Name Solutions

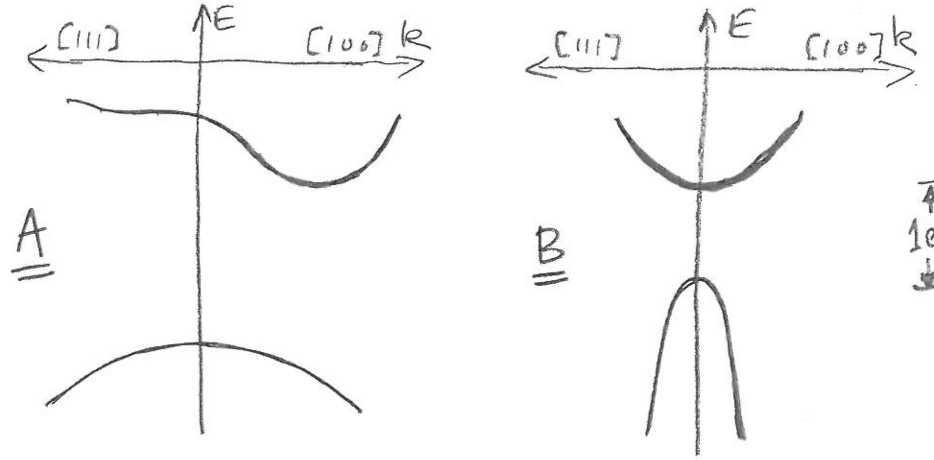
Mean = 55
Median = 58
σ = 24

Exam #1 — EE 482

Winter 2011

The test is open book/open notes. Show all work (use back if needed). Be sure to **state** all assumptions made and **check** them when possible. There are 4 problems on 4 pages. The number of points per problem are indicated in parentheses. Assume $T = 300$K unless otherwise specified.

1. Consider semiconductors with the band structures shown to the right.



(a) Which material would have the larger conduction band effective density of states? Explain. (7)

A The curvatures of conduction band minimum are about the same, so the effective masses are about the same. However, A has multiple minima, since $k_c \neq 0$ at minimum, each with Effective density of states equal to single minimum of B.

(b) Which material would have the larger hole mobility if the scattering lifetimes are equal? Explain. (6)

B $\mu_p = \frac{q \tau_{scatt}}{m_h^*}$ $\quad m_h^* = \frac{1}{\hbar^2}\left(\frac{d^2E}{dk^2}\right)^{-1}$ $\quad \tau_{scatt}^A = \tau_{scatt}^B$

The conduction band of B has larger curvature and thus lower hole effective mass and higher hole mobility

(c) Which material would have the larger intrinsic carrier concentration (n_i)? Explain. (7)

B $n_i = \sqrt{N_c N_v}\exp\left(-\frac{E_g}{2kT}\right)$, Material A has higher N_c & N_v, but B has smaller E_g by almost 1eV. $\exp\left(-\frac{1\text{eV}}{2(0.026\text{eV})}\right) = 4\times10^{-9}$ which overwhelms factor of up to 10 in N_c & N_v.

2. A silicon wafer is uniformly doped with $5 \times 10^{17} \text{cm}^{-3}$ of boron. A region near the surface is doped nearly uniformly to a depth of 100 nm with $1.5 \times 10^{18} \text{cm}^{-3}$ of arsenic (in addition to the B), with negligible As doping deeper in the wafer ("box-shaped" doping profile).

Recombination lifetimes are $\tau_p = 2\mu s$ and $\tau_n = 1\mu s$ in the As-doped region and $\tau_p = 6\mu s$ and $\tau_n = 3\mu s$ in the bulk of the wafer with only B doping. Assume traps dominating lifetime are near midgap.

(a) What are the carrier concentrations and resistivity of the As-doped region in equilibrium? (8)

$N_d^+ - N_a^- = 1.5\times10^{18} - 0.5\times10^{18} = 10^{18} \text{ cm}^{-3} = n_0$

$p_0 = n_i^2 / n_0 = 10^{20} \text{ cm}^{-6} / 10^{18} \text{ cm}^{-3} = 10^2 \text{ cm}^{-3}$

$N_{total} = 2\times10^{18} \text{ cm}^{-3}$, so $\mu_n \cong 200 \text{ cm}^2/\text{V.s}$ (plot on page 5 on Movement...)

$\rho_0 = \frac{1}{q(\mu_n n_0 + \mu_p p_0)} \cong \frac{1}{q\mu_n n_0} = \frac{1}{(1.6\times10^{-19} C)(200 \frac{cm^2}{V.s})10^{18} cm^{-3}} = \underline{0.031 \Omega\text{-cm}}$

(b) If ideal ohmic contacts were made to the As-doped region, what sheet resistance would be measured? (6)

ρ is uniform in As-doped region, so

$R_\square = \frac{\rho_0}{x_j} = \frac{3.1\times10^{-2} \Omega\text{-cm}}{100\times10^{-7} \text{ cm}} = \underline{3.1\times10^3 \Omega/\square}$

Alternatively $R_\square = \frac{1}{q\int \mu_n n\, dx} = \frac{1}{q\mu_n \int n\, dx} = \frac{1}{q\mu_n n x_j} = 3.1\times10^3 \Omega/\square$

(c) If light incident on the wafer generates 10^{20} carriers/(cm^{3}s), unifrmly, what would be the steady-state carrier concentrations in the As-doped region? (8)

Assume LLI $\Rightarrow \Delta n = \Delta p \cong \tau_p G_L = (2\times10^{-6} s)(10^{20} cm^{-3} s^{-1}) = 2\times10^{14} cm^{-3}$

$\Delta n \ll n_0$ so LLI assumption checks

$n = n_0 + \Delta n = 10^{18} + 2\times10^{14} \cong 10^{18} \text{ cm}^{-3}$

$p = p_0 + \Delta p = 10^2 + 2\times10^{14} \cong 2\times10^{14} \text{ cm}^{-3}$

(d) Would the resistivity increase, decrease, or stay about the same under conditions of (c)? Explain. (5)

2×10^{14} is much less than 10^{18}, so almost no change in ρ

(would decrease very slightly)

3. A Si wafer is doped with $N_d(x) = 10^{18}\exp(-x/a)\text{cm}^{-3}$, where $a = 20nm$.

(a) Assuming charge neutrality, what are the majority carrier drift and diffusion current densities in equilibrium at $x = a\ln 10$? (20)

$$J_n = J_n^{drift} + J_n^{diff} = q\mu_n n \mathcal{E} + qD_n \frac{dn}{dx} = 0 \text{ in equilibrium}$$

Two possible approaches:

i) $J_n^{diff} = qD_n \frac{dn}{dx} = q\frac{kT}{q}\mu_n\left[10^{18}\text{cm}^{-3}\left(-\frac{1}{a}\right)\exp\left(-\frac{x}{a}\right)\right]$ — From plot for $N = 10^{17}\text{cm}^{-3}$

$$J_n^{diff}(x = a\ln 10) = (1.6\times10^{-19}\text{C})(0.026\text{V})\left(800\frac{\text{cm}^2}{\text{V}\cdot\text{s}}\right)\left[-\frac{10^{18}\text{cm}^{-3}}{20\times10^{-7}\text{cm}}\exp(-\ln 10)\right]$$

($\exp(-\ln 10) = 1/10$)

$$= -1.66\times10^{5}\ \text{A/cm}^2$$

$$J_n^{drift} = -J_n^{diff} = 1.66\times10^{5}\ \text{A/cm}^2$$

ii) Built-in $\mathcal{E}$-field: $\mathcal{E} = -\left(\frac{kT}{q}\right)\left(\frac{1}{n}\frac{dn}{dx}\right) = -(0.026\text{ V})\left(-\frac{1}{a}\right)$

$$= 0.026\text{V}/(20\times10^{-7}\text{cm}) = +1.3\times10^{4}\ \text{V/cm}$$

$$J_n^{drift} = (1.6\times10^{-19}\text{C})\left(800\frac{\text{cm}^2}{\text{V}\cdot\text{s}}\right)\left(10^{18}\left(\tfrac{1}{10}\right)\text{cm}^{-3}\right)(1.3\times10^{4}\text{V/cm})$$

$$= 1.66\times10^{5}\ \text{A/cm}^2$$

$$J_n^{diff} = -J_n^{drift} = -1.66\times10^{5}\ \text{A/cm}^2$$

(b) What is the net charge density at $x = a\ln 10$? (5)

$\vec{\nabla}\cdot\vec{\mathcal{E}} = \frac{\rho}{K\epsilon_0}$ (for K uniform) $\quad \vec{\nabla}\cdot\vec{\mathcal{E}} = \frac{\partial}{\partial x}\mathcal{E} = 0$ (1D)

$$\rho = 0$$

4. Contact is made between Pt ($\phi_M = 5.3\,\text{eV}$) and Si doped with both 10^{17}cm^{-3} of B and also 10^{17}cm^{-3} of Co (a deep acceptor with ionization level located 0.39 eV above the valence band maximum). There is a large density of states near the metal-semiconductor interface which pin the Fermi level 0.35 eV above the valence band maximum.

(a) What is the semiconductor work function? (10)

$\Phi_s = \chi_s + \frac{1}{q}(E_c - E_F)_{bulk}$ w/10^{17} B plus deep acceptors, E_F near E_V

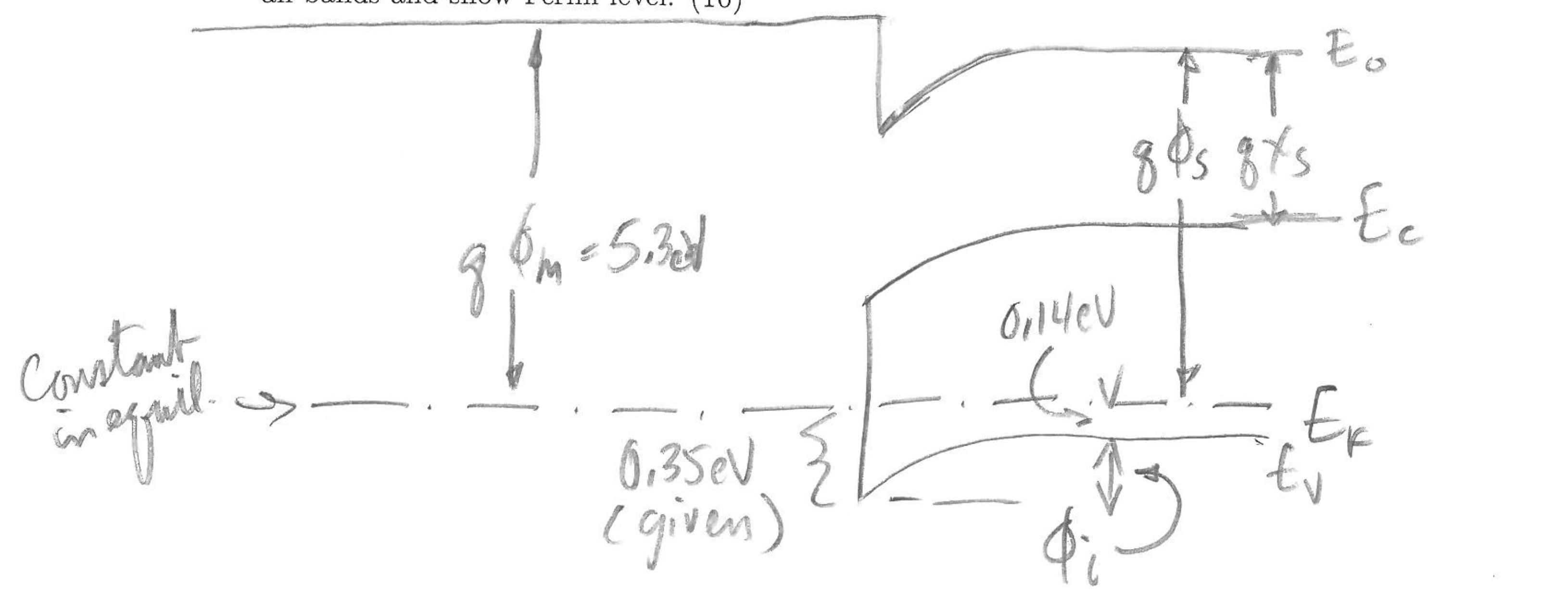
Assume $E_F << E_{Co}$ ⇒ mostly empty ⇒ not ionized acceptor

$E_F - E_V = kT \ln\left(\frac{N_V}{N_a}\right) \cong 0.026\text{eV} \ln\left(\frac{2.5\times10^{19}\text{cm}^{-3}}{10^{17}\text{cm}^{-3}}\right) = 0.14\,\text{eV} << 0.39\,\text{eV}$ so OK

$E_c - E_F = E_g - (E_F - E_V) = 1.12 - 0.14 = 0.98\,\text{eV}$

$\Phi_s = 4.01\,V + 0.98\,V = \underline{4.99\,V}$

(b) Sketch the band diagram for the metal-semiconductor junction in equilibrium. Label all bands and show Fermi level. (10)



(c) What is the barrier (if any) for majority carriers to go from the semiconductor to the metal? Is the junction ohmic or rectifying (Explain)? (8)

$\phi_i = 0.35 - 0.14 = \underline{0.21\,\text{eV}}$ barrier for holes from Si to Pt.

Barrier for majority carriers and depletion region, so Rectifying