IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2018

EEE PART I: MEng, BEng and ACGI

Corrected copy

SEMICONDUCTOR DEVICES

Thursday, 7 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

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
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

$f(E)=\dfrac{1}{1+\exp\left(\dfrac{E-E_F}{kT}\right)}$	Fermi distribution
$n_i=\sqrt{N_V N_C}\exp\left(\dfrac{-E_G}{2kT}\right)$	Intrinsic carrier concentration
$n=N_c e^{\frac{(E_F-E_c)}{kT}}$	Concentration of electrons
$p=N_v e^{\frac{(E_V-E_F)}{kT}}$	Concentration of holes
$\dfrac{dE}{dx}=\dfrac{\rho(x)}{\varepsilon}$	Poisson equation in 1 dimension
$\left.\begin{array}{l} J_n(x)=e\mu_n n(x)E(x)+eD_n\dfrac{dn(x)}{dx} \\ J_p(x)=e\mu_p p(x)E(x)-eD_p\dfrac{dp(x)}{dx}\end{array}\right\}$	Drift and diffusion current densities in a semiconductor
$I_{DS}=\dfrac{\mu C_{ox}W}{L}\left((V_{GS}-V_{th})V_{DS}-\dfrac{V_{DS}^2}{2}\right)$	Current in a MOSFET
$\left.\begin{array}{l} J_n=\dfrac{eD_n n_{p_0}}{L_n}\left(e^{\frac{eV}{kT}}-1\right) \\ J_p=\dfrac{eD_p p_{n_0}}{L_p}\left(e^{\frac{eV}{kT}}-1\right)\end{array}\right\}$	Current densities for a pn-junction with lengths L_n & L_p
$V_{bi}=\dfrac{kT}{e}\ln\left(\dfrac{N_A N_D}{n_i^2}\right)$	Built-in voltage
$c=c_0\exp\left(\dfrac{eV}{kT}\right)$ with $\left\{\begin{array}{l} c=p_n \text{ or } n_p \\ c_0 \text{ bulk minority carrier concentration}\end{array}\right.$	Minority carrier injection under bias V
$D=\dfrac{kT}{e}\mu$	Einstein relation
$w_n(V)=\left[\dfrac{2\varepsilon(V_{bi}-V)N_A}{e(N_A+N_D)N_D}\right]^{1/2}$ & $w_p(V)=\left[\dfrac{2\varepsilon(V_{bi}-V)N_D}{e(N_A+N_D)N_A}\right]^{1/2}$	Depletion widths under bias V
$W_{depl}^{\max}=2\left[\dfrac{\varepsilon kT\ln\left(\dfrac{N_{substrate}}{n_i}\right)}{e^2 N_{substrate}}\right]^{1/2}$	Maximum depletion width

The Questions

1.

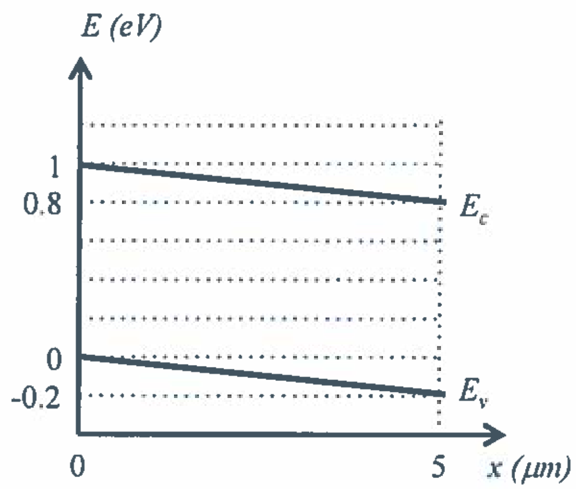

Figure 1.1: Energy band diagram of a semiconductor with $N_v = N_c$.

a) Redraw the energy band diagram of the semiconductor of fig. 1.1 and add:

i) The bandgap E_G and its value. [2]

ii) The intrinsic level E_i. [2]

iii) The electrostatic potential difference ΔV between $x = 0$ and 5 μm and give its amplitude. [4]

iv) The electric field vector $\mathcal{E}$ and give its amplitude. [4]

v) Draw the material cross section of this semiconductor and add a battery with a value and polarity consistent with the energy band diagram in fig. 1.1. Assume no voltage drop at the contacts. [4]

vi) Assuming the semiconductor of fig. 1.1 is doped with acceptor atoms N_A, draw the electron and hole flow (flux) through the material as appropriate for the doping type. [4]

b)

i) Give the relationship between the workfunction of a metal contact and workfunction of p-type Si to obtain a Schottky contact. [2]

ii) The doping density of the p-type Si in b) i) is 10^{16} cm^{-3}. The Schottky barrier height $\phi_B = 0.395$ eV ($\phi_B = |E_F - E_{vs}|$ with E_{vs} the top of the valence band at the metal-semiconductor junction). Give the absolute value of the workfunction difference between the metal and p-type Si. [4]

iii) Give the relationship between the on-voltage, V_{ON} of the Schottky diode based on the material combination in b) ii) and that of a n$^+$p diode with the same doping in the p-region and an n-type doping a factor 100 larger. Justify your answer. [4]

QUESTION CONTINUES ON NEXT PAGE

c) Answer the following questions on semiconductors and semiconductor devices with "yes" or "no".

i) At room temperature, the valence band is almost completely filled with electrons covalently bound to the atoms. [1]

ii) If the mass of holes is smaller than the mass of electrons then the hole mobility will be larger than the electron mobility. [1]

iii) Current through the depletion region of a pn diode is mainly determined by drift. [1]

iv) The reverse bias current through a pn diode is limited by the electric field across the diode. [1]

v) The substrate doping in an n-channel enhancement mode MOSFET is n-type. [1]

vi) Increasing the substrate doping of a MOSFET will decrease the threshold voltage. [1]

vii) The transconductance, g_m of a MOSFET in the triode region (low V_{DS}) will increase when the doping density in the substrate increases. [1]

viii) The equivalent gate-drain capacitance C_{GD} of a MOSFET can be neglected for the MOSFET in saturation. [1]

ix) The current gain in an n^+pn bipolar junction transistor is larger than that of an npn BJT. [1]

x) The output current I_C of a BJT in saturation and in common-emitter configuration increases quasi linearly with increasing bias across the emitter-collector junction, $|V_{CE}|$. [1]

2.

a) Give the general charge neutrality expression for a semiconductor. Define all parameters in your expression. [4]

b) Prove the law of mass action $n \times p = n_i^2$ for a semiconductor in equilibrium. [4]

c) A p-type Si substrate is doped with a density of 10^{17} cm^{-3} boron atoms. To make a pn junction, arsenic atoms are implanted into this substrate creating a final homogeneous doping density of 10^{18} cm^{-3}. Calculate the exact electron and hole densities both in the p-type substrate and the implanted region. [10]

d) The excess carrier concentration of a pn diode under bias is given in fig. 2.1.

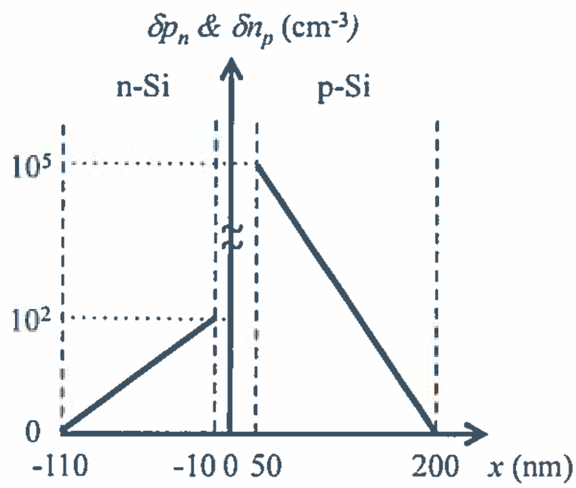

Figure 2.1: The excess minority carrier concentrations of a pn diode under bias.

i) Is the diode in fig. 2.1 in forward or reverse bias? [2]

ii) Which region in fig. 2.1 has the highest majority carrier concentration? Give two features in fig. 2.1 that support your answer. [4]

iii) Calculate the total current density through the pn diode of fig. 2.1. The diffusion constants for the minority carriers are: $D_n = 50$ cm^2 s^{-1} and $D_p = 20$ cm^2 s^{-1}, for electrons and holes respectively. Take the depletion regions into account. [6]

3.

a) Draw the energy band diagram (E_c, E_F, E_v) from emitter through base into the collector of an n^+pn bipolar junction transistor in forward active mode. Indicate the amplitude of the voltage drops $|V_{EB}|$ and $|V_{CB}|$ on the drawing and include the depletion regions. [10]

b) Give the main carrier transport process (drift or diffusion) through the different regions of the "short" BJT in forward active mode.

i) the emitter region. [1]

ii) the emitter-base depletion region. [1]

iii) the base region. [1]

iv) the base-collector depletion region. [1]

v) the collector region. [1]

c) The equivalent circuit of a BJT is given in fig. 3.1.

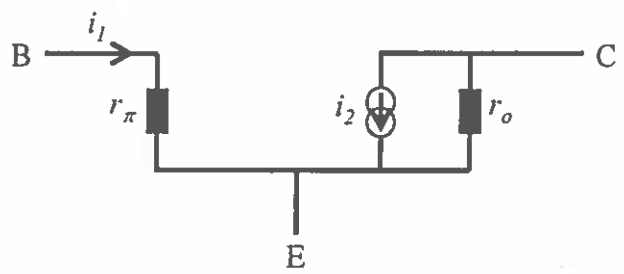

Figure 3.1: Equivalent circuit of a BJT in forward active mode.

i) What is the condition on the emitter-base AC voltage to allow use of the equivalent circuit in fig. 3.1? [4]

ii) Give the expression for i_1 in fig. 3.1 in terms of the BJT material parameters. Use X_E, X_B and X_C as the undepleted lengths of the emitter, base and collector, respectively. Identify clearly the doping type and region in the expression of i_1. [5]

iii) Give the expression of i_2 in fig. 3.1 in terms of transconductance, g_m. [2]

iv) Why is the output conductance of the BJT $g_o = r_o^{-1}$ larger than zero? Give a physical reason for this effect and illustrate with an equation or a sketch. [4]