EE1-03

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2015

EEE PART I: MEng, BEng and ACGI

SEMICONDUCTOR DEVICES

Wednesday, 3 June 10:00 am

Corrected Copy

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.

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 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

$-\frac{\hbar^2}{2m}\frac{d^2\psi(x)}{dx^2}+V(x)\psi(x)=E\psi(x)$	Schrödinger's equation in one dimension
$f(E)=\frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}$	Fermi distribution
$n_i=\sqrt{N_V N_C}\exp\left(\frac{-E_G}{2kT}\right)$	Intrinsic carrier concentration
$n=N_c e^{-\frac{(E_c-E_F)}{kT}}$	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
$c=c_0\exp\left(\frac{eV}{kT}\right)$ 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.

a) Give expressions for the majority and minority carrier density as a function of donor doping, N_D. [4]

b)

i) What is the probability of finding an electron at the Fermi energy, E_F? [2]

ii) What is the density of electrons at $E = E_F$ in an n-doped material? Explain your answer briefly. [4]

c) The doping density in Si is given in Fig. 1.1. Give the direction of the electric field, $\mathcal{E}$ when no bias is applied. Explain your answer briefly. [4]

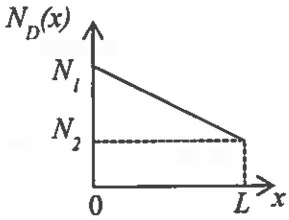

Figure 1.1: the variation of the doping density in Si with length L.

d) Draw the energy band diagram (E_c, E_v, E_F, E_i, E_G) of the material in fig. 1.1. [6]

e) Chose a metal from Table 1.1 that gives an ohmic contact on p-Si with doping $N_A = 3.6\times10^{18}$ cm^{-3}. The electron affinity for Si is $\chi = E_{vac}$-E_c = 4.05 eV. Proof you answer. [10]

metal	ϕ(eV)
Al	4.1
Ti	4.4
W	4.8

Table 1.1: workfunction, ϕ for aluminium, Al; titanium, Ti and tungsten, W.

f) Consider an unbiased Si pn junction with $N_A = N_D$, a built-in potential, $V_{bi} = 0.7$ V and a depletion layer in the p-type region of 2.06×10^{-5} cm. Find the maximum absolute value of the electric field in the depletion region. [6]

g) The material cross section of a MOSFET is given in Fig. 1.2. Sketch the depletion regions for this MOSFET when $0 < V_{GS} < V_{th}$ and $V_{DS} > 0$ V. [4]

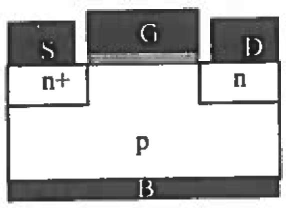

Figure 1.2: material cross section. The source (S) and bulk (B) are grounded. The grey region under the gate (G) is the gate oxide. D is the drain.

2.

a) Explain why the diffusion component of the current in the channel of an n-channel enhancement mode MOSFET with bias $V_{DS} << V_{GS} - V_{th}$ and $V_{GS} >> V_{th}$ is negligible.
Use mathematical expressions as well as energy band diagrams and/or material cross sections in your explanation. [10]

b) Draw the energy band diagrams, (E_c, E_v, E_F, E_G) that explain that a carrier diffusion process controls the magnitude of the source-drain current, I_{DS} at constant V_{DS} for different values of $V_{GS} > V_{th}$. [10]

c)

i) Derive the expression for the inversion charge density, $Q(x)$ in the channel of the MOSFET when $V_{GS} > V_{th}$ and V_{DS} is in the triode (linear) region. Do not write down an equation without a brief explanation for each step. [6]

ii) Calculate the inversion surface charge density Q halfway between source and drain when the oxide thickness is 10 nm, the gate width 5 µm and the gate length 1 µm. $V_{th} = 1$ V, $V_{GS} = 1.5$ V and $V_{DS} = 0.1$ V. [4]

3.

a) Sketch the energy band diagram (E_c, E_v, E_F, E_G) of an n$^+$pn bipolar junction transistor (BJT) in forward active mode. The emitter doping is higher than the base and collector doping, which are the same. Include the depletion regions in your sketch and ensure all relative distances are correct. [10]

b) Sketch the **excess** minority carrier concentration as a function of distance in each region of the BJT in forward active mode. Indicate the minority carrier type in each region and give the expression for the **excess** minority carrier concentration at each junction in the structure. Include the depletion regions in your sketch and ensure all relative distances are correct. [10]

c) For the BJT in a), take an emitter width of L_E, base width W_B and collector width L_C.

i) Derive simplified expressions for emitter, I_E, base, I_B, and collector, I_C, current as a function of excess carrier concentrations and material parameters. Do not neglect the leakage current from collector into the base. Ensure that the symbols for the parameters used, distinguish clearly between the different BJT regions. [6]

ii) Show that the value of the current gain β increases when the leakage current from collector into the base is taken into account compared to when it is neglected. [4]