-20\frac{V}{cm}\right) = -482\frac{A}{cm^2}$$

$$j_n^{diff} = qD_n\frac{dn}{dx} = \left(1.60x10^{-19}C\right)\left(350\cdot0.025\frac{cm^2}{s}\right)\left(\frac{10^4-10^{16}}{2x10^{-4}cm^4}\right) = -70.0\frac{A}{cm^2}$$

$$j_p^{diff} = -qD_p\frac{dp}{dx} = \left(-1.60x10^{-19}C\right)\left(150\cdot0.025\frac{cm^2}{s}\right)\left(\frac{10^{18}-1.01x10^{18}}{2x10^{-4}cm^4}\right) = 30.0\frac{A}{cm^2}$$
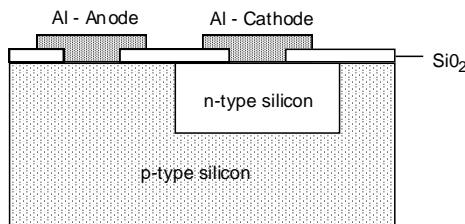
$$j_T = -5.61-482-70.0+30.0 = -528\frac{A}{cm^2}$$

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**2.53**  $N_A = 2N_D$



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**2.54**
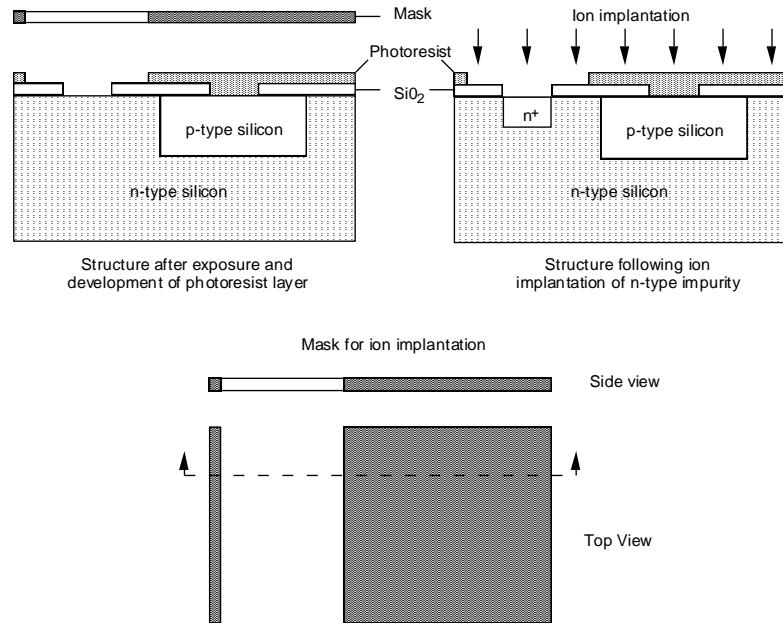
$$\lambda = \frac{hc}{E} = \frac{\left(6.626\,x10^{-34}J-s\right)\left(3x10^8\,m/s\right)}{\left(1.12eV\right)\left(1.602\,x10^{-19}J/eV\right)} = 1.108\ \mu m$$

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**2.55**



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**2.56**

An n-type ion implantation step could be used to form the $n^+$ region following step (f) in Fig. 2.17. A mask would be used to cover up the opening over the p-type region and leave the opening over the n-type silicon. The masking layer for the implantation could just be photoresist.

Mask

Ion implantation

Photoresist

Si0$_2$

$n^+$

p-type silicon

p-type silicon

n-type silicon

n-type silicon

Structure after exposure and
development of photoresist layer

Structure following ion
implantation of n-type impurity

Mask for ion implantation

Side view

Top View

**2.57**

$(a)\ \text{N} = 8\left(\dfrac{1}{8}\right) + 6\left(\dfrac{1}{2}\right) + 4(1) = 8\ atoms$

$(b)\ V = l^3 = \left(0.543x10^{-9}m\right)^3 = \left(0.543x10^{-7}cm\right)^3 = 1.60x10^{-22}cm^3$

$(c)\ \text{D} = \dfrac{8\ \text{atoms}}{1.60x10^{22}cm^3} = 5.00x10^{22}\dfrac{atoms}{cm^3}$

$(d)\ \text{m} = \left(2.33\dfrac{g}{cm^3}\right)1.60x10^{22}cm^3 = 3.73x10^{-22}g$

$(e)$ From Table 2.2, silicon has a mass of 28.086 protons.

$\text{m}_p = \dfrac{3.73x10^{-22}g}{28.082(8)protons} = 1.66x10^{-24}\dfrac{g}{proton}$

Yes, near the actual proton rest mass.