A drift current density of $J_{drf} = 75\ \text{A/cm}^2$ is required in a device using p-type silicon when an electric field of $E = 120$ V/cm is applied. Determine the required impurity doping concentration to achieve this specification.

(Ans. $N_a = 8.14 \times 10^{15}\ \text{cm}^{-3}$)

Consider a sample of silicon at $T = 300$ K doped at an impurity concentration of $N_d = 10^{15}\ \text{cm}^{-3}$ and $N_a = 10^{14}\ \text{cm}^{-3}$. Calculate the drift current density if the applied electric field is $E = 35$ V/cm.

(Ans. $6.80\ \text{A/cm}^2$)

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?

$$\rho = \frac{1}{e\mu_n N_d} = \frac{1}{(1.6\times10^{-19})(1300)(10^{15})}$$
$$= 4.808\,\Omega\text{-cm}$$

$$\sigma = \frac{1}{\rho} = \frac{1}{4.8077} = 0.208\,(\Omega\text{ -cm})^{-1}$$

A p-type silicon material is to have a conductivity of $\sigma = 1.80\ (\Omega\text{-cm})^{-1}$. If the mobility values are $\mu_n = 1250$ cm^2/V-s and $\mu_p = 380$ cm^2/V-s, what must be the acceptor impurity concentration in the material?

$$\sigma = e\mu_p N_a$$

$$N_a = \frac{\sigma}{e\mu_p} = \frac{1.80}{(1.6\times10^{-19})(380)}$$
$$= 2.96\times10^{16}\text{ cm}^{-3}$$

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.

$$\sigma_i = en_i(\mu_n + \mu_p)$$

Then

$$10^{-6} = (1.6\times10^{-19})(1000+600)n_i$$

or

$$n_i\,(300\ \text{K}) = 3.91\times10^{9}\ \text{cm}^{-3}$$

Now

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

or

$$E_g = kT\ln\left(\frac{N_c N_\upsilon}{n_i^2}\right)$$

$$= (0.0259)\ln\left[\frac{(10^{19})^2}{(3.91\times10^{9})^2}\right]$$

which gives

$$E_g = 1.122\ \text{eV}$$

$$n_i^2\,(500\text{K}) = (10^{19})^2 \exp\left[\frac{-1.122}{(0.0259)(500/300)}\right]$$

$$= 5.15\times10^{26}$$

or

$$n_i\,(500\ \text{K}) = 2.27\times10^{13}\ \text{cm}^{-3}$$

Then

$$\sigma_i = (1.6\times10^{-19})(2.27\times10^{13})(1000+600)$$

which gives

$$\sigma_i\,(500\ \text{K}) = 5.81\times10^{-3}\ \ (\Omega\text{-cm})^{-1}$$

(a) Calculate the conductivity at $T = 300$ K of intrinsic (i) silicon, (ii) germanium, and (iii) gallium arsenide. (b) If rectangular semiconductor bars are fabricated using the materials in part (a), determine the resistance of each bar if its cross-sectional area is 85 μm^2 and length is 200 μm.

(a) (i) Silicon: $\sigma_i = en_i(\mu_n + \mu_p)$

$$\sigma_i = (1.6\times10^{-19})(1.5\times10^{10})(1350+480)$$

or

$$\sigma_i = 4.39\times10^{-6}\,(\Omega\text{-cm})^{-1}$$

(ii) Ge:

$$\sigma_i = (1.6\times10^{-19})(2.4\times10^{13})(3900+1900)$$

or

$$\sigma_i = 2.23\times10^{-2}\,(\Omega\text{-cm})^{-1}$$

(iii) GaAs:

$$\sigma_i = (1.6\times10^{-19})(1.8\times10^{6})(8500+400)$$

or

$$\sigma_i = 2.56\times10^{-9}\,(\Omega\text{-cm})^{-1}$$

(b) $R = \dfrac{L}{\sigma A}$

(i) Si:

$$R = \frac{200\times10^{-4}}{(4.39\times10^{-6})(85\times10^{-8})} = 5.36\times10^{9}\ \Omega$$

(ii) Ge:

$$R = \frac{200\times10^{-4}}{(2.23\times10^{-2})(85\times10^{-8})} = 1.06\times10^{6}\ \Omega$$

(iii) GaAs:

$$R = \frac{200\times10^{-4}}{(2.56\times10^{-9})(85\times10^{-8})} = 9.19\times10^{12}\ \Omega$$

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/cm^2. If the electron diffusion coefficient is $D_n = 25$ cm^2/s, determine the electron concentration at $x = 0$.

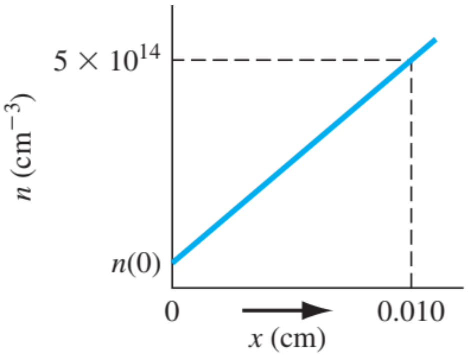

Figure P5.29

$$J_n = eD_n \frac{dn}{dx} = eD_n \left(\frac{5\times10^{14} - n(0)}{0.01-0} \right)$$

$$0.19 = (1.6\times10^{-19})(25)\left(\frac{5\times10^{14} - n(0)}{0.010} \right)$$

Then

$$\frac{(0.19)(0.010)}{(1.6\times10^{-19})(25)} = 5\times10^{14} - n(0)$$

which yields

$$n(0) = 0.25\times10^{14} \text{ cm}^{-3}$$

The steady-state electron distribution in silicon can be approximated by a linear function of x. The maximum electron concentration occurs at $x = 0$ and is $n(0) = 2 \times 10^{16}\ \text{cm}^{-3}$. At $x = 0.012$ cm, the electron concentration is $5 \times 10^{15}\ \text{cm}^{-3}$. If the electron diffusion coefficient is $D_n = 27\ \text{cm}^2/\text{s}$, determine the electron diffusion current density.

$$J_n = eD_n \frac{dn}{dx} = eD_n \frac{\Delta n}{\Delta x}$$

$$J_n = (1.6\times10^{-19})(27)\left[\frac{2\times10^{16} - 5\times10^{15}}{0-0.012}\right]$$

$$J_n = -5.4\ \text{A/cm}^2$$

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 $D_n = 230\ \text{cm}^2/\text{s}$.

(a) $$J_n = eD_n \frac{dn}{dx} = eD_n \frac{\Delta n}{\Delta x}$$

$$-2 = (1.6\times10^{-19})(30)\left[\frac{10^{15} - n(x_1)}{0-20\times10^{-4}}\right]$$

$$4\times10^{-3} = 4.8\times10^{-3} - 4.8\times10^{-18}\, n(x_1)$$

which yields

$$n(x_1) = 1.67\times10^{14}\ \text{cm}^{-3}$$

(b) $$-2 = (1.6\times10^{-19})(230)\left[\frac{10^{15} - n(x_1)}{0-20\times10^{-4}}\right]$$

$$4\times10^{-3} = 3.68\times10^{-2} - 3.68\times10^{-17}\, n(x_1)$$

$$n(x_1) = 8.91\times10^{14}\ \text{cm}^{-3}$$

In silicon, the electron concentration is given by $n(x) = 10^{15}e^{-x/L_n}$ cm^{-3} for $x \geq 0$ and the hole concentration is given by $p(x) = 5 \times 10^{15}e^{+x/L_p}$ 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 $D_n = 25$ cm^2/s and $D_P = 10$ cm^2/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.

For electrons:

$$J_n = eD_n \frac{dn}{dx} = eD_n \frac{d}{dx}\left[10^{15} e^{-x/L_n}\right]$$

$$= \frac{-eD_n\left(10^{15}\right)e^{-x/L_n}}{L_n}$$

At $x = 0$,

$$J_n = \frac{-\left(1.6\times10^{-19}\right)(25)\left(10^{15}\right)}{2\times10^{-3}} = -2 \text{ A/cm}^2$$

For holes:

$$J_p = -eD_p \frac{dp}{dx} = -eD_p \frac{d}{dx}\left[5\times10^{15} e^{+x/L_p}\right]$$

$$= \frac{-eD_p\left(5\times10^{15}\right)e^{+x/L_p}}{L_p}$$

For $x = 0$,

$$J_p = \frac{-\left(1.6\times10^{-19}\right)(10)\left(5\times10^{15}\right)}{5\times10^{-4}} = -16 \text{ A/cm}^2$$

$$J_{Total} = J_n(x=0) + J_p(x=0)$$

$$= -2 + (-16) = -18 \text{ A/cm}^2$$

The hole concentration in p-type GaAs is given by $p(x) = 10^{16}(1 + x/L)^2\ \text{cm}^{-3}$ for $-L \leq x \leq 0$ where $L = 12\ \mu\text{m}$. The hole diffusion coefficient is $D_p = 10\ \text{cm}^2/\text{s}$. Calculate the hole diffusion current density at (*a*) $x = 0$, (*b*) $x = -6\ \mu\text{m}$, and (*c*) $x = -12\ \mu\text{m}$.

$$J_p = -eD_p \frac{dp}{dx} = -eD_p \frac{d}{dx}\left[10^{16}\left(1+\frac{x}{L}\right)^2\right]$$

$$= -eD_p \cdot \frac{10^{16}}{L} \cdot 2\left(1+\frac{x}{L}\right)$$

(a) For $x = 0$,

$$J_p = \frac{-(1.6\times10^{-19})(10)(10^{16})(2)}{12\times10^{-4}}$$

$$= -26.7\ \text{A/cm}^2$$

(b) For $x = -6\ \mu\text{m}$,

$$J_p = \frac{-(1.6\times10^{-19})(10)(10^{16})(2)\left(1-\frac{6}{12}\right)}{12\times10^{-4}}$$

$$= -13.3\ \text{A/cm}^2$$

(c) For $x = -12\ \mu\text{m}$,

$$J_p = 0$$

- As the mobilities are strong functions of temperature because of the scattering processes, the diffusion coefficients are also strong functions of temperature.

- The specific temperature dependence given in Equation is only a small fraction of the real temperature characteristic.

Typical mobility and diffusion coefficient values at $T = 300$ K ($\mu = \text{cm}^2/\text{V-s}$ and $D = \text{cm}^2/\text{s}$)

	μ_m	D_n	μ_p	D_p
Silicon	1350	35	480	12.4
Gallium arsenide	8500	220	400	10.4
Germanium	3900	101	1900	49.2

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 $L = 15\ \mu$m. 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)
$$J_n = eD_n \frac{dn}{dx} = eD_n \frac{d}{dx}\left[2\times10^{15} e^{-x/L}\right]$$
$$= \frac{-eD_n\left(2\times10^{15}\right)e^{-x/L}}{L}$$
$$= \frac{-\left(1.6\times10^{-19}\right)(27)\left(2\times10^{15}\right)e^{-x/L}}{15\times10^{-4}}$$
$$= -5.76e^{-x/L}$$

(b)
$$J_p = J_{Total} - J_n = -10 - \left(-5.76e^{-x/L}\right)$$
$$= \left[5.76e^{-x/L} - 10\right]\ \text{A/cm}^2$$

(c) We have $J_p = \sigma \mathrm{E} = \left(e\mu_p p_o\right)\mathrm{E}$
$$5.76e^{-x/L} - 10 = \left(1.6\times10^{-19}\right)(420)\left(10^{16}\right)\mathrm{E}$$
So $\mathrm{E} = \left[8.57e^{-x/L} - 14.88\right]$ V/cm

A p-type silicon sample with the geometry shown below has parameters L= 0.2 cm, W=10^{-2} cm, and d=8×10^{-4} cm. The semiconductor parameters are p=10^{16} cm^{-3} and μ_p=320 cm^2/V-s. For V_x =10 V and Bz =500 gauss=5×10^{-2} tesla, determine I_x and V_H.

$$I_x = \frac{ep\mu_p V_x W d}{L}$$

$$I_x = \frac{1.6\times10^{-19}.\,10^{22}.\,320\times10^{-4}.\,10.\,10^{-4}\,.\,8\times10^{-6}}{0.2\times10^{-2}}$$

$$I_x = 0.2048mA$$

$$V_H = \frac{I_x B_z}{ped}$$

$$V_H = \frac{0.2048\times10^{-3}.\,5\times10^{-2}.}{10^{22}.\,1.6\times10^{-19}.\,8\times10^{-6}}$$

$$V_H = 0.80mV$$

Germanium is doped with 5×10^{15} donor atoms per cm^3 at T = 300 K. The dimensions of the Hall device are d $= 5 \times 10^{-3}$ cm, W $= 2 \times 10^{-2}$ cm, and L $= 10^{-1}$ cm. The current is $I_x = 250$ μA, the applied voltage is $V_x = 100$ mV, and the magnetic flux density is $B_z = 500$ gauss $= 5 \times 10^{-2}$ tesla. Calculate (i) the Hall voltage, (ii) the Hall field, and (iii) the carrier mobility.

(i) Hall Voltage

$$V_H = \frac{-I_x B_z}{ped}$$

$$V_H = \frac{-(250 \times 10^{-6}).(5 \times 10^{-2})}{(5 \times 10^{21}).(1.6 \times 10^{-19}).(5 \times 10^{-5})}$$

$$V_H = -0.3125 mV$$

(ii) Hall Field

$$E_H = \frac{V_H}{W} = \frac{= -0.3125 \times 10^{-3}}{2 \times 10^{-2}} = -1.56 \times 10^{-2} V/cm$$

(iii) Carrier mobility

$$\mu_n = \frac{I_x L}{e n V_x W d}$$

$$\mu_n = \frac{(250 \times 10^{-6}).(10^{-3})}{(1.6 \times 10^{-19}).(5 \times 10^{21}).(0.1).(2 \times 10^{-4}).(5 \times 10^{-5})}$$

$$\mu_n = 0.3125\ m^2/V - s \ or\ 3125\ cm^2/V - s$$

Consider a gallium arsenide sample at $T = 300$ K. A Hall effect device has been fabricated with the following geometry: $d = 0.0\,1$ cm, $W = 0.05$ cm, and $L = 0.5$ cm. The electrical parameters are: $I_x = 2.5$ mA, $V_x = 2.2$ V, and $B_z = 2.5 \times 10^{-2}$ tesla. The Hall voltage is $V_H = -4.5$ mV. Find: (*a*) the conductivity type, (*b*) the majority carrier concentration, (*c*) the mobility, and (*d*) the resistivity.

(a) $V_H = \text{negative} \Rightarrow \text{n-type}$

(b) $$n = \frac{-I_x B_z}{edV_H}$$

$$= \frac{-(2.5\times10^{-3})(2.5\times10^{-2})}{(1.6\times10^{-19})(0.01\times10^{-2})(-4.5\times10^{-3})}$$

or

$$n = 8.68\times10^{20}\ \text{m}^{-3} = 8.68\times10^{14}\ \text{cm}^{-3}$$

(c) $$\mu_n = \frac{I_x L}{enV_x Wd}$$

$$= \left[\frac{(2.5\times10^{-3})(0.5\times10^{-2})}{(1.6\times10^{-19})(8.68\times10^{20})(2.2)}\right] \times \left[\frac{1}{(0.05\times10^{-2})(0.01\times10^{-2})}\right]$$

or

$$\mu_n = 0.8182\ \text{m}^2/\text{V-s} = 8182\ \text{cm}^2/\text{V-s}$$

(d) $$\sigma = \frac{1}{\rho} = e\mu_n n$$

$$= (1.6\times10^{-19})(8182)(8.68\times10^{14})$$

or

$$\rho = 0.88\ (\Omega\text{-cm})$$