IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2014

EEE PART II: MEng, BEng and ACGI

Corrected Copy

DEVICES

Monday, 16 June 2:00 pm

Time allowed: 1:30 hours

There are THREE questions on this paper.

Answer ALL questions. Question One carries 20 marks. Questions Two and Three each carry 15 marks.

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

Constants and Formulae

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

$$\left.\begin{aligned} J_n(x) &= e\mu_n n(x)E(x) + eD_n\frac{dn(x)}{dx} \\ J_p(x) &= e\mu_p p(x)E(x) - eD_p\frac{dp(x)}{dx} \end{aligned}\right\}$$

Drift-diffusion current equations

$$\left.\begin{aligned} J_n &= \frac{eD_n n_p}{L_n}\left(e^{\frac{eV}{kT}} - 1\right) \\ J_p &= \frac{eD_p p_n}{L_p}\left(e^{\frac{eV}{kT}} - 1\right) \end{aligned}\right\}$$

Diode diffusion currents

$$V_0 = \frac{kT}{e}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

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

$$\delta c = \Delta c\exp\left(\frac{-x}{L}\right) \text{ with } \begin{cases} \delta c = \delta p_n \text{ or } \delta n_p \\ \Delta c \text{ the excess carrier concentration} \\ \text{at the edge of the depletion region} \end{cases}$$

Excess carrier concentration as a function of distance

$$L = \sqrt{D\tau}$$

Diffusion length

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

Einstein relation

$$C_{diff} = \frac{e}{kT}I\tau$$

Diffusion capacitance

$$i(t) = \frac{Q(t)}{\tau} + \frac{dQ(t)}{dt}$$

Time variation of current and charge

$$\delta c_B = C_1 \exp\left(\frac{x}{L_B}\right) + C_2 \exp\left(\frac{-x}{L_B}\right)$$

$$C_1 = \frac{c_B(W_B) - c_{B_0} - \left(c_B(0) - c_{B_0}\right)\exp\left(\frac{-W_B}{L_B}\right)}{2\sinh\left(\frac{W_B}{L_B}\right)}$$

$$C_2 = \frac{\left(c_B(0) - c_{B_0}\right)\exp\left(\frac{-W_B}{L_B}\right) - \left(c_B(W_B) - c_{B_0}\right)}{2\sinh\left(\frac{W_B}{L_B}\right)}$$

Excess minority carrier concentration in the base of a BJT

C_1, C_2: integration constants
EB junction is at $x = 0$
BC junction is at $x = W_B$
c_{B0}: equilibrium concentration
L_B: minority carrier diffusion length in base

$$w_n = \sqrt{\frac{2\varepsilon}{e}\frac{N_A}{N_A N_D + N_D^2}(V_0 - V)}$$

$$w_p = \sqrt{\frac{2\varepsilon}{e}\frac{N_D}{N_A N_D + N_A^2}(V_0 - V)}$$

$$W_{depl} = \sqrt{\frac{2\varepsilon}{e}\frac{N_A + N_D}{N_A N_D}(V_0 - V)}$$

Depletion regions in pn diode

1.

a) Draw the energy band diagram (E_c, E_v, E_F, E_G) of an n^+pn bipolar junction transistor in *reverse active mode*. Draw the electric field vector $\mathcal{E}$, across each region where it is present. Ensure that the relative magnitudes of all parameters are consistent. [5]

b) Draw the minority carrier concentration variation in the base of an n^+pn BJT in *reverse active mode* in the following two cases:

i) no recombination occurs in the base. [2]

ii) recombination has to be taken into account. [2]

Label the axes of your graphs with the correct type of minority carrier and ensure that relative magnitudes are consistent. [1]

c) An n^+pn BJT is connected in common emitter configuration. It is switched ON from a completely discharged base. The base control voltage step V_{step} is applied via a resistor R_B. The collector bias circuit consists of a voltage supply V_{CC} and a resistor R_C. The switching voltage drives the BJT into oversaturation.

i) Sketch the variation of the base charge as a function of time. Indicate the moment the BJT goes into saturation. Give an expression for the value of the base charge for $t \rightarrow \infty$. [5]

ii) Sketch the variation of the collector current as a function of time. Indicate the moment the BJT goes into saturation and give an expression for the value of the collector current at that point. [5]

2.

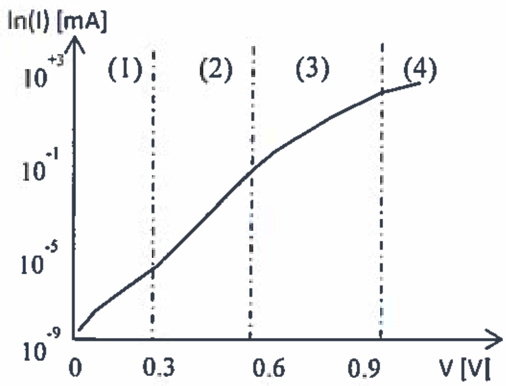

Figure 2.1 The current-voltage characteristics of a real Si pn diode. The current is given on a natural logarithm scale.

a) In Fig. 2.1, four different regions can be observed in the current-voltage characteristics of a forward biased Si pn diode. Explain the physical phenomena that occur in each region that cause the current-voltage characteristic to deviate from a pure exponential. [6]

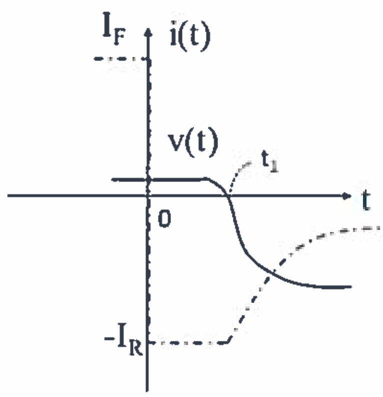

Figure 2.2 Switching characteristic of a Si pn$^+$ diode with long material lengths.

b) The variation of the minority carrier charge stored in the lowest doped region is given by: $Q(t) = -\tau\, I_R + \tau\,(I_R + I_F)\exp\left(\frac{-t}{\tau}\right)$.

with I_F the forward bias current, I_R the magnitude of the reverse bias current and τ the lifetime of the stored charge.

The diode is switched off by applying a reverse bias step voltage at $t = 0$ s of magnitude 1V with a bias resistor of 500 Ω.

Calculate the value of t_1 in Fig. 2.2 when the stored charge at $t = 0$ s is $Q(0) = 10^{-11}$ C. The lifetime of minority carrier holes is 10^{-6} s while that of the minority carrier electrons is 10^{-8} s. [6]

c) How would t_1 vary if the short diode approximation is used? [3]

3.

a) Why is a BJT called a "minority carrier device". [3]

b) A $p^{+}np$ BJT has an emitter efficiency of $\gamma = 0.9$. Recombination happens in the base and the collector but can be neglected in the emitter. Give the expression for the base, I_B, and collector current, I_C, as a function of stored charge and the electron and hole components of the emitter current. Define all parameters and explain all approximations that you make. [5]

c) Derive an expression for the transit time, τ_t, through the base in a $p^{+}np$ BJT for $\gamma = 1$. The final expression has to be a function of material parameters (e.g. doping, length, mobility, diffusion constant, etc.).

Hints: [7]

1. First give the expression for the collector current as a function of transit time.
2. Assume that the variation of the minority carrier concentration in the base can be approximated by a linear equation.