Problem 3.2 Using the work functions listed in table 3.2.1, predict which metal-semiconductor junctions are expected to be ohmic contacts. Use the ideal interface model.

Solution The barrier height on an n-type semiconductor is given by

$$\phi_B = \Phi_M - \chi$$

And on a p-type semiconductor by

$$\phi_B = \chi + \frac{E_g}{q} - \Phi_M$$

Using the metal workfunction from table 3.2.1 and the semiconductor electron affinity and bandgap from appendix 3 one finds that only three combinations yield a negative barrier height as provided in the table below. One expects these metal-semiconductor junctions to yield an ohmic contact.

Au/p-Ge	-0.14 V
Pt/p-Ge	-0.64 V
Pt/p-Si	-0.13 V

From Appendix 3:

Symbol	Germanium	Silicon	Gallium Arsenide
E_g (eV)	0.66	1.12	1.424
χ (eV)	4.0	4.05	4.07

Problem 3.3 Design a platinum-silicon diode with a capacitance of 1 pF and a maximum electric field less than 10^4 V/cm at -10 V bias. Provide a possible doping density and area. Make sure the diode has an area between 10^{-5} and 10^{-7} cm^2. Is it possible to satisfy all requirements if the doping density equals 10^{17} cm^{-3}? What is the corresponding area?

Solution From the capacitance and the area one finds the corresponding depletion layer width, namely:

$$x_d = \frac{\varepsilon_s}{C_j} = 105 \text{ nm and } 1.05 \text{ nm}$$

corresponding to a diode area of 10^{-5} and 10^{-7} cm^2 respectively. Note that the capacitance C_j is the capacitance per unit area. The corresponding doping density is obtain from:

$$N_d = \frac{\mathcal{E}(x=0)\varepsilon_s}{q x_d} = 6.24 \times 10^{15} \text{ and } 6.24 \times 10^{17} \text{ cm}^{-3} \text{ respectively}$$

Any other designs should have a doping density between those two values. Since the doping density of 10^{17} cm^{-3} is also between those two values it is a possible solution. The corresponding area is 6.24×10^{-7} cm^2.

Problem 3.6: A metal-semiconductor junction consists of platinum and gallium arsenide with $N_d = 10^{17}$ cm^{-3}. The applied voltage equals -3 V. Calculate the electric field in the semiconductor at the metal-semiconductor interface. Use $\phi_i = 0.8$ V.

Solution:

$$\mathcal{E}(x = 0) = -\frac{qN_d x_d}{\varepsilon_s} = -\frac{Q_d}{\varepsilon_s} \qquad x_d = \sqrt{\frac{2\varepsilon_s(\phi_i - V_a)}{qN_d}}$$

Substituting parameters for GaAs yields $\varepsilon = 300$ kV/cm

Problem 3.8: A metal-semiconductor junction, biased at an unknown voltage, has a doping density of 10^{17} cm^{-3}and a capacitance of 1 pF. The semiconductor is p-type germanium, the built-in potential of the junction is 0.5 V and the diode area is 10^{-4} cm^2. Calculate the depletion layer width and the applied voltage.

Solution

Using

$$C_j = \left|\frac{dQ_d}{dV_a}\right| = \sqrt{\frac{q\,\varepsilon_s N_d}{2(\phi_i - V_a)}} = \frac{\varepsilon_s}{x_d}$$

yields and x_d of 1.4 x 10^{-4} m.

Then using,

$$x_d = \sqrt{\frac{2\varepsilon_s(\phi_i - V_a)}{qN_d}}$$

yields V_a of -110 V.

Extra Problem

We start from an expression for the drift current and Gauss's law

$$J = qp\mu \mathcal{E}$$

$$\frac{d\mathcal{E}}{dx} = \frac{qp}{\varepsilon}$$

Next we can eliminate the carrier density, p, yielding:

$$\frac{J}{\varepsilon\mu} = \mathcal{E}\frac{d\mathcal{E}}{dx}$$

Integrating this expression from 0 to x, while we assuming the electric field to be zero at x = 0 one obtains:

$$\frac{Jx}{\varepsilon\mu} = \frac{\mathcal{E}^2}{2} \text{ or } \mathcal{E}(x) = \sqrt{\frac{2xJ}{\varepsilon\mu}}$$

integrating once again from x = 0 to x = d with V(0) = V and V(d) = 0,

$$V = \int_0^d \mathcal{E}dx = \sqrt{\frac{2J}{\varepsilon\mu}}\frac{d^{3/2}}{3/2}$$

from which one obtains the expression for the space-charge-limited current:

$$J = \frac{9\varepsilon\mu V^2}{8d^3}$$

Problem 4.4 An abrupt silicon ($n_i = 10^{10}$ cm^{-3}) p-n junction consists of a p-type region containing 10^{16} cm^{-3} acceptors and an n-type region containing 5 x 10^{16} cm^{-3} donors.

a) Calculate the built-in potential of this p-n junction.
b) Calculate the total width of the depletion region if the applied voltage V_a equals 0, 0.5 and -2.5 V.
c) Calculate maximum electric field in the depletion region at 0, 0.5 and -2.5 V.
d) Calculate the potential across the depletion region in the n-type semiconductor at 0, 0.5 and -2.5 V.

Solution The built-in potential equals:

$$\phi_i = V_t \ln \frac{N_d N_a}{n_i^2} = 0.02586 \times \ln \frac{5 \times 10^{16} \times 10^{16}}{10^{20}} = 0.76 \text{ V}$$

The depletion layer width is calculated from:

$$x_d = \sqrt{\frac{2\varepsilon_s(\phi_i - V_a)}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$$

Resulting in a depletion layer width of 0.35, 0.20 and 0.72 μm for an applied voltage of 0, 0.5 and –2.5 V.

The corresponding electric field is obtained from:

$$\mathcal{E}(x = 0) = -\frac{2(\phi_i - V_a)}{x_d}$$

Resulting in a field of -43.8, -25.5 and -90.8 kV/cm. The potential across the depletion region in the n-type semiconductor equals:

$$\phi_n = -\frac{\mathcal{E}(x = 0)}{2} x_n = -\frac{\mathcal{E}(x = 0)}{2} \frac{N_a}{N_a + N_d} x_d$$

Resulting in 0.13, 0.04 and 0.54 V

Problem 4.6 A silicon ($n_i = 10^{10}$ cm^{-3}) p-n diode with $N_a = 10^{18}$ cm^{-3} has a junction capacitance of 10^{-8} F/cm^2 at an applied voltage of 0.5 V. Find the donor density.

Solution The depletion layer width equals:

$$w = \frac{\varepsilon_s}{C_j} = 1.05\ \mu\text{m}$$

The sum of the inverses of the doping densities is then:

$$\frac{1}{N_a} + \frac{1}{N_a} = \frac{qw^2}{2\varepsilon_s(\phi_i - V_a)} = 3.5 \text{ x } 10^{-15} \text{ cm}^3$$

So that the donor density equals:

$$N_d = \left(\frac{1}{N_a} - \frac{1}{N_a}\right)^{-1} = 2.84 \text{ x } 10^{14} \text{ cm}^{-3}$$

While the built-in potential was calculated from:

$$\phi_i = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = 741 \text{ mV}$$

The solution was obtained by starting with a built-in potential of 0.7 V and repeatedly calculating the doping density and the built-in potential from it.