UNIVERSITY OF SASKATCHEWAN

Department of Physics and Engineering Physics

EP 317.3 Final Examination

Instructor: Yansun Yao

April 11th, 2016 Time: 2:00 PM ~ 5:00 PM

ANSWER ALL FIVE QUESTIONS.

FULL MARK IS 100.

MARKS PER EACH QUESTION ARE INDICATED.

Physical Constants:

Elementary charge: $e = 1.602 \times 10^{-19}$ C

Avogadro's number: $N_A = 6.022 \times 10^{23}$ mol^{-1}

Boltzmann constant: $k = 1.381 \times 10^{-23}$ J·K^{-1} = 8.617×10^{-5} eV·K^{-1}

Planck's constant: $h = 6.626 \times 10^{-34}$ J ·s

Electron mass: $m_e = 9.11 \times 10^{-31}$ kg

Q1. VACUUM TUBE. The density of states for free electrons in a metal is,

$$g(E) = (8\sqrt{2}\pi)\left(\frac{m_e}{h^2}\right)^{3/2} E^{1/2}.$$

The concentration of conduction electrons, n, is determinted by,

$$n = \int_0^{\text{Top of band}} g(E) f(E) dE \text{ , } f(E) \text{ : Fermi-Dirac function,}$$

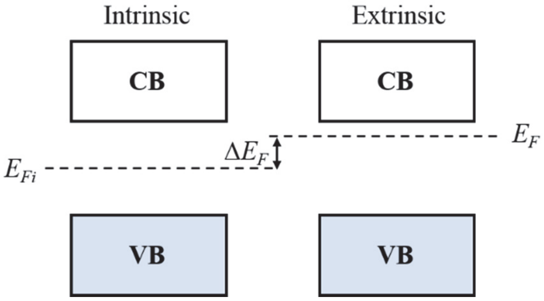
where the intergration is done over all energies in the band.

(1) Determine the relation between the Fermi energy (E_{FO}) and n at 0 K (show how you obtained your answer). (**6%**)

(2) Tatalum (Ta) has two valence electrons per atom; that is, each Ta atom contributes two electrons to the sea of conduction electrons. The atomic mass of Ta is 0.181 kg/mol, and the density is 1.64×10^4 kg/m^3. Calculate the Fermi energy of Ta at 0 K. (**6%**)

(3) The band width in Ta is 12.57 eV. A vacuum tube has a **cylindrical** Ta cathode, which is 5.00 cm long and 2.00 mm in diameter. Given that the emission constant $B_e = 6.0 \times 10^5$ A m^{-2} K^{-2}, calculate the saturation current if the tube is operated at 1800 °C (2073 K). Ignore the temperature dependence of the Fermi level. If you did not obtain an answer for (2), use a value of 8.45 eV. **(8%)**

Q2. SEMICONDUCTOR. A Si sample has been doped *n*-type with As at 27 °C. The Fermi level (E_F) in this sample is 0.43 eV higher than the intrinsic Fermi level E_{Fi}. The intrinsic concentration n_i of Si is 1.0×10^{10} cm^{-3} at 27 °C.



(1) Calculate the concentration of As atoms. (**10%**)

(2) This sample is further doped with 1.0×10^{17} boron atoms cm^{-3} (*p*-type dopant). Calculate the position of the new Fermi level E_F with respect to the intrinsic Fermi level E_{Fi}. If you did not obtain an answer for (2), use a value of 1.70×10^{17} atoms cm^{-3}. (**10%**)

Q3. SCHOTTKY AND OHMIC CONTACTS. Consider, at $T = 300$ K, an n-type Si sample doped with 10^{16} donors cm^{-3}. The length L of the sample is 400 μm; the cross-sectional area A is 1.00 mm^{2}. The electron affinity (χ) and work function (Φ_n) for Si are 4.0 eV and 4.22 eV, respectively. Drift mobility of electrons (μ_e) in the sample is 1350 cm^{2} V^{-1} s^{-1}. For a metal to n-Si junction, effective Richardson constant B_e is 110 A cm^{-2} K^{-2}.

(1) This Si sample is in contact with Cs and the work function (Φ_m) of Cs is 1.80 eV. What is the current across the junction when there is an applied external voltage of 0.5 V? **(6%)**

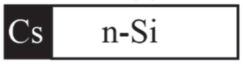
(2) This Si sample is in contact with Ni and the work function (Φ_m) of Ni is 5.1 eV. What is the current across the junction when there is **a forward bias** of 0.8 V? **(6%)**

(3) This Si sample is in contact with Cs on both ends. **Determine and sketch** the *I-V* characteristics of this compound. (**4%**)

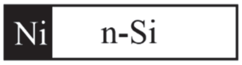
(4) This Si sample is in contact with Ni on both ends. **Determine and sketch** the *I-V* characteristics of this compound. (**4%**)

Hint: You shouldn't be needing new calculations for (3) and (4).

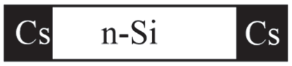
(1)



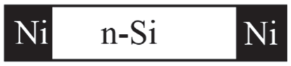
(2)



(3)



(4)



Q4. PN JUNCTION. Consider, at $T = 300$ K, a Si *pn* junction that has 2×10^{16} cm^{-3} acceptors on the *p*-side and 5×10^{15} cm^{-3} donors on the *n*-side. The permittivity (ε) of Si is 1.05×10^{-10} C V^{-1} m^{-1}, and the intrinsic carrier concentration (n_i) is 10^{10} cm^{-3} at 300 K.

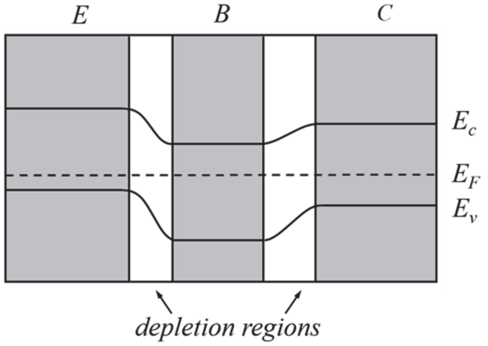
(1) Calculate the built-in potential V_o across the junction. **(6%)**

(2) Calculate the magnitude of the electric field E_o at the junction. (**6%**)

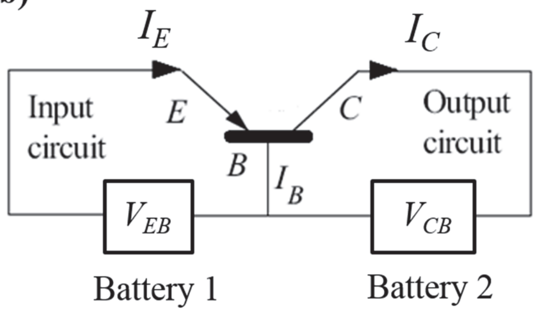
(3) Under **a reverse bias** of 1.5 V, determine the width of the depletion region on the *n*-side, W_n, and the width of the depletion region on the *p*-side, W_p. **(8%)**

Q5. BIPOLAR TRANSISTOR. The band diagram of a Si bipolar junction transistor (BJT) in open circuit condition is shown in Fig. (a). The dopant concentration in one region is 1×10^{18} cm^{-3}. The dopant concentrations in the other two regions are both 2×10^{16} cm^{-3}. The diffusion coefficient for holes in n-region(s) is D_h = 11.65 cm^2 s^{-1}. The base neutral region width is 2 μm when the transistor is under normal operating conditions. The cross-sectional area of the transistor is 0.01 mm^2. The emitter-base voltage V_{EB} is 0.85 V. Intrinsic carrier concentration (n_i) is 10^{10} cm^{-3}.

(a)



(b)



(1) Examining the band diagram in (a), identify the type of this BJT and briefly explain your reasoning. Use a superscript plus sign for the heavier doped region. **(6%)**

(2) This transistor operates in the normal and active mode in the common base configuration (b). Determine the polarities of the two batteries. **(6%)**

(3) Assuming that the emitter has 100 percent injection efficiency, $\boldsymbol{\gamma = 1}$, calculate the emitter current I_E. **(8%)**

****************** **END OF EXAM** *******************