ECE 305 Homework SOLUTIONS: Week 10

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1) Consider an ideal metal-semiconductor junction with the band diagram shown below. The semiconductor has a relative dielectric constant of 12 and an electron affinity of 4.0 eV. Answer the following questions.

1a) What is the workfunction of the metal?

1b) What is the built-in potential of the semiconductor?

1c) At $V = 0$, we measure a capacitance of 17 pF for a 100 µm x 100 µm diode. What is the doping density in the semiconductor?

Solution:

1a) What is the workfunction of the metal?

$$\Phi_{BN} = \Phi_M - \chi$$

$$\Phi_M = \Phi_{BN} + \chi = 0.4 + 4.0 = 4.4 \text{ eV}$$

$$\Phi_M = 4.4 \text{ eV}$$

1b) What is the built-in potential of the semiconductor?

It is the bandbending in the semiconductor divided by $q$. From the figure we see:

$$qV_{bi} = q(0.4 - 0.1)$$

$$V_{bi} = 0.3 \text{ V}$$
HW10 Solutions (continued):

1c) At $V = 0$, we measure a capacitance of 29 pF for a 100 $\mu$m x 100 $\mu$m diode. What is the doping density in the semiconductor?

$$C_j = \frac{K_s \varepsilon_0 A}{2K_s \varepsilon_0 V_{bi}} \to N_D = \frac{2V_{bi} C^2}{qN_D A^2}$$

$$N_D = \frac{2V_{bi} C^2}{qK_s \varepsilon_0 A^2} = \frac{2(0.3)(29 \times 10^{-12})^2}{(1.6 \times 10^{-19})(12)(8.854 \times 10^{-14})(10^{-2})^2} = 3 \times 10^{17} \text{ cm}^{-3}$$

$$N_D = 3 \times 10^{17} \text{ cm}^{-3}$$

2) You are given a metal semiconductor at room temperature in which the workfunction of the metal equals the electron affinity of the semiconductor plus $3k_B T$ (i.e. $\Phi_M = \chi + 3k_B T$) and the Fermi level in the semiconductor is $3k_B T$ below $E_C$. The semiconductor has a bandgap of 1 eV.

2a) Is the semiconductor n-type, p-type, or intrinsic?

The Fermi level is near the conduction band. **The semiconductor is n-type.**

2b) What is the numerical value of $V_{bi}$?

2c) Is the metal contact to the semiconductor ohmic or rectifying?

Solutions:

2a) Is the semiconductor n-type, p-type, or intrinsic?

The Fermi level is near the conduction band. **The semiconductor is n-type.**

2b) What is the numerical value of $V_{bi}$?

The band diagram before putting the two materials together is shown below. Note that the semiconductor workfunction is equal to the metal workfunction. There is no charge transfer when the put the two together, so $V_{bi} = 0$.

$$qV_{bi} = \Phi_M - \Phi_S = 0$$

$$V_{bi} = 0$$
HW10 Solutions (continued):

2c) Is the metal contact to the semiconductor ohmic or rectifying?

Since there is no barrier for electrons to flow from the semiconductor to metal and only a small barrier for electrons to flow from the metal to semiconductor, the junction is ohmic.

3) You are given a metal semiconductor at room temperature in which the workfunction of the metal equals the electron affinity of the semiconductor plus $3k_B T$ (i.e., $\Phi_M = \chi + 3k_B T$). For this problem, the Fermi level in the semiconductor is $3k_B T$ above $E_V$. The semiconductor has a bandgap of 1 eV.

3a) Is the semiconductor n-type, p-type, or intrinsic?
3b) What is the numerical value of $V_{bi}$?
3c) Is the metal contact to the semiconductor ohmic or rectifying?
HW10 Solutions (continued):

Solutions:

3a) Is the semiconductor n-type, p-type, or intrinsic?

In this case, the Fermi level is near the valence band, so the semiconductor is p-type.

3b) What is the numerical value of $V_{bi}$?

The energy band is shown below. A substantial built-in potential will be needed to alight the Fermi levels.

$$qV_{bi} = \Phi_s - \Phi_M = \left( \chi + E_G - 3k_B T \right) - \left( \chi + 3k_B T \right) = E_G - 6k_B T$$

$$V_{bi} = \frac{E_G}{q} - 6 \frac{k_B T}{q} = 1.0 - 0.16 = 0.84 \text{ V}$$

$$V_{bi} = 0.84 \text{ V}$$

3c) Is the metal contact to the semiconductor ohmic or rectifying?

The energy band is shown below. We see an energy barrier for holes in the semiconductor to be injected into the metal, so this junction is rectifying.
HW10 Solutions (continued):

4) You are given a room temperature semiconductor with a bandgap of 1.43 eV and 
   $n_i = 2 \times 10^6$ cm$^3$ and an electron affinity of $\chi = 4.0$ eV ideally contacted by a metal with 
   $\Phi_M = 4.1$ eV. Answer the following questions.

4a) What is the numerical value of $\Phi_{BN}$?

$\Phi_{BN} = \Phi_M - \chi = 4.1 - 4.0 = 0.1$ eV

$\Phi_{BN} = 0.1$ eV

4b) What is the numerical value of $\Phi_{BP}$?

$\Phi_{BP} = E_G + \chi - \Phi_M = 1.43 + 4 - 4.1 = 1.33$ eV

$\Phi_{BP} = 1.33$ eV

Note that $\Phi_{BN} + \Phi_{BP} = E_G$

4c) If the semiconductor is doped so that $\Phi_M = \Phi_S$, is the MS junction rectifying or ohmic?

There is no charge transfer between the metal and semiconductor. The bands will be flat in the semiconductor, so that electrons can easily cross the junction. This junction will be ohmic.
HW10 Solutions (continued):

5) An ideal MS diode is described by \( I_D = I_0 \left( e^{\frac{qV_A}{k_T}} - 1 \right) \), but real diodes have series resistance. Consider an MS diode with \( I_0 = 10^{-12} \) A at room temperature. A forward bias of 1 V is applied and a current of 1 A is measured. What is the series resistance of this diode?

Solution:

Since we are strongly forward biased, \( I_D = I_0 e^{\frac{qV_A}{k_T}} \). The internal voltage across the junction is found from

\[
I_D = I_0 e^{\frac{qV_A}{k_T}} = 10^{-12} e^{V_A/0.026}
\]

\[
V_A = \frac{k_B T}{q} \ln \left( \frac{I_D}{I_0} \right) = 0.026 \ln(10^{12}) = 0.718
\]

Since one volt was applied to the terminals, 0.282 V must have been dropped across the series resistance.

\[
I_D R_S = 0.282 \text{ V}
\]

\[
R_S = \frac{0.282}{1} \Omega = 0.282 \Omega
\]

The situation is illustrated in the figure below.