2024

Q1: Semiconductor Fundamentals

(a) Explain the differences in energy band structures between conductors, semiconductors, and insulators. Include in your explanation:

(i) Definition of a band gap and description on how it relates to different material types, considering its impact on conductivity. [3]

(ii) Discuss how the position of the Fermi level affects electrical conductivity and analyze its significance in different materials. [3]

(iii) Sketch labelled diagrams to illustrate the energy band structures of a conductor, a semiconductor, and an insulator. [3]

(i)

band gap: When the atoms are packed together in a crystal each energy levels splits in a band with large number of very closely packed states. The bands are seperated by regions of forbidden energies for the electrons called band gap E_g.

(ii) ① electrical conductivity $\sigma = ne\mu$

Fermi level is the top of the collection of electron energy levels at absolute zero temperature.

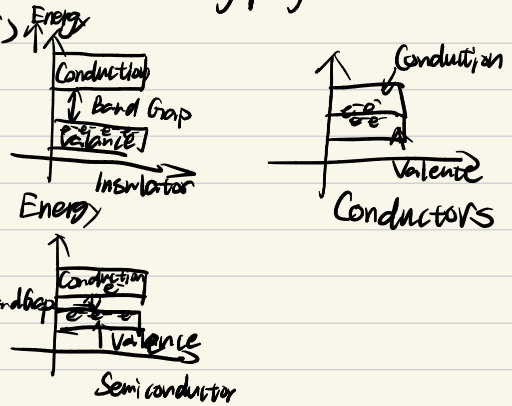
So, Fermi level affect the density of free carriers.

② Conductors: Fermi level is among conduction band

Semiconductors: Fermi level is between conduction band and valence band (Forbidden band)

Insulators: Fermi level is among valence band

(iii)



(b) Describe the photoelectric effect. In your answer, include:

(i) Define the photoelectric effect and illustrate it using a diagram. [2]

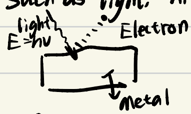
(ii) Analyze the relationship between the energy of incident photons and the kinetic energy of ejected electrons by using energy versus frequency plot. [3]

(iii) Evaluate the significance of the threshold frequency in the context of the photoelectric effect. [2]

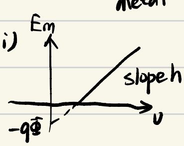
(i)

photoelectric effect:

the emission of electrons when electromagnetic radiation, such as light, hit the materials.



(ii)



$E_m = h\upsilon - W_0$

E_m: the maximum kinetic energy of ejected electrons

υ: frequency of incident photons

W_0: work function

iii) the proof of the quantum nature of light and electrons.

(c)

(c) Explain the concept of doping in semiconductors and describe the difference between n-type and p-type semiconductor materials. In your answer, include:

(i) Define doping and explain its purpose in modifying semiconductor properties. [2]

(ii) Identify the types of impurity atoms used to create n-type and p-type semiconductors, and analyze their effects. [2]

(iii) Discuss the effect of doping on the charge carrier concentration in both n-type and p-type materials, and evaluate how these changes influence conductivity. [2]

(iv) Create diagrams to illustrate the energy band structures of both n-type and p-type semiconductors, and analyze how these structures differ. [3]

(i) ①

Doping: The process of adding impurity atoms to the pure semiconductors.

② Purpose: The conductivity of semiconductors can be greatly improved by introducing a small number of impurity atoms.

(ii)

N-type: When a pure semiconductors is doped by pentavalent impurity (P, As, Sb, Bi)

P-type: When a pure semiconductors is doped by trivalent impurity (Al, In, Ga)

N-type donate free electron for conduction

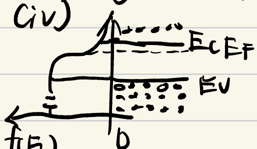
P-type accept bonded electrons.

(iii)

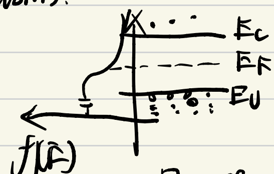
For N-type, density of electrons > density of holes; For P-type, density of holes > density of electrons.

Therefore, both of these will increase conductivity compared to Intrinsic Semiconductors

(iv)



N-type



P-type

In n-type, E_F is closer to E_C; while E_F is close to E_V in p-type.

Q2: p-n junction

(a) You are tasked to design a silicon-based p-n junction diode for a specific application. The desired characteristics of the diode are: the p-type region should have an acceptor concentration $N_a = 1 \times 10^{18}$ cm^{-3} and the n-type region should have a donor concentration $N_d = 1 \times 10^{15}$ cm^{-3}. The diode will operate at room temperature (300 K). The relative permittivity of silicon is 11.7. The intrinsic carrier concentration of silicon n_i=1.5×10^{10} cm^{-3}. Assume no external voltage is applied.

(i) Determine the width of the depletion region. [2]

(ii) Calculate the built-in potential of the diode. [3]

(iii) Estimate the reverse breakdown voltage. [2]

(i)(ii)

$$W = \sqrt{\frac{2\varepsilon_0\varepsilon_r V_{bi}}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)}$$

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_aN_d}{n_i^2}\right) = 0.259 \times \ln\left(\frac{1\times10^{33}}{2.25\times10^{20}}\right)$$

$$= 0.259 \times \ln\left(\frac{4}{9}\times10^{13}\right)$$

$$= 7.542 \ V$$

$$\therefore W = \sqrt{\frac{2\times11.7\times8.854\times10^{-14}}{1.6\times10^{-19}}\times\left(\frac{1}{10^{18}}+\frac{1}{10^{15}}\right)} = 1.44\times10^{-4} \ cm$$

(iii)

$$V_{Br} = \frac{\varepsilon_s E_c^2}{2qN_B} \qquad E_c \approx 3.0\times10^5 \ V/cm$$

N_B ↑ 最低掺杂区的浓度 $\quad \varepsilon_s = \varepsilon_0\varepsilon_r$

$V_{Br} \approx 291V$

(b) An abrupt silicon p-n junction has doping concentrations of $N_a = 10^{17}$ cm^{-3} on the p-side and $N_d = 10^{16}$ cm^{-3} on the n-side. At 300 K:

(i) Calculate the Fermi levels for both sides. [3]

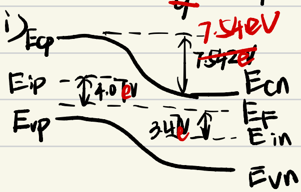
(ii) Draw the equilibrium energy band diagram. [3]

(i)

$$E_{ip} - E_F = \frac{kT}{\cancel{q}}\ln\frac{N_a}{n_i} = 4.07eV$$

$$E_F - E_{in} = \frac{kT}{\cancel{q}}\ln\frac{N_b}{n_i} = 3.47eV$$

(ii)



$$E_{cp} - E_{cn} = 4.07 + 3.47eV$$

$$= 7.54eV$$

(c) An abrupt silicon p-n junction with an area of 10^{-4} cm² is operated at 300 K, with the properties listed in Table 1.

Table 1

p-side	n-side
Concentration of acceptors $N_a = 10^{17}$ cm^{-3}	Concentration of donors $N_d = 10^{15}$ cm^{-3}
Recombination lifetime of e$^-$ $\tau_n = 0.1\mu s$	Recombination lifetime of h$^+$ $\tau_p = 10\mu s$
$\mu_p = 200$ cm^2/V-s	$\mu_n = 1300$ cm^2/V-s
$\mu_n = 700$ cm^2/V-s	$\mu_p = 450$ cm^2/V-s

Calculate the forward current when the junction is forward-biased by 0.5 V. Similarly, calculate the current when the junction is reverse-biased by −0.5 V. Ensure that all steps of the calculations are clearly shown. [12]

$A = 10^{-4} \ cm^2$

①

$$I_0 = qD_p\frac{dp}{dx} - qD_n\frac{dn}{dx}$$

$$= qA\cdot\left(\frac{D_p}{L_p}\cdot p_n + \frac{D_n}{L_n}n_p\right)$$

$$p_n = \frac{n_i^2}{N_d} = 2.25\times10^5 \ cm^{-3}$$

$$n_p = \frac{n_i^2}{N_a} = 2.25\times10^3 \ cm^{-3}$$

$$D_p = \frac{kT}{q}\cdot\mu_p = 0.0259\times450 = 11.66 \ cm^2/s$$

$D_n = 0.0259 \times 700 = 18.13 \ cm^2/s$

$L_p = \sqrt{D_p\tau_n} = 1.08\times10^{-2} \ cm$

$L_n = \sqrt{D_n\tau_p} = 1.35\times10^{-2} \ cm$

$I_0 = 4.370\times10^{-15} A$

$= I_0$

∴ Forward:

$$I_0\left(e^{V/0.0259} - 1\right)$$

Reverse: $N_a \gg N_d \quad |V| \gg V_T$

$\therefore \ I = -I_0$

Q3 BJTs and FETs

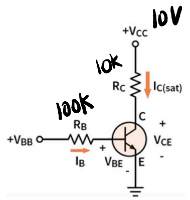
(a) The BJTs are current-controlled devices while FETs are voltage-controlled devices. Discuss the implications of the difference in controlling mechanism of these devices in terms of power consumption, signal amplification and switching efficiency. [5]

	BJT	FET
power consumption	Higher (continuous base current needed)	Very low (almost no gate current)
Speed (Switching)	Moderate (slower switching)	Very fast (excellent switching speed)
Linearity	Very good linearity	less linear

(b) For the saturation region NPN transistor circuit shown in Fig. Q3b, consider V_{CC} = 10 V, β = 150, R_C = 10 kΩ and R_B = 100 kΩ.

(i) What minimum value of base voltage V_{BB} would put the transistor into saturation. [5]

(ii) Assuming, for a given application, the base voltage V_{BB} cannot exceed 1.2 V. Which circuit element will you replace to ensure that you can put the circuit into saturation? Show with your calculations that saturation would be possible with your proposed change in the circuit. [5]



$\beta = 150$

Figure Q3b

(i)
saturation: $V_{BC} > 0$ $V_{CE} = 0$ $V_{BE} = 0.7V$

$\therefore I_{C(sat)} = \frac{V_{CC} - V_{CE}}{R_C} = \frac{10V}{10k} = 1mA$

$\therefore I_B = \frac{I_{C(sat)}}{\beta} = \frac{1mA}{150} = 6.67 \times 10^{-6} A$

$\therefore V_{BB} = V_{BE} + I_B \cdot R_B = 0.7 + 0.667 = 1.367V$

(ii) $V_{BB} \le 1.2V$

$\Rightarrow (I_B)_{max} = \frac{1.2V - 0.7V}{100k\Omega} = 5 \times 10^{-6} A$

$\therefore I_{C(sat)} = 7.5 \times 10^{-4} A$

$\because V_{CC} = 10V$

$\therefore R_{C(new)} = \frac{V_{CC}}{I_{C(sat)}} = \frac{10\ V}{7.5 \times 10^{-4} A} = 13.3 k\Omega$

(c) In Figure Q3c a common source n-channel JFET configuration is shown to act as an amplifier. The pinch-off voltage (V_p) is 7.5V and I_{DSS} = 12mA. The gate-to-source bias voltage (V_{GS}) is -1.5V. Suppose that V_{DD} = 20V.

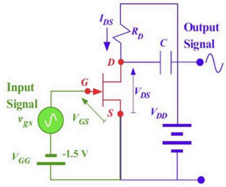


Figure Q3c

(i) If a small signal voltage gain of -6V is needed, what value of drain resistance R_D would you use? [5]

(ii) If a sinusoidal signal of 0.5sin(4πt) is applied as v_{gs}, what will be the peak-to-peak value of output signal v_{ds}? Why do you think the output peak-to-peak voltage is not symmetric? [5]

(i) $I_{DS} = I_{DSS}\left[1 - \frac{V_{GS}}{V_{GS(off)}}\right]^2$

$= 12mA \times \left[1 - \frac{-1.5}{-7.5}\right]^2$

$= 12mA \times \frac{16}{25}$

$= 7.68mA$

$g_m = -\frac{2[I_{DSS} I_{DS}]^{\frac{1}{2}}}{V_{GS(off)}}$

$= \frac{2 \times \sqrt{12 \times 7.68}}{7.5} = 2.56\ mA/V$

$A_v = -g_m R_D = -6$

$\Rightarrow R_D = 2.3k\Omega$

(ii) $A_v = -6 = \frac{V_{ds}}{V_{gs}}$

$V_{ds} = -3\sin(4\pi t)$

~~which is not symmetric~~

peak-to-peak value: 6V

When the input signal have large magnitude, g_m is not linear, which contribute to not symm

Q4 OD

(a) Optoelectronic devices are light-emitting or light-detecting devices, either producing light or using light in their operation.

(i) Plot the energy band diagram in a Photodiode, while schematically showing the electron-hole pair generation. [4]

(ii) Compare the first, third, and fourth quadrants of a photodiode's I–V characteristic in terms of power usage and extraction. Discuss how the operation in each quadrant affects the power delivery to or from the external circuit. [4]

(iii) You are using a photodetector that has the following parameters:

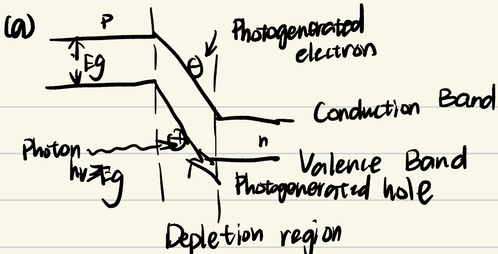
Quantum efficiency (η): 0.80

Electron Charge (q): 1.6×10^{-19} C

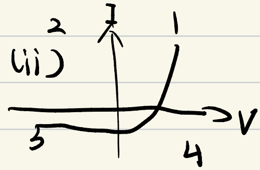
Frequency of incident light (f): 3.8×10^{14} Hz

Calculate the spectral responsivity of the photodetector based on these parameters. [3]

(a)



(ii)



In first and fourth quadrants, power is delivered to the device by external circuit.

In third quadrant, the device deliver power to the load.

(iii) $R = \eta \cdot \frac{q}{hf} \approx 0.80 \times \frac{1.6\times10^{-19}}{6.63\times10^{-34}\times3.8\times10^{14}} = 0.508$

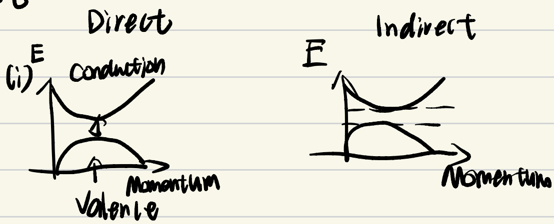
(b) A light-emitting diode is a semiconductor device that emits light when current flows through it. Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons.

(i) Provide schematic plots to illustrate the differences between direct and indirect band gaps in terms of the momentum of the valence and conduction bands. [4]

(ii) Given that the refractive index of GaAs is 3.4, calculate the critical angle for total internal reflection in a planar GaAs LED encapsulated in air. Assume the refractive index of air is 1. [3]

(iii) Based on the description of the quantum well LED device, identify one commonly used pair of materials for the quantum well and the confining layers. [2]

(i)



(ii)

$\theta_c = \sin^{-1}\left(\frac{1}{3.4}\right) = 17.1^\circ$

(iii) AlGaAs and GaAs;

↑ confining layers

(c) Consider a silicon solar cell with dimensions of 2 cm × 2 cm and a thermal current (I_{th}) of 30 nA. The cell experiences an optical generation rate of 10^{18} (EHP/cm^3-s) in a region where the diffusion lengths for electrons (L_n) and holes (L_p) are 2 μm and 4 μm respectively. Given that the depletion region width is 1 μm, calculate both the short-circuit current and the open-circuit voltage parameters for this solar cell at a temperature of 300.29 K. [5]

$g_p = 10^{18}$ $A = 4\ \text{cm}^2$

$$I_{op} = qAg_p(L_n + L_p + W)$$
$$= 7\times10^{-4} \times 4\times10^{18} \times 1.6\times10^{-19}$$
$$= 4.48\times10^{-5}\ \text{A}$$

$$I_{sc} = I_{th}(e^{qV/kT} - 1) - I_{op} = -I_{op} = 0.0448\text{mA}$$

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_{op}}{I_{th}} + 1\right) = 0.0259 \times \ln = 0.189\ \text{V}$$