EE2-10A

General comments on EE2 Devices paper 2012

Q1.

All these questions have been discussed during the lectures for a pn diode and pnp BJT, what has changes is the orientation of p and n layer in the exam question and the pnp BJT has been changed for npn. The switching question d) is bookwork.

Q1.c it is surprising that the hole and electron current across a diode are still drawn in a direction opposite to eachother by students in the second year. A diode current is the sum of both electrons and holes thus the currents need to point in the same direction.

This problem is maybe associated to the problem that some students still do not grasp the different between current and carrier flux.

Q2.

a. This is a pn diode question with a twist. In principle it is the contents of the first year, the only difference is now that the cross section area is different for p and n and that has not been done before.
b. Bookwork but for an npn instead of a pnp
c. Bookwork but for npn instead of pnp
d. Is not done explicitly in the class but something similar appears in the example questions
e. Bookwork but with a twist. Normally the switching is solved for the BJT into saturation, however here there is no saturation before switch off thus the time delay that is normally plotted in the classes and lectures does not occur here.

Q2.a in general the signs of the currents are wrong because the structure given is an np structure and not a pn structure. pn structures are normally drawn in lectures. In order to avoid students just copying and pasting what is memorised this structure is often turned over in the exam question. Principles remain exactly the same but the directions of the arrows change.

In the formulae list the current through a diode are give in function of the diffusion length. This is the correct equation for the long diode and for the special case for the short diode. However if a short diode has a length smaller than the diffusion length, this has to be changed in the equation that is copied from the formulae list.

There still seems to be confusion that the p current is calculated in the n region and the n current in the p region. The students should be aware that currents are due to minority carrier diffusion, thus electrons in p-region -> electron current and holes in n-typre region -> hole current.

Q2.ei there is a confusion about with τ to use for the switching.

✓ CA

EE2-10A

IMPERIAL COLLEGE LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2012

EEE PART II: MEng, BEng and ACGI

Corrected Copy
Q2 d)

DEVICES

Monday, 18 June 2:00 pm

Time allowed: 1:30 hours

There are TWO questions on this paper.

Answer BOTH questions. Question One carries 20 marks. Question Two carries 30 marks.

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

Examiners responsible First Marker(s) : K. Fobelets
Second Marker(s) : E. Shamonina

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:	$n_i = 1.45 \times 10^{10}\ \mathrm{cm}^{-3}$ 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

$$W_{depl} = \left[\frac{2\varepsilon V_0}{e}\frac{N_A + N_D}{N_A N_D}\right]^{1/2}$$ Depletion width in pn diode

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

$$i(t) = \frac{Q(t)}{\tau} + \frac{dQ(t)}{dt}$$ Time variation of current and charge.

1. The geometry of a diode is given in Fig.1.1. The definition of the parameters used in Fig.1.1 is:
X_i, i = n or p, is the diffusion length
w_i, i = n or p, is the length of the layer in the carrier transport direction.
t_i, i = y or z, is the dimension of the diode in the y respectively z direction.

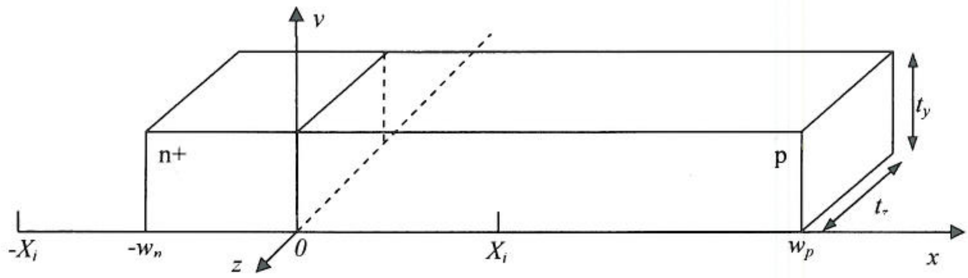


Figure 1.1: Geometry of a pn diode.

a) i) Define the type of the majority and minority carriers in each region of the diode. [2]
ii) Which carrier type determines the diffusion length X_i in each region of the diode [2]

b) Sketch the variation of the amplitude of the electron and hole current as a function of transport direction in both layers of the diode of Fig. 1.1 when the diode is in forward bias. Assume no recombination in the depletion region. [6]

c) Re-draw Fig. 1.2 and add the direction and magnitude of all hole, I_p and electron, I_n currents in each layer of the short npn BJT in forward active mode. The BJT should be in common base configuration. [4]

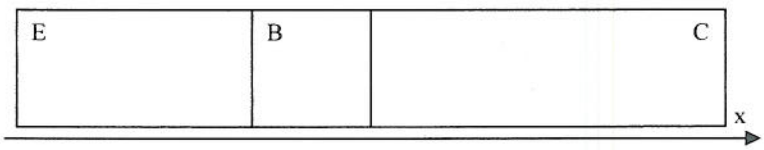


Figure 1.2: 2D cross section of a short npn bipolar transistor.

Question continues on next page

d) Fig. 1.3 gives the variation of the collector current of a BJT as a function of time during switch on.

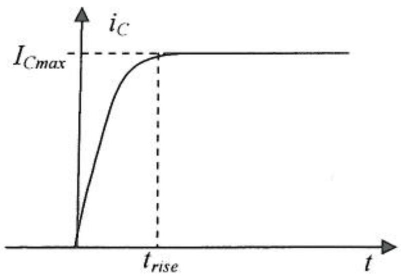


Figure 1.3: Variation of the collector current of a BJT as a function of time during switch-on.

i) Explain why a maximum collector current, I_{Cmax} is reached. [3]

ii) Explain the physical origin of the time delay t_{rise}. [3]

2.

a) Derive the ratio I_n/I_p for the short pn diode in forward bias, given in Fig.2.1. I_n is the electron and I_p the hole current. The ratio I_n/I_p should be expressed as a function of p-Si material parameters only.

Material parameters are:

- doping densities: $N_D = 2\times N_A$,
- dimensions: $t_{yp} = 2\times t_{yn}$, $t_{zp} = 2\times t_{zn}$,
- layer widths: $w_n = w_p$
- diffusion constants: $D_n = D_p$
- diffusion lengths: $L_n = L_p$.

You can assume that all the carriers arriving at x=0 cross without hindrance. [5]

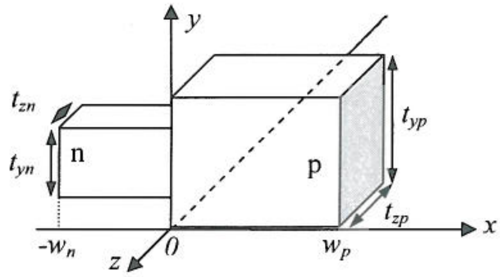


Figure 2.1: Geometry of a short pn diode.

b) Sketch the energy band diagram (E_c, E_v, E_G, E_F) for a n^+pn BJT at zero bias. Ensure that the relative distances between E_c, E_v, & E_F and the widths of the depletion regions are consistent with the doping density. [5]

c) Sketch the energy band diagram for the n^+pn BJT in b) when both emitter-base and collector-base junctions are reverse biased. [5]

n^+pn

d) Sketch the minority carrier concentration variation in each layer for the BJT in ~~b)~~ c). The emitter is short and recombination neglected, the base is short but recombination happens and the collector is long. Take depletion regions into account. [5]

The question continues on the next page.

e) The collector and base current through the BJT in Fig. 2.2, at $t < 0$ are: $I_C < \frac{E_{CC}}{R_L}$ and $I_B = \frac{E}{R_S}$. Derive the following parameters as a function time for $t > 0$.

i) The base charge $Q_B(t)$. [3]

ii) The collector current $i_c(t)$. [3]

iii) Sketch both $Q_B(t)$ and $i_c(t)$ as a function of time for $t > 0$. [4]

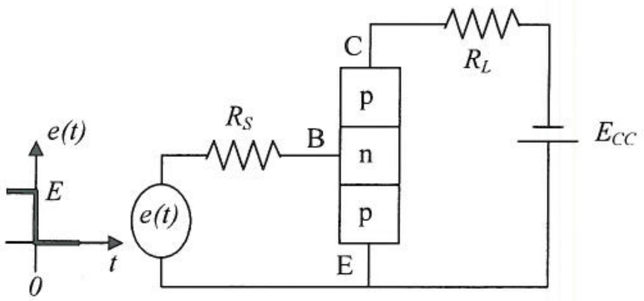


Figure 2.2: Switching off a pnp BJT in common emitter configuration.

Final Copy EE2-10A Devices

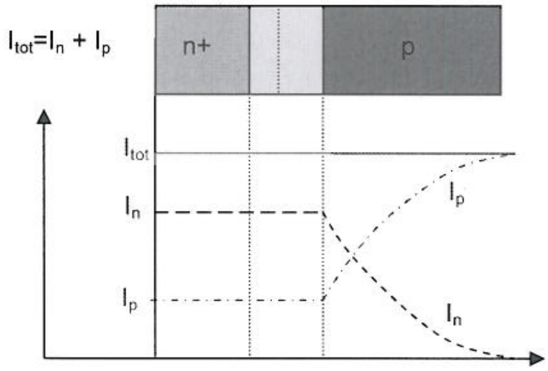
ANSWERS 2012

1.

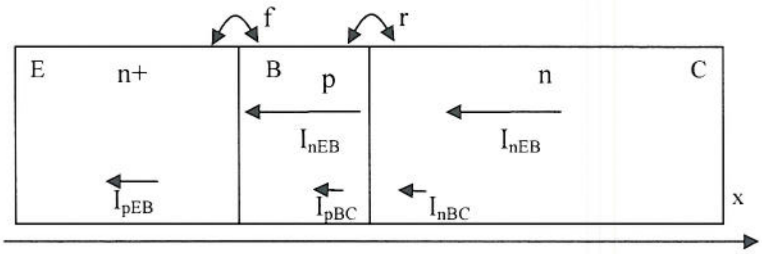
a) i) n+: majority carrier electron, minority carrier hole. P: majority carrier hole, minority carrier electron.

In n-region: X_n : hole and in p-region: X_p: electron minority carrier diffusion length [4]

b) [6]



c) [4]



d) i) When the base current is sufficiently large, it will build up a minority carrier charge in the base that is larger than the charge that causes saturation of the collector current. At saturation, the collector current is no longer controlled by the current gain β $I_C = \beta I_B$ because it is limited by the load: $I_{C\,sat} = \dfrac{E_{CC}}{R_L}$ with E_{CC} the E-C bias and R_L the load resistor. [3]

ii) t_{rise} is the time it takes the base charge to reach the point where the collector current saturates: $Q_B = \tau_t \times I_{C\,sat} = \tau_t \dfrac{E_{CC}}{R_L}$. Q_B keeps increasing but I_C saturates (constant). τ_t is the base transit time: the time it takes the minority carriers to diffuse from EB to VC junction. [3]

ANSWERS

2.

a) [5]

Take formulae from sheet for the current through diode, or take the results obtained in question 1b for the short layer. Write down current densities and fill in parameters:

$$J_n = -\frac{eD_n n_{p0}}{w_p}\left(e^{\frac{eV}{kT}} - 1\right) \quad J_p = -\frac{eD_p p_{n0}}{w_n}\left(e^{\frac{eV}{kT}} - 1\right)$$

introducing the doping:

$$J_n = -\frac{eD_n n_i^2}{w_p N_A}\left(e^{\frac{eV}{kT}} - 1\right) \quad J_p = -\frac{eD_p n_i^2}{w_n N_D}\left(e^{\frac{eV}{kT}} - 1\right)$$

simplifying:

$$J_n = -\frac{eD_p n_i^2}{w_p N_A} e^{\frac{eV}{kT}} \quad J_p = -\frac{eD_p n_i^2}{2w_p N_A} e^{\frac{eV}{kT}}$$

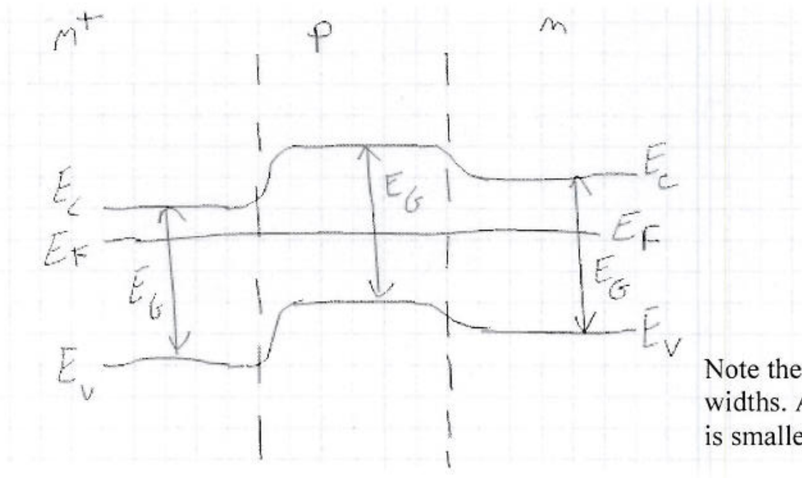
multiplying by appropriate cross sectional area:

$$I_n = -\frac{eD_p n_i^2}{w_p N_A} e^{\frac{eV}{kT}} \left(t_{yp} \times t_{zp}\right)$$

$$I_p = -\frac{eD_p n_i^2}{2w_p N_A} e^{\frac{eV}{kT}} \left(\frac{t_{yp}}{2} \times \frac{t_{zp}}{2}\right) = -\frac{eD_p n_i^2}{8w_p N_A} e^{\frac{eV}{kT}} \left(t_{yp} \times t_{zp}\right)$$

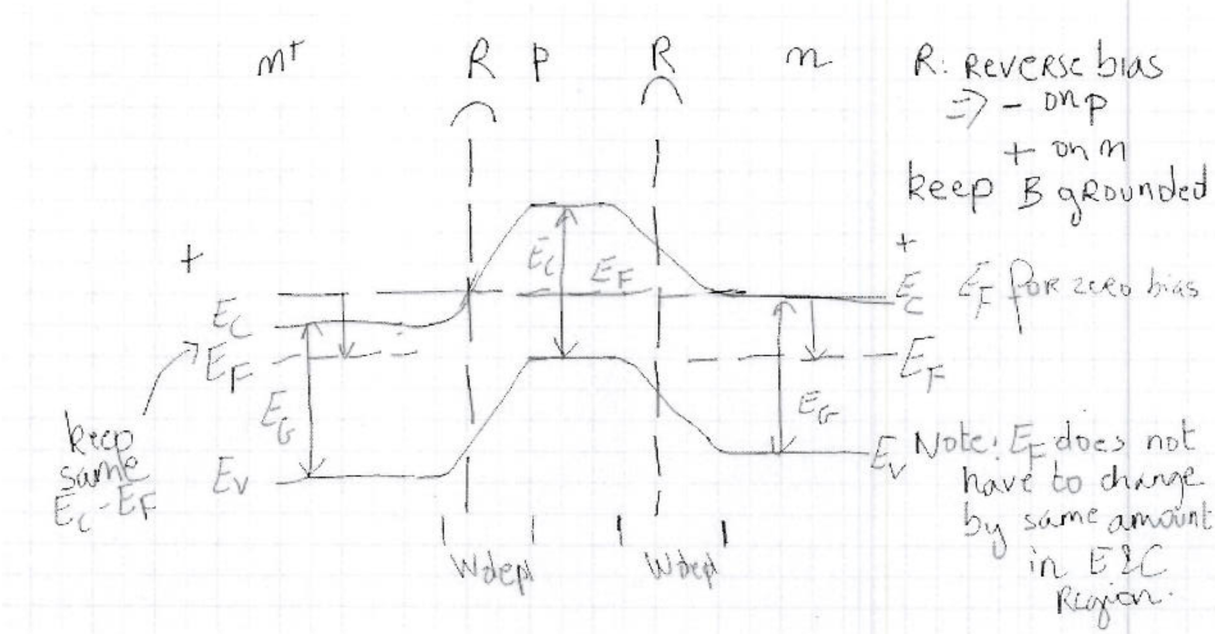
ratio $\frac{I_n}{I_p} = 8$

b) [5]

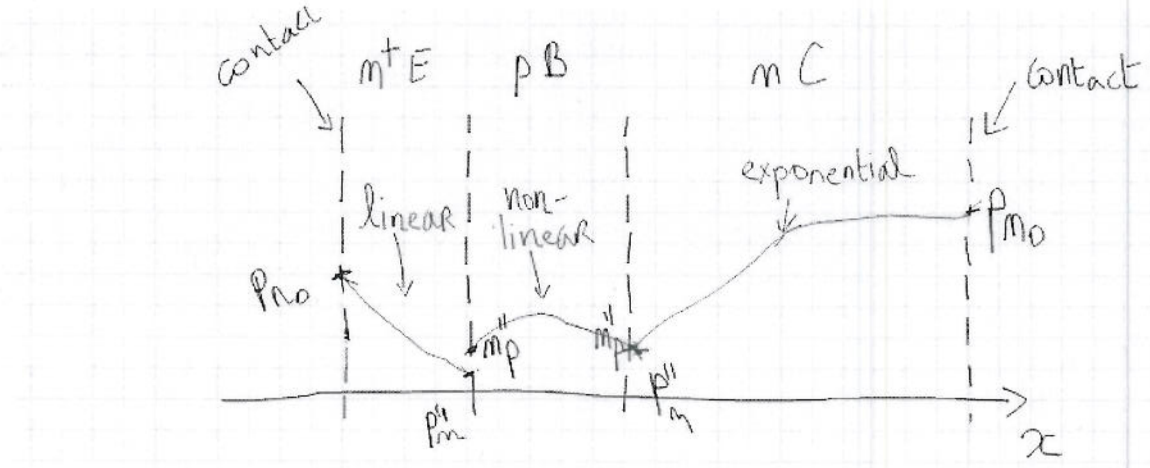


Note the small depletion widths. Also W_{depl} in E is smallest

c) Note that depletion widths must be much larger. The one in E is still the smallest. The potential barriers should have increased at both junctions. [5]



d) [5]



Note that the gradients of the minority carrier concentration in the base have to exist because recombination happens.

e)

i) $Q_B(t)$ take the equation in the formulae sheet that describes the variation of the current and charge as a function of time. τ_p is the average recombination time, it is the average time for a minority carrier hole to recombine with a majority carrier electron in the base. [3]

ANSWERS

$$i(t) = \frac{dQ_B(t)}{dt} + \frac{Q_B(t)}{\tau_p}$$

$$@t = 0 \rightarrow I_B = Q_B(0)/\tau_p$$

$$t > 0, I_B(t \rightarrow \infty) = 0 \Rightarrow$$

$$0 = \frac{dQ_B(t)}{dt} + \frac{Q_B(t)}{\tau_p} \rightarrow \frac{dQ_B(t)}{Q_B(t)} = -\frac{dt}{\tau_p} \rightarrow \ln\left(Q_B(t)\right)\Big|_0^t = -\frac{t}{\tau_p}\Big|_0^t$$

$$\ln\left(Q_B(t)\right) - \ln\left(Q_B(0)\right) = -\frac{t}{\tau_p} \rightarrow \ln\left(\frac{Q_B(t)}{Q_B(0)}\right) = -\frac{t}{\tau_p}$$

$$Q_B(t) = Q_B(0)\exp\left(\frac{-t}{\tau_p}\right)$$

$$Q_B(t) = I_B \tau_p \exp\left(\frac{-t}{\tau_p}\right)$$

ii) $i_c(t)$. Since $I_C < \frac{E_{CC}}{R_L}$, BJT not in saturation → no t_{sd} delay, $i_c(t)$ immediately follows $Q_B(t)$.

The collector current is related to the transit time of the minority carriers τ_t → [3]

$$i_C(t) = \frac{Q_B(t)}{\tau_t} = \frac{I_B \tau_p}{\tau_t}\exp\left(\frac{-t}{\tau_p}\right) = \beta I_B \exp\left(\frac{-t}{\tau_p}\right)$$

The current gain is given by $\beta = \tau_p/\tau_t$.

iii) Sketch both $Q_B(t)$ and $i_c(t)$ as a function of time for $t > 0$. [4]