

CITY UNIVERSITY OF HONG KONG

Module code and title: EE3111 Semiconductor Materials and Devices

Session : Semester B 2002/2003

Time allowed : Two hours

This paper consists of NINE pages (including this one)

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1. This paper consists of **three** sections
 2. Answer **all** questions in **Section A**
 3. Answer any **one** question in **Section B**
 4. Answer any **two** questions in **Section C**
 5. Remember to start a **new page** for **each question** in **Section B and C**
 6. Remember that a complete answer to questions in Section B and C ought to include all your steps
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Materials, aids and instruments permitted to be used during the examination:

1. Approved electronic calculator
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Section A (20% + 20%)

PART A (Students are required to answer ALL questions in this part)

Attempt **all** questions in this part by choosing the most suitable (**ONLY ONE**) answer to each question. (each chosen answer carries 2 marks, Total 20 marks)

1. In an ***n-channel enhancement MOSFET*** transistor, both boron and phosphorus are usually present as the dopants in the channel region, which one of the dopants has a higher concentration in the channel region?
(a) boron (b) phosphorus (c) boron and phosphorus have the same concentration
2. The carrier mobilities in intrinsic semiconductors are (chosen answer) those in extremely lightly doped semiconductors.
(a) higher than (b) lower than (c) the same as
3. In a ***pn*** transistor which of the following mechanisms dominates when the reverse-bias on the collector junction is increased far enough?
(a) Avalanche breakdown (b) Zener breakdown (c) Punch-through breakdown
(d) None of the above
4. When a practical bipolar transistor is operating in the inverted mode, the collector current keeps increasing as a function of increasing collector bias. This is due to
(a) the saturation current at the collector-base junction
(b) the diffusion of minority carriers in the base region
(c) the electron-hole recombination in the base region
(d) the modulation of base width by the collector bias
5. If an ***npn*** transistor is operated in the saturation mode, which one of the following biasing combination is possible?
(a) $V_E > V_B > V_C$ (b) $V_E < V_B < V_C$ (c) $V_E > V_B < V_C$ (d) $V_E < V_B > V_C$
6. Drift current is the type of current flow that normally occurs in conductors and semiconductors, which one of the following formula is used to get the electrical conductivity?
(a) $D/\mu = kT/q$ (b) $J = qDdp/dx$ (c) $\mu = q\tau/m^*$ (d) $J = nq\mu E$
7. Which one of the following formulas is used for calculating the maximum depletion layer width of an ideal metal-insulator-semiconductor FET (MOS) ?
(a) $W = \left(\frac{2\epsilon V_0}{qN_d} \right)^{\frac{1}{2}}$ (b) $W = \left[\frac{2\epsilon V_0}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right) \right]^{\frac{1}{2}}$ (c) $W = \left[\frac{2\epsilon_s \phi_s}{qN_a} \right]^{\frac{1}{2}}$
(d) None of the above.

8. Manufacturers' data sheets for transistors do not usually list the values of all parameters. Most often, only the common emitter parameters are stated. The parameter h_{fc} is called the common collector current gain of a bipolar junction transistor. Which two currents equations are needed to find the corresponding ratio to calculate the common collector current gain h_{fc} of a BJT?

- (a) $I_C = qA(D_P/L_P)\Delta P_E(L_P/W_b)$, $I_B = qA(D_P/L_P)\Delta P_E(W_b/2L_P)$
 (b) $I_B = qA(D_n/L_n)\Delta n_E(W_b/2L_n)$, $I_E = qA(D_n/L_n)\Delta n_E(L_n/W_b)$
 (c) $I_C = qA(D_n/L_n)\Delta n_E(L_n/W_b)$, $I_E = qA(D_n/L_n)\Delta n_E(L_n/W_b)$

9. A piece of silicon is doped with phosphorus atoms. Which equation is used to calculate the hole concentration at 300 K ?

(a)

(b)

$$P = n_i \exp \frac{(E_i - E_F)}{kT}$$

$$L_P = \sqrt{D_P \tau_P}$$

$$P = \frac{n_i^2}{n}$$

(c) $P = n + N_a - N_d$

(d)

10. In the calculation for the diode current, we have simply calculated the excess minority carrier diffusion current. Which formula is used to calculate the excess minority carrier diffusion concentration?

(a)

$$I_p(X_n) = qA \frac{D_p}{L_p} P_n e^{\frac{-X_n}{L_p}} (e^{\frac{qV}{kT}} - 1)$$

(b)

$$I_n(X_n) = I - I_p(x_n) = qA \left[\frac{D_p}{L_p} (1 - e^{\frac{-X_n}{L_p}}) P_n + \frac{D_n}{L_n} n_p \right] (e^{\frac{qV}{kT}} - 1)$$

(c)

$$I = qA \left(\frac{D_p}{L_p} P_n + \frac{D_n}{L_n} n_p \right) (e^{\frac{qV}{kT}} - 1)$$

(d)

$$P(X_n) = P_n + P_n (e^{\frac{qV}{kT}} - 1) e^{\frac{-X_n}{L_p}}$$

PART B 20% (students are required to answer ALL questions in this part)

Fill in the Blank

(20 marks)

- a) The energy levels are measured in electron volts (ev) . An electron volt is defined as the amount of energy required to move _____ through a _____ difference of one volt.
- b) Bonding between atoms in a solid. _____ bonding occurs in conductors. _____ bonding is found in semiconductors and in some types of insulating material. In glass and similar solids, the bonding force is _____ .
- c) If the two blocks of material have equal doping densities, the depletion layers on each side of the junction are equal in thickness. If the p-side is more heavily doped than that of the n-side, the depletion region _____ more _____ into the n-side in order to include an equal number of _____ atoms on each side of the junction.
- d) The _____ may be large, small, or nonexistent. The distinction between conductors, insulators, and semiconductors is largely concerned with the relative widths of the _____ .
- e) Pure semiconductor material is referred to as _____ material. Before semiconductor material can be used for device manufacture, _____ atoms must be added to it. This process is called doping, and it improves the _____ of the material very significantly.
- f) Typical forward and reverse characteristics for silicon and germanium diodes. The most important parameters of the diode are: _____ V_F , _____ $I_{F(max)}$, _____ r_d , _____ I_R , _____ V_{BR} .
- g) A pn junction have a depletion region witch is called the transition region, and potential difference V_o is call the _____ potential (or _____ potential). This potential is necessary to the maintenance of _____ at the junction.
- h) A major application of diodes is _____ , other applications are _____ , _____ and _____ .
- i) A Voltage-variable capacitor diodes (VVC) device is simply a _____ diode, and its capacitance is that of the junction _____ .
- j) In a metal-semiconductor junction, the absence of _____ carrier injection and the associated storage _____ is an important feature of Schottky barrier diodes. So their high-frequency properties and _____ are therefore generally better than typical *pn* junctions.
- k) Barrier potential and depletion regions exist at the two *pn*-junctions in a transistor, The barrier potentials are always _____ on the p-side and _____ on the n-side of each junction. The depletion regions penetrate deeply into the _____ doped base.
- L) Electrons in solid obey what is known as Fermi-Dirac statistics. The number of free electrons in the conduction band depends on 3 factors:
- total number of _____ available,
 - number of _____ in conduction band,
 - probability of an _____ occupying an energy level at a particular _____

Section B (20%) (select only one out of two questions in this part)

Question B-1

(20 marks)

- (a) The symmetrical *pnp* transistor of Fig.B-1, is connected as a diode in the four configurations shown. Assume that $V \gg KT/q$. Sketch $\delta P(X_n)$ in the base region for each case. Which connection seems most appropriate for use as a diode? Why? (10 marks)
- (b) Suppose that V is negative in Fig.B-1-d, write down the current (I) equations and sketch $\delta P(X_n)$ in the base area. (10 marks)

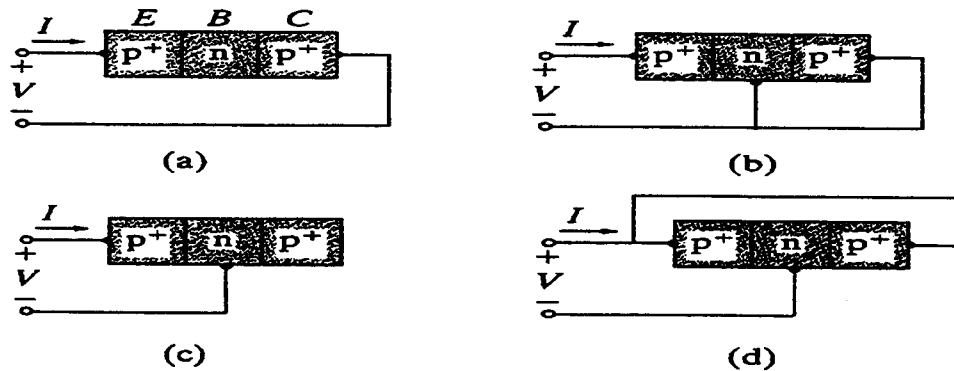


Fig.B-1

Question B-2

(20 marks)

- Finish Fig. B-2 and draw the device symbol of an enhancement-type n-channel MOSFET transistor;
- Draw the cross section of the device;
- Schematic and explanation of the induced n-channel and the depletion region near pinch-off;
- Drain current-voltage characteristics as a function of gate voltage (I_D versus V_D). (4 x 5 marks)

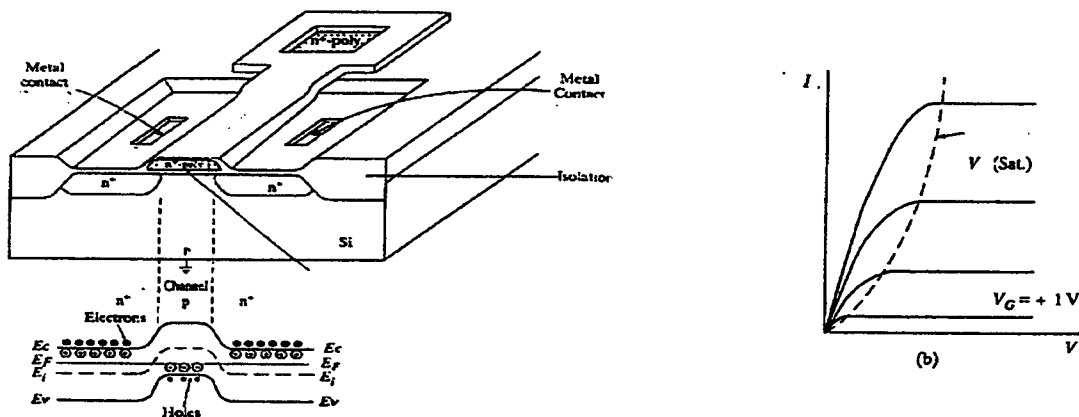


Fig.B-2

Physical Constants and Parameters at 300 K

Boltzman constant	k	$1.38 \times 10^{-23} \text{ J/K}$
Electronic charge (eV)	q	$1.6 \times 10^{-19} \text{ C}$
Permittivity of free space	ϵ_0	$8.85 \times 10^{-14} \text{ F/cm}$
Thermal energy at 300 K	kT	0.0258 eV
Intrinsic carrier concentration in Si	n_i	$1.5 \times 10^{10} \text{ cm}^{-3}$
Bandgap of Si	E_g	1.12 eV
Dielectric constant of Si	ϵ_{Si}	11.8
Dielectric constant of GaAs	ϵ_{GaAs}	13.1
Dielectric constant of Ge	ϵ_{Ge}	16.0
Intrinsic carrier concentration in Ge	n_i	$2.5 \times 10^{13} \text{ cm}^{-3}$
Bandgap of Ge	E_g	0.66 eV
Electron rest mass	m^0	$9.1 \times 10^{-31} \text{ kg}$
Permittivity in vacuum	ϵ_o	$8.85 \times 10^{-12} \text{ F/m}$
Electron mobility of GaAs	μ_e	$8500 \text{ cm}^2/\text{V}_s$

Section C (40%) (select only two out of three questions in this part)

Question C1

(20 marks)

An n-type Ge sample is used in the experiment shown in Fig.C-1. The length (L_0) of the sample is 1.02 cm, and probes (1) and (2) are separated by 0.95 cm (L). The battery voltage E_0 is 2 V. A pulse arrives at point (2) $t_d = 0.25 \text{ ms}$ after injection at (1); the width of the pulse Δt is $117 \mu\text{s}$. Assume $\tau = t_d$, that

$$L_p = L \frac{\Delta t}{4 t_d} . \text{ Calculate the hole mobility and diffusion coefficient, and}$$

check the results against the Einstein relation

(3 x 7 marks)

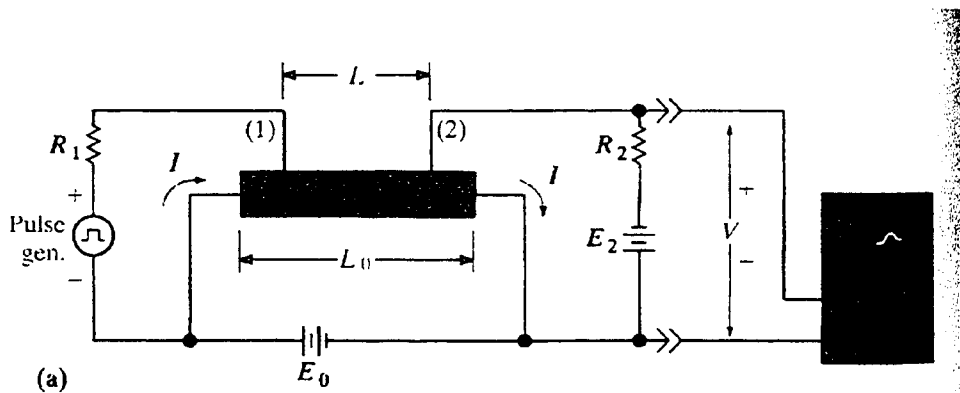
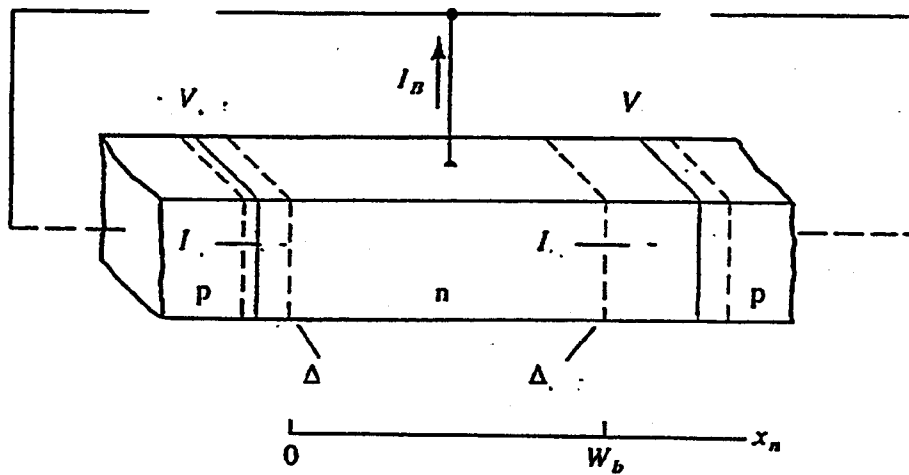


Fig. C-1

Question C2**(20 marks)**

A *pn*p transistor at 300 K has a base width of $1\mu\text{m}$, and base doping concentration is $2 \times 10^{16} \text{ cm}^{-3}$. Assume the hole lifetime and diffusion coefficient in the base region are given by $1\mu\text{s}$ and $11 \text{ cm}^2 \text{ S}^{-1}$, respectively. If the emitter hole current density is 1 mA/cm^2 ,

- (a) Draw and finish Fig.C-2. **(3 marks)**
- (b) Find the excess base hole density near the BE junction. **(7 marks)**
- (c) Find the base-emitter junction voltage V_{BE} . **(5 marks)**
- (d) Find the base transport factor B . ($B = I_c / I_{\text{Ep}} = \text{sech } W_b/L_p$). **(5 marks)**

**Fig. C-2**

Question C3**(20 marks)**

A symmetrical *npn* bipolar transistor has a junction area of 10^{-2} cm^2 and a base width of $1 \mu\text{m}$. The parameters of base, emitter and collector are given below:

$$\begin{aligned}\text{Emitter/Collector} \\ N_d &= 5 \times 10^{18} \text{ cm}^{-3} \\ \tau_p &= 0.1 \mu\text{s} \\ \tau_n &= 2 \mu\text{s} \\ \mu_p &= 150 \text{ cm}^2/\text{V}\cdot\text{s} \\ \mu_n &= 500 \text{ cm}^2/\text{V}\cdot\text{s}\end{aligned}$$

$$\begin{aligned}\text{Base} \\ N_a &= 5 \times 10^{15} \text{ cm}^{-3} \\ \tau_n &= 0.1 \mu\text{s} \\ \tau_p &= 1 \mu\text{s} \\ \mu_p &= 200 \text{ cm}^2/\text{V}\cdot\text{s} \\ \mu_n &= 700 \text{ cm}^2/\text{V}\cdot\text{s}\end{aligned}$$

The transistor is operating at 300 K.

- (a) When $V_{EB} = 1.0 \text{ V}$ and $V_{CB} = 3.0 \text{ V}$ are applied to the transistor, (i) calculate the energy barrier heights at the emitter-base junction and the collector-base junction; (ii) sketch an energy band diagram of the transistor at the above bias condition, indicating the relative positions of Fermi levels in different regions and the barrier heights at different junctions, and (iii) what is the operating mode of the transistor at these biasing conditions?

(6 marks)

- (b) Assume the base width remains constant at $1 \mu\text{m}$ during device operation, (i) calculate the collector current (I_C) and base current (I_B) when $V_{BE} = 0.5 \text{ V}$ and $V_{CB} = 2.0 \text{ V}$, and (ii) calculate common-emitter current gain at these biasing conditions.

(8 marks)

- (c) Taking into account that the base width is modulated by the collector-base voltage, calculate the common-emitter current gain again at the bias conditions given in part (b).

(6 marks)

$$V_0 = \frac{KT}{q} \ln \frac{N_d N_a}{n_i^2} = \frac{E_0 W}{2}$$

$$\beta = \frac{I_C}{I_B} = \frac{2 L_n^2}{W_b^2}$$

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