October 31, 2003

University of Saskatchewan
Department of Electrical Engineering

EE372 Electronic Materials and Devices
Midterm Examination
Professor Robert E. Johanson

PART B
(open textbook)

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Welcome to the EE372 Midterm. The examination has two parts. Part A consists of questions that test knowledge of basic concepts, and part B requires more involved calculations. Part A is closed book and closed notes. When you finish part A, hand it in (raise your hand) and then proceed to part B. Part B is open book; you may refer to your textbook (Kasap, any edition) but not to any other material such as notes or other books. You may also use a calculator for both parts. The examination lasts **2** hours.

Each problem is weighted equally. Show your work if the question involves more than a simple answer; credit will be given only if the steps leading to the answer are **clearly** shown. Partial credit will be given for partially correct answers but only if correct intermediate steps are shown. Write your answers on these pages.

For part B, answer 3 of the 4 questions. Do not answer more than 3 questions.

1. 3
2. 10
3. 10
4. —

86%

total 23 / 30

PHYSICAL CONSTANTS

$c = 2.9979\times10^{8}$ m s^{-1}
$e = 1.6021\times10^{-19}$ C
$m_e = 9.1091\times10^{-31}$ kg
$h = 6.62608\times10^{-34}$ J s
$k = 1.3807\times10^{-23}$ J K^{-1}
$\varepsilon_o = 8.8542\times10^{-12}$ F m^{-1}

X. Semiconductor Statistics

a) A silicon crystal is uniformly doped with 3×10^{16} cm^{-3} of boron acceptors. What is the density of holes in the valence band and electrons in the conduction band? Calculate the position of the Fermi level with respect to the valence band edge E_V at T = 300 K.

b) The above silicon crystal is ion implanted with 2×10^{17} cm^{-3} phosphorous donor atoms creating compensated silicon. What is the density of holes in the valence band and electrons in the conduction band now? Calculate the new position of the Fermi level with respect to the conduction band edge E_C.

a) $N_a = 3\times10^{16} cm^{-3}$ Since $N_a >> n_i \approx 1.45\times10^{10} cm^{-3}$ we get

$p = N_a = 3\times10^{16} cm^{-3}$ ✓

$N_d = 0$ b/c all e⁻'s go into acceptors

what is n? ✗

$n = \frac{n_i^2}{p} \cong 7\times10^{3} cm^{-3}$

E_f w.r.t. E_V at T=300K?

3 $p = N_V \exp\left[-\frac{(E_{fn}-E_V)}{kT}\right] = N_a$, for doped Si

$E_F - E_V = -kT \ln \frac{p}{N_V} = 0.151$

$E_{fn} - E_V = -kT \ln\left(\frac{N_a}{N_V}\right) = (-0.02594 eV) \ln\left(\frac{3\times10^{16} cm^{-3}}{N_V}\right)$

$N_V = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} = 2\left(\frac{2\pi (0.02594 eV)(0.56)(9.1094\times10^{-31} kg)}{(6.62608\times10^{-34} J.s)^2}\right)\cdot\left(\frac{1.6022\times10^{-19} J}{1 eV}\right)^{3/2}$

$N_V = 2.52\times10^{25}$ ✗ $N_V = 1.0\times10^{19} cm^{-3}$

$\therefore E_{fn} - E_V = (0.02594 eV) \ln\left(\frac{3\times10^{16} cm^{-3}}{2.52\times10^{25} cm^{-3}}\right) = -0.532 eV$ below

(This is too low as it would behave like a metal and won't happen with this amount of doping.)

b) $n = N_d - N_a = 2\times10^{17} - 3\times10^{16} = 1.7\times10^{17} cm^{-3}$ ✓

$N_V \approx 3\times10^{16} cm^{-3}$

$N_c = 2\left(\frac{2\pi (m_e^*) kT}{h^2}\right)^{3/2} = 2\left[\left(\frac{2\pi (1.08) m_e (0.02594 eV)}{(6.62608\times10^{-34} J)^2}\right) \frac{1.6022\times10^{-19} J}{eV}\right]^{3/2}$

$N_c = 2.83\times10^{25}$ ← this is m^{-3}

$p = \frac{n_i^2}{n} \cong 1.2\times10^{3} cm^{-3}$ what is p?

$E_{fn} - E_c = (0.02594 eV) \ln\left(\frac{N_d}{N_c}\right) = (0.02594 eV) \ln\left(\frac{1.7\times10^{17} cm^{-3}}{2.83\times10^{25} cm^{-3}}\right) =$

$= 0.490 eV$

Once again this is too high for the amount of doping

$E_c - E_f = -kT \ln \frac{n}{N_c} \sim 0.132 eV$

2. Hydrogen Atom

a) A gas of hydrogen atoms absorbs light with wavelength 102.518 nm. To what energy level are the electrons excited by absorbing this light.

b) Calculate all possible wavelengths of light that are emitted by the above excited hydrogen atoms as they return to the ground state.

a) $\lambda = 102.518 \times 10^{-9} m$ $\quad \nu = \frac{c}{\lambda}$

$$E = h\nu = \frac{hc}{\lambda} = \frac{(6.626068 \times 10^{-34} J\cdot s)(3.0 \times 10^{8} m s^{-1})}{102.518 \times 10^{-9} m}\left(\frac{1 eV}{1.6022 \times 10^{-19} J}\right) = 12.1 eV$$

$$12.1 eV = 13.6 eV - \frac{13.6 eV}{n^2}$$

$$n^2 = \frac{13.6 eV}{13.6 eV - 12.1 eV} = 3.01 \approx 3$$

e⁻'s get excited to level n=3 from this light

b) 3-2, 2-1, 3-1 $\quad$ 3 possible λ's

3→1

$\Delta E_{31} = (-1.51 eV) - (-13.6 eV) = 12.09 eV$

emitted light will have $\lambda = \frac{hc}{\Delta E}$

$$\lambda_{31} = \frac{hc}{\Delta E_{31}} = \frac{(6.626068 \times 10^{-34} J\cdot s)(3.0 \times 10^{8} m s^{-1})}{(12.09 eV)\left(\frac{1.6022 \times 10^{-19} J}{1 eV}\right)} = 102.6 nm$$

3→2

$\Delta E_{32} = (-1.51 eV) - (-3.40 eV) = 1.89 eV$

$$\lambda_{32} = \frac{hc}{\Delta E_{32}} = \frac{(6.626068 \times 10^{-34} J\cdot s)(3.0 \times 10^{8} m s^{-1})}{(1.89 eV)\left(\frac{1.6022 \times 10^{-19} J}{1 eV}\right)} = 656 nm$$

2→1

$\Delta E_{21} = -3.40 eV - (-13.6 eV) = 10.2 eV$

$$\lambda_{32} = \frac{hc}{\Delta E_{32}} = \frac{(6.626068 \times 10^{-34} J\cdot s)(3.0 \times 10^{8} m s^{-1})}{(10.2 eV)\left(\frac{1.6022 \times 10^{-19} J}{1 eV}\right)} = 121.6 nm$$

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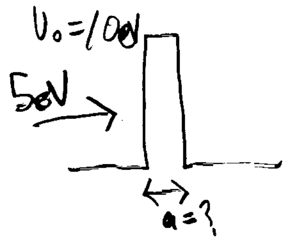
3 Quantum Tunneling

An insulator in an electronic device presents a potential barrier that is 10 eV high. If the electrons' energy is 5 eV, how thick must the insulator be so that the probability of tunneling through the barrier is 0.05?



Prob = 0.05

$T = 0.05$

$$\alpha = \left[\frac{2m(V_0 - E)}{\hbar^2}\right]^{1/2} = \left[\frac{2(9.1091 \times 10^{-31} kg)(10 eV - 5 eV)(1.60218 \times 10^{-19} J\, eV^{-1})}{(1.05 \times 10^{-34} J s)^2}\right]^{1/2}$$

$\alpha = 1.15 \times 10^{10} m^{-1}$ ✓

assuming αa will be > 1 use wide-barrier transmission coefficient in Equation 3.26 from KASAP

$$T = T_0 \exp(-2\alpha a)$$

$$T_0 = \frac{16E(V_0 - E)}{V_0^2} = \frac{16(5eV)(10eV - 5eV)}{(10eV)^2} = 4$$ ✓

∴ $T = 4\exp(-2\alpha a)$

when $T = 0.05$ what is a?

$$\ln\left[\frac{0.05}{4}\right] = -2\alpha a$$

$$a = \frac{\ln\left[\frac{0.05}{4}\right]}{-2\alpha} = \frac{\ln[0.0125]}{-2(1.15 \times 10^{10} m^{-1})} = \boxed{0.191 nm}$$ ✓

When insulator is 0.191nm probability of tunneling through the barrier is 0.05.

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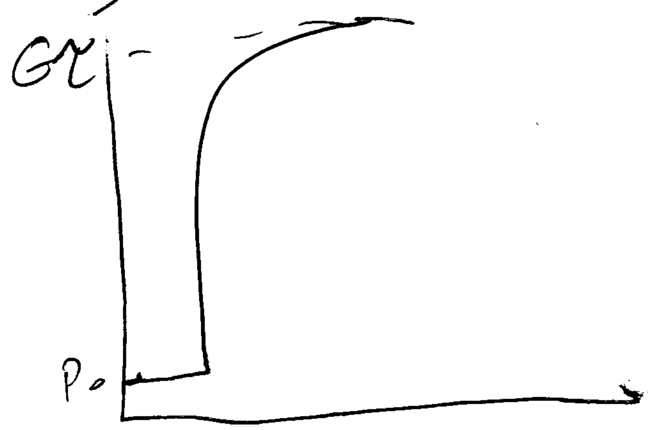
4. Generation and Recombination

A piece of n-type Si is doped with 10^{15} cm^{-3} phosphorous donor atoms. The hole (minority carrier) lifetime is 1 μs. The silicon is illuminated with light such that the generation rate is $G = 3\times10^{20}$ cm^{-3}s^{-1}.

a) What are the steady-state electron (majority carrier) and hole (minority carrier) densities while the silicon is illuminated?

b) The electron and hole mobilities are $\mu_e = 1300$ cm^{2}V^{-1}s^{-1} and $\mu_h = 450$ cm^{2}V^{-1}s^{-1}. What is the conductivity of the silicon in darkness and during illumination?



a) $G\tau = p = 3\times10^{14}\ cm^{-3}$

$\therefore n = n_0 + \Delta n$ where $\Delta n = \Delta p$

$n = 10^{15}\ cm^{-3} + 3\times10^{14}\ cm^{-3} = 1.3\times10^{15}\ cm^{-3}$

b) $\sigma = e(\mu_e n + \mu_h p)$

$\sigma_{dark} = e\mu_e n = 0.208\ \Omega^{-1}cm^{-1}$

$\sigma_{illuminated} = e(\mu_e n + \mu_h p) = 0.292\ \Omega^{-1}cm^{-1}$