IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2014

EEE PART I: MEng, BEng and ACGI

Corrected Copy

SEMICONDUCTOR DEVICES

Wednesday, 4 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

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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

$-\dfrac{\hbar^2}{2m}\dfrac{d^2\psi(x)}{dx^2}+V(x)\psi(x)=E\psi(x)$	Schrödinger's equation in one dimension
$f(E)=\dfrac{1}{1+\exp\left(\dfrac{E-E_f}{kT}\right)}$	Fermi distribution
$n_i=\sqrt{N_V N_C}\exp\left(\dfrac{-E_G}{2kT}\right)$	Intrinsic carrier concentration
$n=N_c e^{-\frac{(E_c-E_F)}{kT}}$	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
$V_0=\dfrac{kT}{e}\ln\left(\dfrac{N_A N_D}{n_i^2}\right)$	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
$W_{depl}^{\max}=2\left[\dfrac{\varepsilon kT\ln\left(\dfrac{N_{substrate}}{n_i}\right)}{eN_{substrate}}\right]^{1/2}$	Maximum depletion width

1.

a) At room temperature, pure, undoped Si has a certain density of electrons and holes. Give the concentration of holes and electrons in this material. [2]

b) If Si is doped with an acceptor (B) concentration of 10^{17} cm^{-3}, calculate the position of the Fermi Level, E_F, with respect to the conduction band in this material. [5]

c) Sketch the energy band diagram (E_c, E_v, E_F, E_i, E_G) of the material in 1b). [5]

d) Calculate the resistance of the material in fig. 1.1. The material characteristics are the same as in question 1b). The electron mobility is 300 cm^2/Vs and the hole mobility is 200 cm^2/Vs. [5]

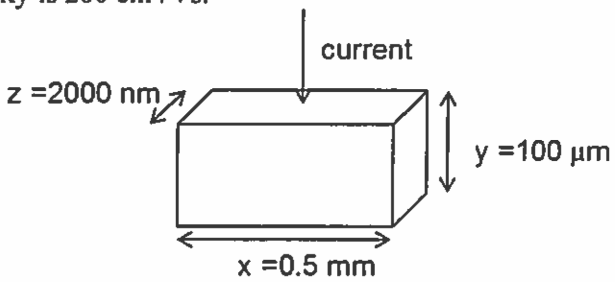


Figure 1.1: Silicon with material parameters from 1b). The current direction and dimensions are given.

e) Fig. 1.2 gives a sketch of a Si pn junction under bias.

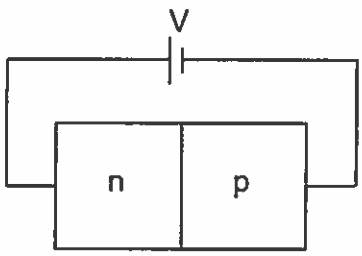


Figure 1.2: pn diode with biasing voltage. The relative difference between the donor and acceptor concentration is: $N_D > N_A$.

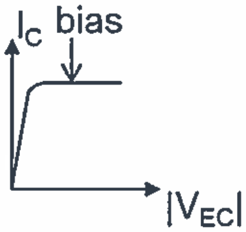
i) Sketch the current voltage characteristics of the pn diode in fig. 1.2 for $0\text{ V} < |V| < 1\text{ V}$. [4]

ii) Sketch the material cross section and include the depletion width in each region. Make sure the relative magnitudes of the depletion widths are correct. [4]

iii) Add the variation of the minority carrier concentration to the sketch of 1e)ii). Ensure the relative magnitude of the plots is correct. Label the axis. [5]

f) Give the relationship between V_{eE} and V_{eB} and the relationship between V_{eB} and V_{eC}, such that the BJT in fig. 1.3 is biased as indicated by the arrow. [4]

Question 1 continues on next page



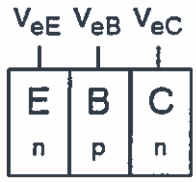


Figure 1.3: Left: the output characteristic of a npn BJT in common emitter mode. The arrow with the word "bias" indicates the point at which the BJT is operating. Right: the material cross section with the nodal voltages on each contact E, B, and C.

g) Consider two npn BJTs with exactly the same dimensions and material parameters. The only difference is the doping density in the emitter: $N_{E1} > N_{E2}$ with N_{Ei} the emitter doping of BJT$_i$ (i = 1,2). Under the same biasing conditions, will I_{C1} be >, < or = than I_{C2}? Verify your answer. [6]

2.

a) Consider a pn diode with homogeneously doped p and n regions. The doping concentrations used are $N_A = 10^{16}$ cm^{-3} and $N_D = 10^{19}$ cm^{-3}. The depletion regions (not shown) are w_n and w_p. The section lengths are $X_n = X_p = 0.035$ cm.

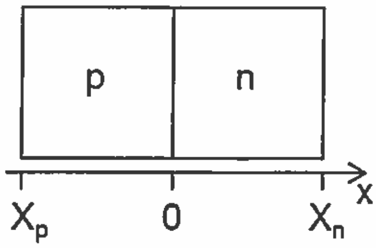


Figure 2.1: un-biased pn diode.

i) At which position in x is the absolute value of the electric field maximum? [2]

ii) Write the total charge $\rho(x)$ in the depletion region of the p-type material. You can use the depletion approximation and assume that the majority carrier concentration is equal to the doping concentration. [2]

iii) Using the Poisson equation, derive the expression of the electric field in the p-section depletion region as a function of doping concentrations. Depletion widths w_n and w_p should not appear in your final expression. Simplify the expression but do not fill in the values. [6]

b) Assume that the doping concentration in the n-type region is not homogeneous but varies slowly, and is defined by the function:

$N(x) = 10^{17} - 5 \times 10^{18} x$

i) Sketch the variation of the concentrations of electrons and holes in this layer when no bias is applied. [4]

ii) Derive the expression for the internal electric field. Eliminate all material parameters so that the equation is only a function of constants and x. [4]

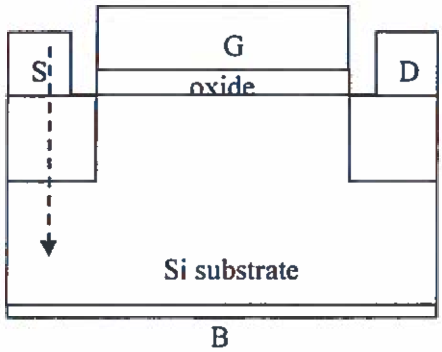
iii) Draw the direction of the electric field on the graph in 2b)i). [2]

c) Using charge neutrality in the homogeneously doped p-type region and the law of mass action, show that:

$p \approx N_A$

if the acceptor doping density, N_A, is sufficiently larger than the intrinsic carrier concentration. [10]

3.



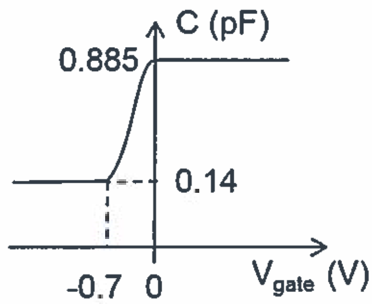


Figure 3.1: Left: material cross-section of an enhancement mode MOSFET. Right: Its capacitance-voltage (C-V) characteristics. V_{gate} is the voltage applied between the gate and bulk with the bulk grounded. The symbols: G, S, D, denote gate, source and drain respectively.

The geometric parameters of the MOSFET are:
Gate width, $W_G = 100$ µm
Gate length, $L_G = 5$ µm

a)

i) Is the MOSFET in fig. 3.1 a p-channel or n-channel MOSFET? [2]

ii) Give the doping type in the source, drain and substrate regions. [2]

iii) Sketch the energy band diagram (E_c, E_v, E_F, E_G) along the dashed line in fig. 3.1 ensuring that the specific characteristics of the contact are clear. [6]

b)

i) Extract the thickness of the oxide from the C-V measurements. [2]

ii) Calculate the doping density in the substrate if you know that at $V_{GS} = 0$ V, flat band condition (no band bending between gate and substrate) is obtained. The work function of the metal is $\phi_m = 4.259$ eV and the difference between the local vacuum level and the conduction band in the semiconductor is: $E_{vac} - E_c = 4.050$ eV. [4]

iii) Give the expression for the maximum depletion, $W_{depl_{max}}$ width in function of the measured capacitance in fig. 3.1. Use symbols C_{min}, C_{max}, $C_{depl_{max}}$, etc... and do not fill in the values. [4]

c)

i) Give the threshold voltage, V_{th} for the MOSFET in fig. 3.1. [2]

ii) Estimate the mobility of the carriers in the channel from the data in fig. 3.2, assuming that the doping density in the substrate is 10^{16} cm^{-3}. [2]

iii) Sketch the output characteristic of the MOSFET for $V_{GS} = -1$ V and 0 V < $|V_{DS}|$ < 1 V. Indicate the voltage and current at saturation. [6]

Question 3 continues on next page

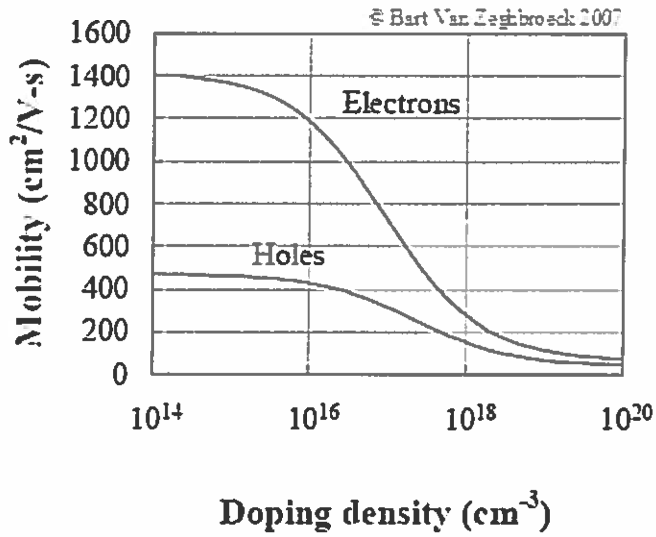


Figure 3.2: The variation of the hole and electron mobility as a function of doping.