Outline:

**p-n Junctions**

p-type material (dopant is electron acceptor)

\[
p_v \approx N_A \\
 n_c \approx \frac{n_i^2}{N_A}
\]

\[
f = F_v + \frac{E_g}{2} + \frac{3}{4}k_B T \ln \left( \frac{m_v^*}{m_c^*} \right) - k_B T \ln \left( \frac{N_A}{n_i} \right)
\]

n-type material (dopant is electron donor)

\[
p_v \approx \frac{n_i^2}{N_D} \\
 n_c \approx N_D
\]

\[
f = F_v + \frac{E_g}{2} + \frac{3}{4}k_B T \ln \left( \frac{m_v^*}{m_c^*} \right) + k_B T \ln \left( \frac{N_D}{n_i} \right)
\]

When p-type and n-type materials are brought together, they form a **p-n** junction. Immediately upon joining, holes will flow from p-type to n-type and electrons from n-type to p-type until an equilibrium is reached when the chemical potential/Fermi energies of each side are equal. This junction results in a redistribution of charge and thus the creation of an electric field being built into the system in a region called the depletion region.

Recall: \( E(x) = \int \frac{\rho(x)}{\varepsilon_r \varepsilon_0} \, dx \) & \( V(x) = -\int E(x) \, dx \)

The built in potential results in no current flowing. To make current flow, an applied forward bias must be applied to the system for current to flow.
\[ qV_{BI} = E_{Fn} - E_{FP} = k_B T \ln \left( \frac{N_D N_A}{n_i^2} \right) \]

\[ W = x_p + x_n = \sqrt{\frac{2 \epsilon_r \epsilon_0 V_{BI} N_D}{q} \frac{N_A}{N_D N_A}} \]

\[ x_p = \sqrt{\frac{2 \epsilon_r \epsilon_0 V_{BI} N_D}{q} \frac{N_A}{N_D N_A}} \]

\[ x_n = \sqrt{\frac{2 \epsilon_r \epsilon_0 V_{BI} N_A}{q} \frac{N_D}{N_D N_A}} \]

\[ N_A x_p = N_D x_n \]

e.g. Variable band gap semiconductor.

You are working on creating light absorbing \( p-n \) junction devices and have found a material semiconducting alloy whose band gap energy can be controlled with an external magnetic flux \( B \).

You have empirically determined that \( E_g = 4.4 \ \text{eV} - 0.3 \ \frac{eV}{T^2} B^2 \), where \( B \) is measured in Tesla T.

The effective mass of the electrons in the system are \( \sim 0.5 \ m_e \) and the effective mass of the holes in the system are \( \sim 1.5 \ m_e \). The system is at room temperature \( T = 300 \ \text{K} \).

(a) What magnetic flux must you apply to get an intrinsic carrier concentration of \( 10^{15} \ \text{cm}^{-3} \)?

\[ n_c(T)p_v(T) = N_c(T)P_v(T)e^{\frac{-E_g}{k_BT}} \]

\[ n_c = p_v = n_i \]

\[ N_c(T) \approx \frac{1}{4} \left( \frac{2m_e^* k_BT}{\pi \hbar^2} \right)^{\frac{3}{2}} \]

\[ P_v(T) \approx \frac{1}{4} \left( \frac{2m_\nu^* k_BT}{\pi \hbar^2} \right)^{\frac{3}{2}} \]

\[ n_i^2 = \frac{1}{4} \left( \frac{2m_e^* k_BT}{\pi \hbar^2} \right)^{\frac{3}{2}} \frac{1}{4} \left( \frac{2m_\nu^* k_BT}{\pi \hbar^2} \right)^{\frac{3}{2}} e^{\frac{-E_g}{k_BT}} \]

\[ \frac{16n_i^2}{(m_e^* m_\nu^*)^2 \left( \frac{2k_BT}{\pi \hbar^2} \right)^3} = e^{\frac{-E_g}{k_BT}} \]

\[ E_g = -k_B T \ln \left( \frac{16n_i^2}{(m_e^* m_\nu^*)^2 \left( \frac{2m_e^* k_BT}{\pi \hbar^2} \right)^3} \right) \]

\[ E_g = \frac{3}{2} k_B T \ln \left( \frac{m_e^* m_\nu^*}{m_e^2} \right) + k_B T \ln \left( \frac{\left( \frac{2m_e^* k_BT}{\pi \hbar^2} \right)^3}{16n_i^2} \right) \]
3.024 Electrical, Optical, and Magnetic Properties of Materials  
Recitation 10

4.4 eV − \( \frac{eV}{T^2} B^2 \)

\[
= 8.62 \times 10^{-5} \frac{eV}{K} 300 \text{ K} \left( \frac{3}{2} \ln(1.5 \times 0.5) + \ln \left( \frac{\left( \frac{2 \times 9.11 \times 10^{-31} \text{kg} 1.38 \times 10^{-23} \frac{1}{K} \frac{1}{300 \text{ K}} \right)^3}{\pi^3 1.05 \times 10^{-34} \text{J}^6 \text{s}^6 16 \times 10^4 \text{m}^6} \right) \right)
\]

\( B = 3.6 \text{ T} \)

(b) What wavelength of photons does this magnetic flux correspond to as the maximum wavelength the system can absorb?

\[
E_g = 4.4 \text{ eV} - 0.3 \frac{\text{eV}}{T^2} B^2 = 0.514 \text{ eV}
\]

\[
E_g = E = h\nu = \frac{hc}{\lambda}
\]

\[
0.514 \text{ eV} = 1240 \text{ eV} \frac{\text{nm}}{\lambda}
\]

\[
\lambda = 2414 \text{ nm}
\]

This wavelength is in the infrared.

(c) What is the location of the Fermi energy for this band gap at this applied magnetic flux?

\[
\mu = \mu_F = E_v + \frac{E_g}{2} + \frac{3}{4} k_B T \ln \left( \frac{m_v^*}{m_c^*} \right)
\]

\[
F = E_v + \frac{0.514 \text{ eV}}{2} + \frac{3}{4} 8.62 \times 10^{-5} \frac{\text{eV}}{K} 300 \text{ K} \ln \left( \frac{1.5}{0.5} \right)
\]

\[
F = E_v + 0.278 \text{ eV}
\]

This is very close to the middle of the band gap.

(d) If we dope the material with an n-type dopant, what donor concentration would we have to dope to move the Fermi level to within 0.1 eV under the conduction band?

\[
E_c - \mu_F = 0.1 \text{ eV} = E_c - \left( E_v + \frac{E_g}{2} + \frac{3}{4} k_B T \ln \left( \frac{m_v^*}{m_c^*} \right) + k_B T \ln \left( \frac{N_D}{n_i} \right) \right)
\]

\[
0.1 \text{ eV} = E_c - \left( E_v + 0.278 \text{ eV} + k_B T \ln \left( \frac{N_D}{n_i} \right) \right)
\]

\[
0.1 \text{ eV} = E_g - 0.278 \text{ eV} - k_B T \ln \left( \frac{N_D}{n_i} \right)
\]

\[
0.1 \text{ eV} = E_g - 0.278 \text{ eV} - k_B T \ln \left( \frac{N_D}{n_i} \right)
\]

\[
0.1 \text{ eV} - 0.514 \text{ eV} + 0.278 \text{ eV} = -8.62 \times 10^{-5} \frac{\text{eV}}{K} 300 \text{ K} \ln \left( \frac{N_D}{10^{17} \text{cm}^{-3}} \right)
\]

\[
N_D = 1.9 \times 10^{17} \text{cm}^{-3}
\]

(e) If we dope the material with a p-type dopant, what acceptor concentration would we have to dope to move the Fermi level to within 0.1 eV over the valence band?
If we combine the p-type and n-type dopant from (f) and (g) together, what is the dielectric constant of the material if the depletion region width \( W = 750 \text{ nm} \)?

\[
W = \sqrt{\frac{2\varepsilon_r \varepsilon_0 V_{BI} N_A + N_D}{q \frac{N_A N_D}{N_A + N_D}}}
\]

\[
qV_{BI} = E_{Fn} - E_{FP} = 0.514 - 0.1 - 0.1 \text{ eV} = 0.314 \text{ eV}
\]

\[
V_{BI} = 0.314 \text{ V}
\]

\[
W = \sqrt{\frac{2\varepsilon_r \varepsilon_0 V_{BI} N_A + N_D}{q \frac{N_A N_D}{N_A + N_D}}}
\]

\[
750 \text{ nm} = \sqrt{\frac{2\varepsilon_r 8.85 \times 10^{-12} \frac{F}{m} 0.314 \text{ V}}{1.6 \times 10^{-19} \text{ C} \frac{9.8 + 1.9}{9.8 \times 1.9 \times 10^{17} \text{ cm}^{-3}}}}
\]

\[
\varepsilon_r = 2577
\]