CHE323/384 Chemical Processes for Micro- and Nanofabrication
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Homework #1 Solutions

1. For dopant atoms uniformly distributed in a silicon crystal, how far apart are these dopant atoms when the doping concentration is a) 2 X 10^{15} cm^{-3}, b) 10^{18} cm^{-3}, c) 7 X 10^{20} cm^{-3}.

The average distance between dopant atoms is the cubed root of the concentration. Thus,

a) d = (2 X 10^{15} $cm^{-3})^{-1/3}$ = 0.794 X 10^{-5} cm ≈ 80 nm (keeping one digit of precision)
b) d = (1 X 10^{18} $cm^{-3})^{-1/3}$ = 1 X 10^{-6} cm = 10 nm
c) d = (7 X 10^{20} $cm^{-3})^{-1/3}$ = 1.13 X 10^{-7} cm ≈ 1.1 nm

2. What is the resistivity of pure silicon at room temperature?

$$\frac{1}{\rho} = \sigma = q(n\mu_n + p\mu_p), \quad n = p = n_i$$

$$\sigma = 1.6 \times 10^{-19} C(1.5 \times 10^{10} cm^{-3}) \left(1500 \frac{cm^2}{Vs} + 450 \frac{cm^2}{Vs}\right) = 4.7 \times 10^{-6} (\Omega cm)^{-1}$$

$$\rho = 2.1 \times 10^5 \Omega cm$$

(Note that silicon dioxide has a resistivity of about 10^{14} Ωcm, and copper is about 10^{-6} Ωcm.)

3. a) Show that the minimum conductivity of a semiconductor occurs when $n = n_i\sqrt{\mu_p/\mu_n}$.

Use the mass action equation $np = n_i{}^2$ to put *p* in terms of *n* in the conductivity equation.

$$\sigma = q\left(n\mu_n + \frac{n_i^2}{n}\mu_p\right)$$

Now take the derivative wrt *n*, set it equal to zero, and solve for *n*.

$$\frac{d\sigma}{dn} = q\left(\mu_n - \frac{n_i^2}{n^2}\mu_p\right) = 0, \qquad n^2 = n_i^2\frac{\mu_p}{\mu_n}, \qquad n = n_i\sqrt{\frac{\mu_p}{\mu_n}}$$

3. b) How does the minimum conductivity for silicon compare to the intrinsic conductivity of silicon at room temperature?

Using the results of 3a in the equation for the conductivity, $\sigma_{min} = 2qn_i\sqrt{\mu_n\mu_p}$.

$$\sigma = 2(1.6 \times 10^{-19}C)(1.5 \times 10^{10}cm^{-3})\sqrt{\left(1500\frac{cm^2}{Vs}\right)\left(450\frac{cm^2}{Vs}\right)} = 3.9 \times 10^{-6}(\Omega cm)^{-1}$$

This is only a little smaller (16%) than the value for intrinsic silicon calculated in problem 2.

4. Consider a resistor made of pure silicon with a cross-sectional area of 0.5 μm^2, and a length of 50 μm. What is the resistance of this silicon piece? For an applied voltage of 5 V, how much current would flow through it?

$$R = \rho\frac{L}{A} = 2.1 \times 10^5 \Omega cm \frac{50\mu m}{0.5\mu m^2}\left(\frac{10{,}000\mu m}{1cm}\right) = 2.1 \times 10^{11}\Omega$$

(That's a big resistance!)

$$V = IR, \qquad I = \frac{5V}{2.1 \times 10^{11}\Omega} = 24 \text{ pA}$$

5. Suppose the resistor of problem 4 were made of p-type silicon. What doping level would be required to make the resistance equal to 25 kΩ? 25Ω?

The required conductivity is $\sigma = \frac{1}{\rho} = \frac{1}{R}\frac{L}{A} = \frac{1}{25{,}000}\frac{50\mu m}{0.5\mu m^2}\left(\frac{10{,}000\mu m}{1cm}\right) = 40(\Omega\text{cm})^{-1}$

For p-type silicon, the electron concentration can be ignored and the conductivity will be

$\sigma = qp\mu_p = qN_A\mu_p$ (since $p \approx N_A$). Thus,

$$N_A = \frac{\sigma}{q\mu_p} = \frac{40(\Omega\text{cm})^{-1}}{(1.6 \times 10^{-19}C)\left(450\frac{cm^2}{Vs}\right)} = 5.6 \times 10^{17}cm^{-3}$$

To make a 25Ω resistor, the doping level would have to be 1000 time higher: $5.6 \times 10^{20}cm^{-3}$. This can be hard to do, since it is near the solid solubility limit for most dopants.