11/10/2021

Midterm Exam of Solid-State Electronic Devices (v6/1027)

Part I Multiple Choice Questions (30%)

1. For a material with E-K band diagram as below, which of the following statements are right? (b)

ac

(a) Direct bandgap material

(b) E_i-(Ev+Ec)/2 >0

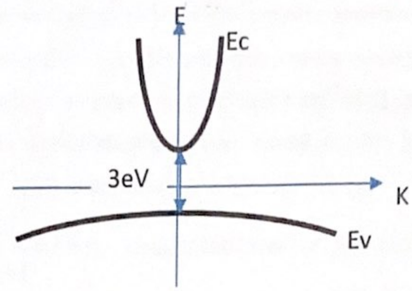
(c) $N_C < N_V$ ∵ $m_h^* > m_e^*$

(d) Electron effective mass > hole effective mass

(e) Can directly absorb light with wavelengh of 600nm

Golden Rule $E(eV)\lambda(\mu m) = 1.24$

$\lambda = 0.6\mu m$, $E = 2.06eV < 3eV$



2. For a region of Si with compensation doping, its energy band diagram is below, which of the following statements are right? (b)

abd

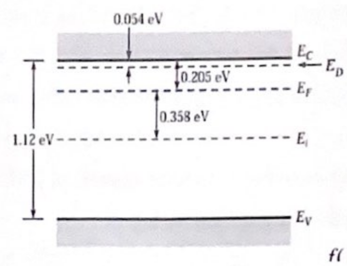
(a) $n_0 > p_0$

(b) $N_D > N_A$

(c) It can considered as a degenerate semiconductor

(d) $n_0 * p_0 = ni^2$

(e) $n_0 = N_D + N_A$



3. Refer to the plot of mobility vs. Temperature of 2 different samples doped with N_{D1} (solid) and N_{D2} (dash), which of the following statements are right? (b)

bce

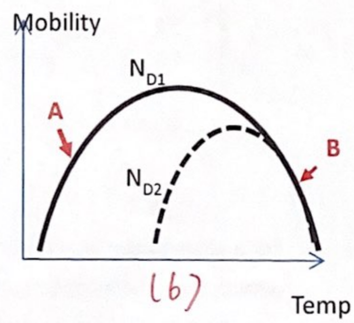
(a) Phonon scattering dominates in Region A,

(b) Lattice scattering dominated in Region B

(c) Phonon scattering event increases with rising temperature

(d) Impurity scattering event increases with rising temperature

(e) $N_{D2} > N_{D1}$



4. For a piece of intrinsic GaAs at thermal equilibrium, which are true? (b)

bcd

(a) $E_f = (Ev+Ec)/2$

(b) $n_0 * p_0 = ni^2$

(c) $n_0 = p_0$

(d) Effective mass of electrons is smaller than that of holes

(e) Nc > Nv

5. For a pn junction with increasing doping concentrations on both sides, which are true? (b)

ae

(a) Maximum electric field increases $|E_{max}| = \frac{2V_{bi}}{W}$, $V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) \uparrow$ & $W\downarrow$ ⇒ $E_{max}\uparrow$

(b) Depletion region widen $W\downarrow$

(c) Work function difference decreases (no change)

(d) Potential difference in Fermi between p-side and n-side increase E_F is constant.

(e) Barrier height for electron in the conduction band increases $V_{bi}\uparrow$

Part II Calculations (70%)

Constants and Parameters (if not otherwise specified)

$q = 1.6 \times 10^{-19}$ C ; $m_0 = 9 \times 10^{-31}$ kg ; $h = 6 \times 10^{-34}$ J•sec ; $\hbar = 1 \times 10^{-34}$ J•sec ; $c = 3\times10^{8}$ m/s ; kT(300°K) = 0.026eV ;
$c = 3\times10^{8}$ m/s ; Si (300°K): $n_i = 10^{10}$ cm^{-3} ; Eg = 1.12eV, N_C (Si) = N_V (Si) = 2.5×10^{19} cm^{-3}; $\epsilon_0=8.85 \times 10^{-12}$ F/m; $\epsilon_{Si}=11.9$;

1. Assume a semiconductor with $E_C = 0.5 + 0.1\sin^2(Ka/2)$ and $E_V = -0.3 - 0.5\sin^2(Ka/2)$ in eV. **(10%)**
   (a) Draw the conduction and valance bands of E-K diagrams in the range between (-π/a ~ π/a). (5%)
   (b) For a = 0.5nm, find the effective mass for electrons near the bottom of the conduction band and that for the holes near the top of the valence band. (5%)

2. According to Fermi distribution: $f(E)=\dfrac{1}{1+e^{(E-E_f)/kT}}$; when the probability (300°K) of electron occupancy in silicon at E= Ec is 10^{-2}, answer the following questions. **(10%)**
   a) What is Ef – Ei (eV)? Draw the energy band diagram and locate the levels of E_i and E_f. (5%)
   b) Use Boltzman's approximation, find n_o and p_o. (5%)

3. Consider a degenerate semiconductor with bandgap narrowing effect vs. doping level are shown in Fig.1. **(10%)**
   a) At 300°K, Si with N_D of 1×10^{19}cm^{-3} in the Si, find the corresponding n_o and p_o. (5%)
   b) What is the difference in ratio of p_o(from (a)) to p_o(without bandgap narrowing effect). (5%)

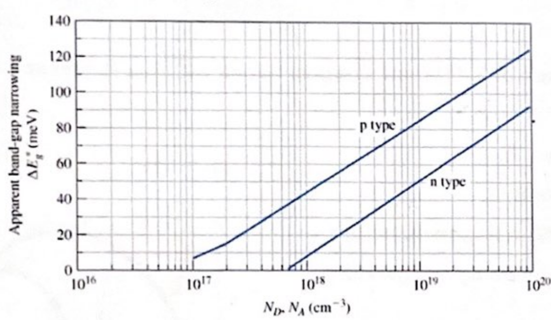


Fig.1

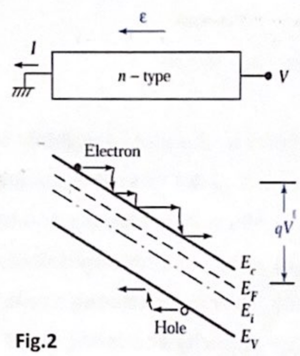


Fig.2

4. For a strained semiconductor, the mean free time between collisions under low electric field equals 0.2psec for both electrons and holes and m_{ce}*=0.2m_0; m_{ch}*=0.5m_0; **(20%)**
   a) Find the low-field mobilities for electron and hole for this material. (5%)
   b) Let Saturation velocity = 10^7cm/sec, estimate the critical field(V/cm) for both carriers, respectively, of which the carrier's speed reach its high-field regime and saturates.(5%)
   c) *For N_D = 10^{15}cm^{-3}*, with length of 0.2μm in Fig.2, find the conductivity σ(ohm cm)$^{-1}$of this n-Si? (5%)
   d) Find total drift current density, J_{drift} for V=0.2V? (5%)

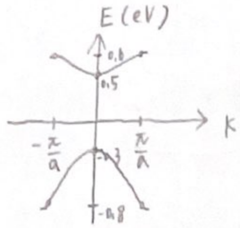
5. For a n/p junction in Si where p-type at x<0 with N_A=1×10^{16}cm^{-3}, and n-type at x>=0 with N_D= 2×10^{17}cm^{-3}. **(20%)**
   (a) Draw energy band diagram (indicate Ec/Ev/Ei/Efn/Efp/Eg) at V_A = 0V.
   (b) What is the build-in potential (V) of this pn junction?
   (c) Let the depletion width under zero bias is 0.32 33 μm, what is the depletion width (μm) of n-type region?
   (d) Draw the plot of the electrical field (E, V/μm) vs. x (in μm) at zero bias condition Please label peak E and edge points.

$E_c = 0.5 + 0.1 \sin^2\left(\frac{ka}{2}\right)$

$E_v = -0.3 - 0.5 \sin^2\left(\frac{ka}{2}\right)$

$\sin\left(\frac{ka}{2}\right) = 0 \ , \ k = \pm \frac{2\pi}{a}$

$\sin\left(\frac{ka}{2}\right) = \pm 1 \ , \ k = \pm \frac{\pi}{a}$



(b)

$$m^* = \hbar^2 \left[\frac{d^2E}{dk^2}\right]^{-1}$$

Ans: $m_e^* = 5.56\, m_0$

$m_h^* = 1.11\, m_0$

$$\frac{dE_c}{dk} = (0.05a) \cdot \sin(ka)$$

$$\frac{d^2E_c}{dk^2} = 0.05a^2 \cos(ka) \longrightarrow \frac{d^2E_c}{dk^2}\Big|_{k=0} = 0.05a^2$$

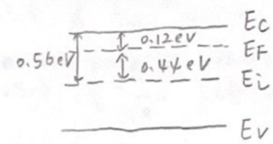
$$m_e^* = \frac{\hbar^2}{0.05a^2} = \frac{(10^{-34})^2}{0.05(1.6\times10^{-19})(0.5\times10^{-9})^2} = 5\times10^{-30}\ kg = \boxed{5.56\, m_0}$$

$$\frac{d^2E_v}{dk^2}\Big|_{k=0} = -0.25a^2$$

$$m_h^* = \frac{\hbar^2}{0.25a^2} = \frac{(10^{-34})^2}{0.25(1.6\times10^{-19})(0.5\times10^{-9})^2} = 10^{-30}\ kg = \boxed{1.11\, m_0}$$

2.

(a) Since $N_c = N_v$, $E_i = \frac{E_c + E_v}{2}$, $E_c - E_i = 0.56\,eV$



$$f(E_c) = \frac{1}{1+e^{(E_c-E_F)/kT}} = 10^{-2}, \quad 1 + e^{\frac{E_c-E_F}{kT}} = 100, \quad e^{\frac{E_c-E_F}{kT}} = 99$$

$$\frac{E_c-E_F}{kT} = \ln(99) = 4.6, \quad E_c - E_F = 4.6(kT) = 4.6(0.026) = 0.12\,eV \Rightarrow \boxed{E_F - E_i = 0.56 - 0.12 = 0.44\,eV}$$

(b) (I) from E_c, $E_F - E_c = -0.12\,eV$

$$n_0 = N_c \exp\left(-\left(\frac{E_c - E_F}{kT}\right)\right) = 2.5\times10^{19} \times \exp\left(-\frac{0.12}{0.026}\right) = 2.5\times10^{17}\ cm^{-3}, \quad p_0 = \frac{10^{20}}{2.5\times10^{17}} = 400\ cm^{-3}$$

(II) from E_i

$$n_0 = n_i \exp\left(\frac{E_F - E_i}{kT}\right) = 10^{10} \exp\left(\frac{0.44}{0.026}\right) = 2.2\times10^{17}\ cm^{-3}, \quad p_0 = \frac{10^{20}}{2.2\times10^{17}} \cong 450\ cm^{-3}$$

Ans: $n_0 = 2.2 \sim 2.5\times10^{17}\ cm^{-3}$

$p_0 = 400 \sim 450\ cm^{-3}$

3.

(a) $$n_0 p_0 = \frac{N_D}{N_c} \exp\left(\frac{\Delta E_g^*}{kT}\right) n_i^2 = \frac{10^{19}}{2.5\times10^{19}} \cdot \exp\left(\frac{0.05}{0.026}\right) \cdot 10^{20} = 2.74\times10^{20}\ cm^{-3}$$

$$n_0 = 10^{19}\ cm^{-3}, \quad p_0 = \frac{2.74\times10^{20}}{10^{19}} = \boxed{27.4\ cm^{-3}}$$

(b) w/o bandgap narrowing, $p_0 = \frac{n_i^2}{n_0} = \frac{10^{20}}{10^{19}} = 10\ cm^{-3}$

$$\frac{p_0\,(\text{w/ bandgap narrowing})}{p_0\,(\text{w/o bandgap narrowing})} = \frac{27.4}{10} = \boxed{2.74}$$

4.

(a) $\mu_n = \frac{q\bar{\tau}_n}{m_{ce}^*} = \frac{1.6\times10^{-19}\times0.2\times10^{-12}}{0.2\times9\times10^{-31}} = 0.176\ m^2/V\cdot s = 1760\ cm^2/V\cdot s$

$\mu_p = \frac{q\bar{\tau}_p}{m_{ch}^*} - 0.07\ m^2/V\cdot s = 700\ cm^2/V\cdot s$

(b)

$V_{sat} = \frac{-q\mathcal{E}\bar{\tau}_n}{m_{ce}^*} = \frac{q\mathcal{E}\bar{\tau}_p}{m_{ch}^*} \Rightarrow \mathcal{E} = \frac{V_{sat}}{\mu_n \text{ or } \mu_p}$

$\mathcal{E}_{ce} = \frac{10^7}{1760} = 5700\ V/cm$

$\mathcal{E}_{cp} = \frac{10^7}{700} = 14000\ V/cm$

(c)

$\sigma = q(\mu_n n + \mu_p p) = 1.6\times10^{-19}\left(1760\cdot10^{15} + 700\cdot\frac{10^{20}}{10^{15}}\right) = 0.28\ (\Omega\cdot cm)^{-1}$

(d)

$E = \frac{0.2V}{0.2\,\mu m} = 1\ V/\mu m = 10^6\ V/m = 10^4\ V/cm > \mathcal{E}_{ce} \Rightarrow$ velocity saturation

$J_{drift} = qnV_{sat} = 1.6\times10^{-19}\times10^{15}\times10^7 = 1600\ A/cm^2$

Ans: (a) $\mu_n = 1760\ cm^2/V\cdot s$, $\mu_p = 700\ cm^2/V\cdot s$

(b) $\mathcal{E}_{ce} = 5700\ V/cm$, $\mathcal{E}_{cp} = 14000\ V/cm$

(c) $0.28\ (\Omega\cdot cm)^{-1} = \sigma$

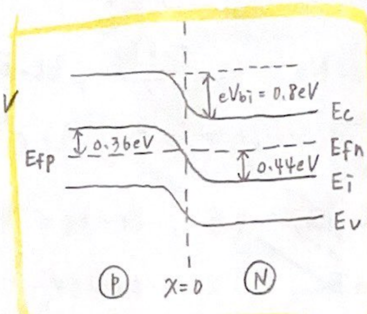
(d) $1600\ A/cm^2 = J_{drift}$

5.

$x<0: N_A = 10^{16}\ cm^{-3}$ & $x>0: N_D = 2\times10^{17}\ cm^{-3}$

(a)

$eV_{bi} = KT\ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.026\ln\left(\frac{10^{16}\cdot2\cdot10^{17}}{10^{20}}\right) = 0.8eV$



$E_{fn} - E_i = KT\ln\left(\frac{N_D}{n_i}\right) = 0.44eV$

$E_i - E_{fp} = KT\ln\left(\frac{N_A}{n_i}\right) = 0.36eV$ #

(b) $\boxed{0.8V}$ # $= V_{bi}$

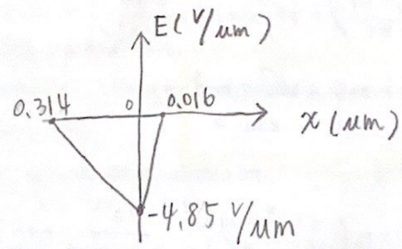
(c)

$x_n = W\times\frac{N_A}{N_A+N_D} = 0.33\times\frac{10^{16}}{10^{16}+2\times10^{17}} = \boxed{0.016\ \mu m}$ #

(d)

$x_p = 0.33 - 0.016 = 0.314\ \mu m$

$|E_{max}| = \frac{2(V_{bi})}{W} = \frac{2\times0.8}{0.33} = \boxed{4.85\ V/\mu m}$ #



Ans: (a)

$E_{fn} - E_i = 0.44eV$

$E_i - E_{fp} = 0.36eV$

(b) $V_{bi} = 0.8\ V$

(c) $x_n = 0.016\ \mu m$

(d) $x_n = 0.016\ \mu m$

$x_p = 0.314\ \mu m$

$E_{max} = -4.85\ V/\mu m$