**Prob. 4.1**

State expected charge state for Ga, Zn, and Au in Si sample with $E_F > 0.4 eV$ above valence band.

- $E_v$  
- $E_i$  
- $Zn^+$  
- $Au^-$

From Figure 4-9,
- Ga: $E_F > Ga^-$ so singly negative
- Zn: $E_F > Zn^+$ but $E_F < Zn^+$ so singly negative
- Au: $Au^+ < E_F < Au$ so neutral

**Prob. 4.2**

Find the separation of the quasi-Fermi levels and the change of conductivity when shining light.

The light induced electron-hole pair concentration is determined by:

\[ \delta n = \delta p = g_{op} \cdot \tau = 10^{10} \cdot \frac{1}{cm^3} \cdot 10^5 s = 10^4 \frac{1}{cm^3} \]

\[ \delta n \ll \text{dopant concentration of } n_o = 10^{16} \frac{1}{cm^3} \text{ so low level} \]

\[ n = n_o + \delta n = 10^{16} \frac{1}{cm^3} + 10^{14} \frac{1}{cm^3} \approx 10^{16} \frac{1}{cm^3} \]

\[ p = p_o + \delta p = \frac{n_i^2}{n_o} + \delta p = \frac{(1.5 \cdot 10^{15} \frac{1}{cm^3})^2}{10^{16} \frac{1}{cm^3}} + 10^{14} \frac{1}{cm^3} \approx 10^{14} \frac{1}{cm^3} \]

\[ kT \text{ for } 450K = 0.0259 eV \cdot \frac{450K}{300K} = 0.039 eV \]

\[ F_n - E_i = kT \cdot \ln \left( \frac{n}{n_i} \right) = 0.039 eV \cdot \ln \left( \frac{10^{16} \frac{1}{cm^3}}{10^{14} \frac{1}{cm^3}} \right) = 0.18 eV \]

\[ E_i - F_p = kT \cdot \ln \left( \frac{p}{n_i} \right) = 0.039 eV \cdot \ln \left( \frac{10^{14} \frac{1}{cm^3}}{10^{14} \frac{1}{cm^3}} \right) = 0 eV \]

\[ F_n - F_p = 0.18 eV \]

\[ \mu_n = \frac{D_n}{kT} = \frac{36 cm^2}{s \cdot 0.039 V} = 927 \frac{cm^2}{V s} \]

\[ \mu_p = \frac{D_p}{kT} = \frac{12 cm^2}{s \cdot 0.039 V} = 309 \frac{cm^2}{V s} \]

\[ \Delta \sigma = q \cdot (\mu_n \cdot \delta n + \mu_p \cdot \delta p) = 1.6 \cdot 10^{-19} C \cdot (927 \frac{cm^2}{V s} \cdot 10^{14} \frac{1}{cm^3} + 309 \frac{cm^2}{V s} \cdot 10^{14} \frac{1}{cm^3}) = 0.0198 \frac{1}{\Omega cm} \]
Prob. 4.6

Find the separation of the quasi-Fermi levels and the change of conductivity when shining light.

The light induced electron-hole pair concentration is determined by:
\[ \delta n = \delta p = g_{\text{sp}} \cdot \tau = 10^{10} \frac{1}{\text{cm}^2 \cdot \text{s}} \cdot 10^5 \text{s} = 10^{14} \frac{1}{\text{cm}^3} \]
\[ \delta n \ll \text{dopant concentration of } n_o = 10^{15} \frac{1}{\text{cm}^3} \text{ so low level} \]
\[ n = n_o + \delta n = 10^{15} \frac{1}{\text{cm}^3} + 10^{14} \frac{1}{\text{cm}^3} = 1.1 \cdot 10^{15} \frac{1}{\text{cm}^3} \]
\[ p = p_o + \delta p = \frac{n^2}{n_o} + \delta p = \frac{(1.5 \cdot 10^{10} \frac{1}{\text{cm}^3})^2}{10^{15} \frac{1}{\text{cm}^3}} + 10^{14} \frac{1}{\text{cm}^3} \approx 10^{14} \frac{1}{\text{cm}^3} \]
\[ \mu_n = 1300 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \text{ from Figure 3-23} \]
\[ \mu_p = \frac{D_p}{kT} = 12 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} = 463 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \]

quasi-Fermi level separation = \( E_n - E_p = kT \cdot \ln \left( \frac{n \cdot p}{n_i^2} \right) = 0.0259 \text{eV} \cdot \ln \left( \frac{1.1 \cdot 10^{15} \frac{1}{\text{cm}^3} \cdot 10^{14} \frac{1}{\text{cm}^3}}{(1.5 \cdot 10^{10} \frac{1}{\text{cm}^3})^2} \right) = 0.518 \text{eV} \)

\[ \Delta \sigma = q \cdot (\mu_n \cdot \delta n + \mu_p \cdot \delta p) = 1.6 \cdot 10^{-19} \text{C} \cdot (1300 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \cdot 10^{14} \frac{1}{\text{cm}^3} + 463 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \cdot 10^{14} \frac{1}{\text{cm}^3}) = 0.0282 \frac{\text{V} \cdot \text{cm}}{\text{V} \cdot \text{cm}} \]

Prob. 4.9

Design a 5μm CdS photoconductor with 10MΩ dark resistance in a 0.5 cm square.

In the dark neglecting \( p_o \)
\[ \rho = \frac{1}{\sigma} = \frac{1}{q \cdot \mu_n \cdot n_o} = \frac{1}{1.609 \cdot 10^{-19} \text{C} \cdot 250 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \cdot 10^{14} \frac{1}{\text{cm}^3}} = 250 \Omega \cdot \text{cm} \]

\[ R = \frac{\rho \cdot L}{w \cdot t} \rightarrow L = \frac{R \cdot w \cdot t}{\rho} = \frac{10^7 \Omega \cdot w \cdot 5 \cdot 10^{-4} \text{cm}}{250 \Omega \cdot \text{cm}} = 20 \cdot w \]

a number of solutions fulfill this L-w relation including that shown below with w=0.5mm and L=1cm

\[ \rho = \frac{1}{\sigma} = \frac{1}{q \cdot [\mu_n \cdot (n_o + \delta n) + \mu_p \cdot \delta p]} = \frac{1}{1.609 \cdot 10^{-19} \text{C} \cdot \left[ 250 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \cdot (10^{14} \frac{1}{\text{cm}^3} + 10^{15} \frac{1}{\text{cm}^3}) + 15 \frac{\text{cm}^2}{\text{V} \cdot \text{s}} \cdot 10^{15} \frac{1}{\text{cm}^3} \right]} = 21.6 \Omega \cdot \text{cm} \]
\[ R = \frac{\rho \cdot L}{w \cdot t} = \frac{21.6 \Omega \cdot \text{cm} \cdot 1 \text{cm}}{5 \cdot 10^{-5} \text{cm} \cdot 5 \cdot 10^{-4} \text{cm}} = 8.62 \cdot 10^5 \Omega \]
\[ \Delta R = 10^7 \Omega - 8.62 \cdot 10^5 \Omega = 9.14 \text{M} \Omega \]
Prob. 4.13

*Show current flow in the n-type bar and describe the effects of doubling the electron concentration or adding a constant concentration of electrons uniformly.*

\[ \text{electron diffusion (high to low concentration)} \]
\[ \text{current density (} J_n \text{) for diffusion} \]
\[ \text{electron drift} \]
\[ \text{current density (} J_n \text{) for drift} \]

*note: currents are opposite electron flow because of negative charge*

initially:
\[ J_n \text{ diffusion } = q \cdot D_n \frac{dn}{dx} \]
\[ J_n \text{ drift } = q \cdot n \cdot \mu_n \cdot \varepsilon \]

*double electron concentration :*
\[ J_n \text{ diffusion } = q \cdot D_n \cdot 2 \frac{dn}{dx} \rightarrow \text{doubles} \]
\[ J_n \text{ drift } = q \cdot n \cdot \mu_n \cdot \varepsilon \rightarrow \text{doubles} \]

*add constant concentration (} n_+ \text{) :*
\[ J_n \text{ diffusion } = q \cdot D_n \cdot \frac{dn}{dx} \rightarrow \text{does not change} \]
\[ J_n \text{ drift } = q \cdot (n + n_+) \cdot \mu_n \cdot \varepsilon \rightarrow \text{increases by } q \cdot n_+ \cdot \mu_n \cdot \varepsilon \]

Prob. 4.15

*Draw band diagrams for exponential donor and acceptor dopings. Show field directions and direction of drift of minority carriers.*

![Band Diagrams](image)

*Note: Both minority carriers are accelerated “downhill” in the doping gradient.*