IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2017

EEE PART I: MEng, BEng and ACGI

SEMICONDUCTOR DEVICES

Wednesday, 14 June 10:00 am

Time allowed: 2:00 hours

There are THREE questions on this paper.

Answer ALL questions.

Question One carries 40% of the marks. Questions Two and Three each carry 30%.

Any special instructions for invigilators and information for candidates are on page 1.

Examiners responsible	First Marker(s) :	K. Fobelets
	Second Marker(s) :	S. Lucyszyn

Special instructions for invigilators

Special instructions for students

Do not use red nor green ink.

Do not use pencils.

Constants

permittivity of free space:	$\varepsilon_o = 8.85 \times 10^{-12}$ F/m
permeability of free space:	$\mu_o = 4\pi \times 10^{-7}$ H/m
intrinsic carrier concentration in Si:	$n_i = 1.45 \times 10^{10}$ cm^{-3} at $T = 300$ K
dielectric constant of Si:	$\varepsilon_{Si} = 11$
dielectric constant of SiO_2:	$\varepsilon_{ox} = 4$
thermal voltage:	$V_T = kT/e = 0.026$ V at $T = 300$ K
charge of an electron:	$e = 1.6 \times 10^{-19}$ C
Planck's constant:	$h = 6.63 \times 10^{-34}$ Js
bandgap of Si:	$E_G = 1.12$ eV at $T = 300$ K
electron affinity of Si	$\chi = 4.05$ eV at $T = 300$ K
effective density of states of Si:	$N_C = 3.2 \times 10^{19}$ cm^{-3} at $T = 300$ K $N_V = 1.8 \times 10^{19}$ cm^{-3} at $T = 300$ K

Formulae

$$f(E)=\frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}$$ Fermi distribution

$$n=N_c e^{-\frac{(E_c-E_F)}{kT}}$$ Concentration of electrons

$$p=N_v e^{\frac{(E_v-E_F)}{kT}}$$ Concentration of holes

$$\frac{dE}{dx}=\frac{\rho(x)}{\varepsilon}$$ Poisson equation in 1 dimension

$$\left.\begin{aligned}J_n(x)&=e\mu_n n(x)E(x)+eD_n\frac{dn(x)}{dx}\\ J_p(x)&=e\mu_p p(x)E(x)-eD_p\frac{dp(x)}{dx}\end{aligned}\right\}$$ Drift and diffusion current densities in a semiconductor

$$I_{DS}=\frac{\mu C_{ox}W}{L}\left((V_{GS}-V_{th})V_{DS}-\frac{V_{DS}^2}{2}\right)$$ Current in a MOSFET

$$\left.\begin{aligned}J_n&=\frac{eD_n n_{p_0}}{L_n}\left(e^{\frac{eV}{kT}}-1\right)\\ J_p&=\frac{eD_p p_{n_0}}{L_p}\left(e^{\frac{eV}{kT}}-1\right)\end{aligned}\right\}$$ Current densities for a pn-junction with lengths L_n & L_p

$$V_{bi}=\frac{kT}{e}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$ Built-in voltage

$$c=c_0\exp\left(\frac{eV}{kT}\right)\text{ with }\begin{cases}c=p_n\text{ or }n_p\\ c_0\text{ bulk minority carrier concentration}\end{cases}$$ Minority carrier injection under bias V

$$D=\frac{kT}{e}\mu$$ Einstein relation

$$w_n(V)=\left[\frac{2\varepsilon(V_{bi}-V)N_A}{e(N_A+N_D)N_D}\right]^{1/2}\ \&\ w_p(V)=\left[\frac{2\varepsilon(V_{bi}-V)N_D}{e(N_A+N_D)N_A}\right]^{1/2}$$ Depletion widths under bias V

$$W_{depl}^{\max}=2\left[\frac{\varepsilon kT\ln\left(\frac{N_{substrate}}{n_i}\right)}{e^2 N_{substrate}}\right]^{1/2}$$ Maximum depletion width

1. Basic principles of semiconductors

a) Give all correct statements to describe a *hole* from the list below: [2]

i) An antielectron in a semiconductor;
ii) A positive mobile charge in a semiconductor;
iii) A positive ionised atom in a semiconductor;
iv) A positron in a semiconductor;
v) A proton in a semiconductor;
vi) A void in a semiconductor.

b) Why is the drift velocity of electrons higher than that of holes in intrinsic Si? [2]

c) Prove that $n \times p = n_i^2$ in equilibrium. [4]

d) The mathematical expression for the hole diffusion current is given by:

$$I_p = -eD_pA\frac{dp}{dx}$$

Explain, using appropriate graphs, the reason for the "–" sign. [4]

e) Figure 1.1 gives an energy band diagram of Si with two free carriers denoted by black dots.

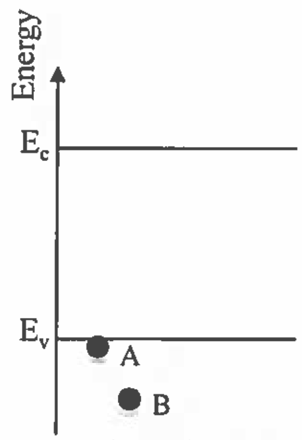

Figure 1.1: Energy band diagram with two free carriers denoted by black dots.

i) Do the black dots in Fig.1.1 represent electrons or holes? [2]

ii) Which carrier, A or B has the highest potential energy? [2]

f) The workfunction of Si is 5.035 V. Determine the doping type and the doping concentration. [6]

g) The forward bias current density of a p^+n junction is 6.11×10^{-11} A cm^{-2}. The width of the p and n region are equal to their minority carrier diffusion length, $L_p = 5\times10^{-4}$ cm and $L_n = 4\times10^{-4}$ cm. The diffusion constants of the minority carrier hole and electron are $D_p = 2$ cm^2/s and $D_n = 3$ cm^2/s, respectively. Calculate the excess minority carrier concentration at the edge of the depletion region in the n-region of the diode. State any assumption you make. [6]

h) A Si substrate with acceptor doping density of 10^{17} cm^{-3} is implanted with a donor doping density of 10^{18} cm^{-3}. Calculate the hole and electron concentrations in the implanted region. [8]

i) Is the threshold voltage, V_{th} in an enhancement mode p-channel MOSFET >, <, = 0? [2]

j) Which region in the short BJT determines the magnitude of the collector current? [2]

2. The pnp BJT with short material layers

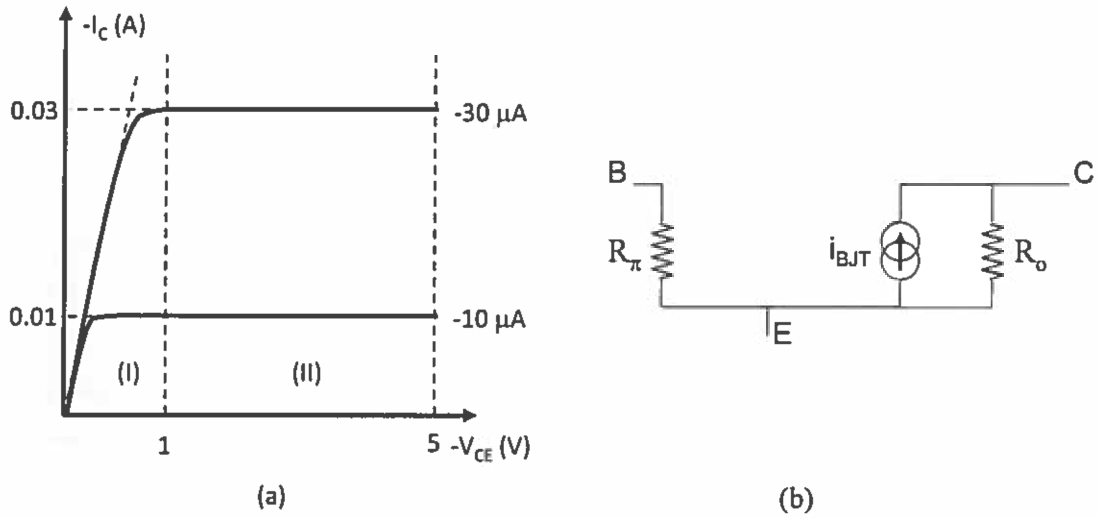

Figure 2.1: (a): Output characteristics of an ideal BJT in common emitter mode. The I_C vs V_{CE} curves are for I_B = -10 μA and -30 μA. (b) An equivalent circuit of the BJT.

a) Sketch the minority carrier concentration variations in the emitter, base and collector regions for the BJT, which is biased in region (II) of Fig. 2.1. Show the depletion widths, define all material parameters in the different layers and give symbols for the voltages across the junctions. [6]

b) Give the expressions for I_E, I_C and I_B of the BJT biased in region (II) in terms of material parameters and junction bias voltages as defined in a). Make appropriate assumptions to simplify the expressions. [6]

c) Calculate the value of I_E and I_B for I_C = 1 mA (in region II), ignoring base width modulation. [3]

d) Derive expressions for the equivalent circuit components, R_π, R_o and i_{BJT} as a function of currents I_E, I_C and I_B. [6]

e) The BJT in Fig. 2.1 has an input resistance of R_π = 8 kΩ and an output conductance of g_o= 4 mS. Calculate the value of the transconductance, g_m. [3]

f) Using the result of e), plot the output characteristic for I_B = -30 μA taking base width modulation into account. Give the value for the collector current I_C at V_{CE} = -5 V. [6]

3. The p-channel depletion mode MOSFET

a) Describe briefly the key characteristics a p-channel depletion mode MOSFET and give two possible fabrication methods. [6]

b) Choose one method given in a) and draw the material cross section for the MOSFET. Define all regions in your plot. [6]

c) For the MOSFET in b), sketch the energy band diagram (E_F, E_c, E_v) from the gate into the substrate for $V_{DS} = V_{GS} = V_{BS} = 0$ V. State any assumptions you make. [6]

d) For the MOSFET in b), sketch the transfer characteristic (I_{DS} vs. V_{GS}) for one drain voltage in the saturation region. Indicate the position of the threshold voltage, V_{th}. [6]

e) For the MOSFET in b), sketch the high frequency capacitance-voltage characteristic (C_{GS} vs. V_{GS}). Give the expression of the maximum capacitance as a function of t_{ox} and indicate the position of the threshold voltage, V_{th} on the plot. [6]

Examination Paper Submission document for 2016-2017 academic year.

For this exam, please write the main course code and the course title below.

Code: EE1-03

Title: Semiconductor Devices

We, the exam setter and the second marker, confirm that the following points have been discussed and agreed between us.

1. There is no full or partial reuse of questions.
2. This examination yields an appropriate range of marks that is well balanced, reflecting the quality of student (with weak students failing, capable students getting at least 40% and bright industrious students obtaining more than 70%)
3. The model answers give a fair indication of the amount of work needed to answer the questions. Each part has a comment indicating to the external examiners the nature of the question; i.e. whether it is bookwork, new theory, a new theoretical application, a calculation for a new example, etc.
4. The exam paper does not contain any grammar and spelling mistakes.
5. The marking schedule is shown in the answers document and the resolution of each allocated mark is better than 3/20 for each question.
6. The examination paper can be completed by the students within time allowed.

Signed (Setter):

Date: 27/03/2017

Signed (Second Marker): S. L

Date: 27/03/2017

Please submit this form with exam paper and model answers, and associated coursework to the Undergraduate Office on Level 6 by the required submission date.