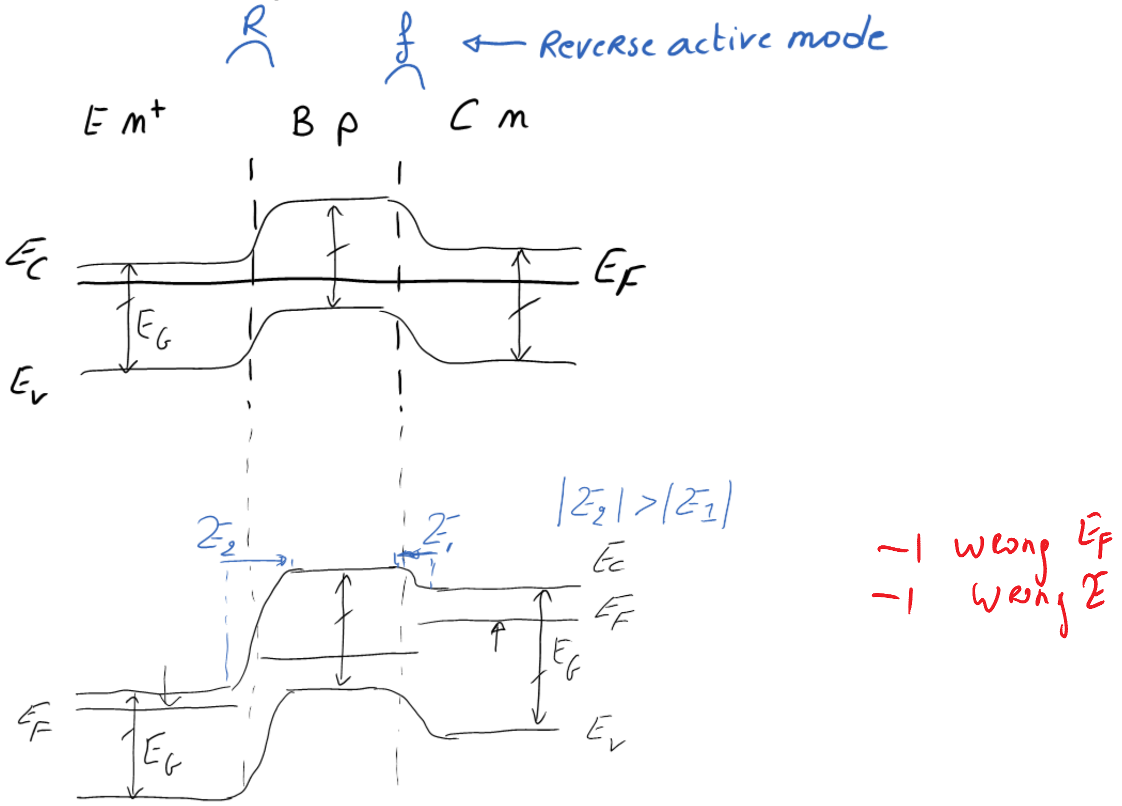
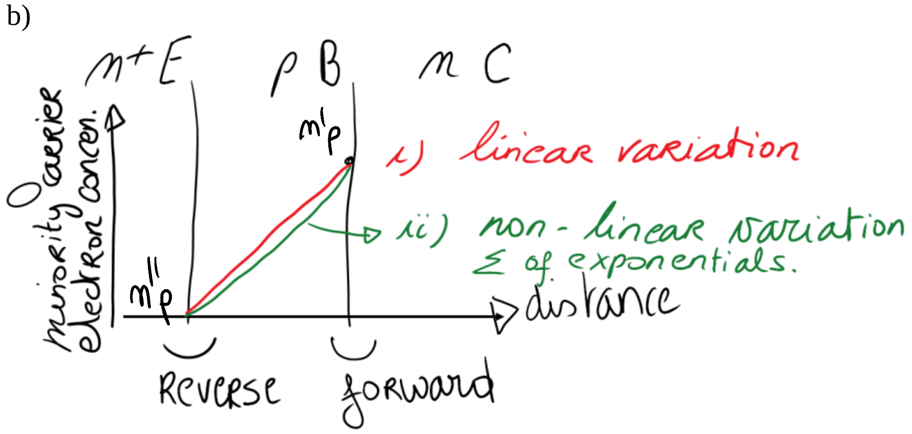
1.a) [5]

First a quick sketch at zero bias. Then apply reverse bias to emitter (=n, so positive voltage -> E_F moves down) and apply forward bias to collector (=n, so negative voltage -> E_F moves up). Note that there are only electric fields across the interfaces. At the EB junction the resultant electric field must be larger than at the BC junction. Small potential barrier at BC junction, large at EB junction. The relationship between doping density and type and the position of the Fermi level with respect to the conduction band must be correct. Thus E_C close to E_F in emitter (n+) and a little further away in collector (n). E_v closer to E_F for p-type in base. Don't forget to indicate E_G and make sure that it remains constant throughout.

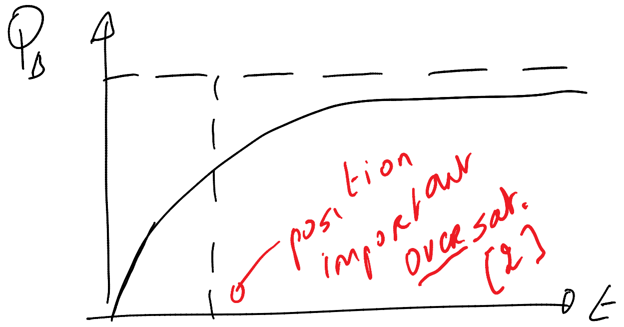


Many mistakes in this question: EF was often kept constant which cannot be correct because a voltage is applied across each junction. EF moves up when the voltage applied is negative, and moves down when the voltage applied is positive. Most students did keep the base EF constant (thus ground node) which is good. Almost no-one had the relative magnitudes of the electric field E1 and E2 correct.

b) [5]



c) t_1 is the time where saturation starts. i) the base charge for $t \rightarrow \infty$ is



$$Q_B(t\to\infty) = \frac{V_{step}\,\tau_B}{R_B} \quad [2]$$

[5]

$$Q_B = I_B\,\tau_B = \frac{V_{step}}{R_B}\cdot\tau_B$$

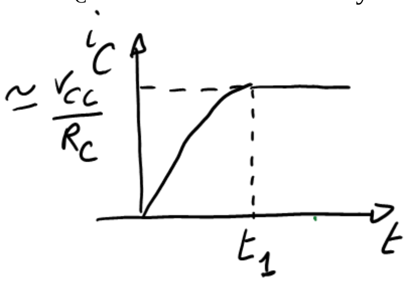
Many errors were made against the position of t1 (time of saturation). Since the transistor goes in oversaturation, the charge in the base increases till it reaches at t=infinity the value determined by the base current. Note that IB is determined by the external circuit.

The second error is introducing different slopes in the non-linearly increasing part. If you look at the formulae for QB derived in the class you will see that it is only 1 function that describes this region. Those people who plotted different curves actually just copied the curve in the ppt slides which is simplified to be able to do the explanations. When the calculations are done it is proven that this is just 1 equation. Do not learn by heart, understand what the derived equations mean. All changes are exponentials, do not draw linear variations in that case.

ii) The saturation current is approximately determined by the load:

$$i_C^{sat} \cong \frac{V_{cc}}{R_C}$$

The variation of the collector current as a function of time when the BJT goes from off (no charge in base = i_C=0 to saturation and beyond). [5]



Most students had this correct apart from linear instead of exponential variations and different slopes in the graph between 0<t<t1

2. a) [6]

(1) recombination of the carriers in the depletion region that are crossing this with low numbers and thus impact can be measured.
(2) is the ideal region governed by minority carrier diffusion in the neutral regions.
(3) high current injection region. The minority carrier concentration is of the same order of magnitude as the majority carrier concentration. Approximations no longer valid.
(4) resistive region. The resistance of material and contacts is limiting the current as they take up a part of the applied voltage.

Bookwork, (2) is obviously ideal, (4) the mistake people made on this is associating is to voltage rather than to high current. Once the current is high then the voltage drop associated to the resistor Rc and neutral regions Vparasitic = (Rn + Rc) I becomes important because of high I.

b) pn^+ diode with both layers long, means that the current will be mainly carried by electrons (as the n-doped layer is more heavily doped than the p-doped layer) and thus the largest stored charge is electron charge in the p-region. The life time in the calculations must thus be the electron minority carrier lifetime $\tau = 10^{-8}$ s.

The forward bias current flowing for t<0 is related to the stored charge:

$I_F = Q_n(0)/\tau_n = 10^{-11}$ C/10^{-8} s = 1 mA

The immediate reverse bias current is related to the reverse bias voltage across the resistor. This is the case because at t = 0+ the diode is still conducting in its low resistance mode due to the stored charge. Thus:

$I_R \approx V/R = 1\text{V}/500\Omega. = 2$ mA

The variation of the stored minority carrier charge in the lowest doped region is given by:

$$Q(t) = -\tau\, I_R + \tau\,(I_R + I_F)\exp\left(\frac{-t}{\tau}\right).$$

You need to remember the key point in the switching of diodes and that is that at time $t = t_1$ the stored minority carrier charge has become zero. $Q(t_1) = 0$ C. Then the diode voltage goes through 0.

Derive equations (put in values at the very last moment):

$$0 = -\tau_n I_R + \tau_n (I_R + I_F)\exp\left(-\frac{t_1}{\tau_n}\right)$$

[6]

$$t_1 = -\tau_n \ln\left(\frac{I_R}{(I_R + I_F)}\right) = \tau_n \ln\left(\frac{(I_R + I_F)}{I_R}\right) = 10^{-8}\ln\left(\frac{3}{2}\right) = 4\times 10^{-9}\,s$$

Surprising error was that different students actually solved the differential equation: $i(t) = \dfrac{Q(t)}{\tau} + \dfrac{dQ(t)}{dt}$. This however is not necessary as the solution is given. The 2nd error made was to assume $I_F = I_R$. Finally, errors in units led to many errors in the end result.

c) When the short diode approximation is applied, it is assumed that the recombination time is infinite. Thus the formula for Q(t) cannot be derived under those conditions.
Take time variation of charge differential equation from formulae list: [3]

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

For the short diode approximation this becomes: $i(t) = \dfrac{dQ(t)}{dt}$

Thus the time variation of the charge for i(t) constant after switch is: $Q(t) = Q(0) - |I_r|\, t$

At t=t1 Q(t1)=0 thus t1=Q(0) |/|Ir = 10^{-11} C/10^{-3}A=10^{-8} s

Very few students actually gave the result for t1. A mistake made was stating that t1 is linearly varying – incorrect as it is a constant. The statement that Q(0) is different cannot be made as Q(0) is given.

3.a) because the currents in the BJT are calculated from the gradients of the minority carrier concentrations in each region. This is due to the approximation taken that no electric field occurs across the neutral regions. [3]

Key words are gradient, diffusion and the assumption that there is no electric field in the neutral region. This last one was missed by almost all students. A copy of the answer to the question on with is it called bipolar is also wrong as it doesn't answer the minority carrier gradient/diffusion part.

b) Since γ<1 both electron and hole currents in the emitter current need to be taken into account. Thus emitter current is: $I_E = I_n + I_p$.

I_n is the electron and I_p the hole current across the base-emitter junction.

Since recombination is happening in the base the base current will be $I_B = I_n + I_r$

I_n is the electron current flowing from the n-type base into the emitter and I_r is the resupply of electrons into the base that have disappeared due to recombination. This current can be written in terms of charge in the base Q_B and the recombination time of the minority carrier electrons in the base, τ_p. Thus the base current becomes:

$$I_B = I_n + \frac{Q_B}{\tau_p}$$

We ignore the reverse bias electron supply from the collector into the base. Then the collector current is the hole current injected from the emitter into the base minus the holes that are recombining with the electrons in the base. The latter is I_r. Thus the collector current becomes:

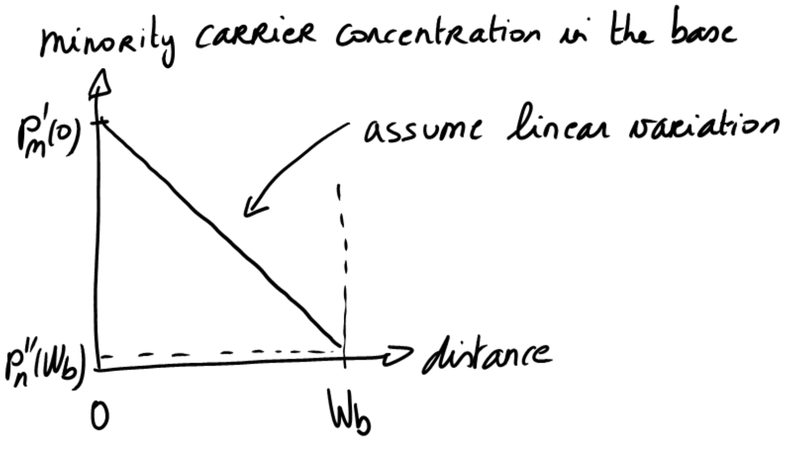
$$I_C = I_p - \frac{Q_B}{\tau_p}$$ [5]

I_C was often expressed as a function of τ_t, but this lacks the relation with IE components. Also, the fact that one has to ignore the reverse bias electron supply was overlooked by many.

c) total mark [7]

1. The expression of the collector current as a function of transit time when γ=1: $I_C = \frac{Q_B}{\tau_t}$ [1]

2.



Based on the approximation that we can represent the minority carrier hole concentration in the base as linearly varying, we can calculate Q_B and I_C easily.

Q_B can be derived by calculating the area under the minority carrier concentration and realising that the minority carrier concentration at the BC junction is much smaller than at the EB junction.

$$Q_B = eA\frac{\left(p'_n(0) - p''_n(W_b)\right)\times W_b}{2} \approx eA\frac{p'_n(0)\times W_b}{2} \qquad [2]$$

I_C can be calculated from the definition of the diffusion current by still making the linear approximation of the charge variation in the base and ignoring I_{CB0}.

$$I_C = eAD_p\frac{dp_n(x)}{dx} = eAD_p\frac{p'_n(0) - p''_n(W_b)}{W_b} \approx eAD_p\frac{p'_n(0)}{W_b} \qquad [3]$$

Thus from (1.):

$$\tau_t = \frac{Q_B}{I_C} \approx \frac{eA\dfrac{p'_n(0)\times W_b}{2}}{eAD_p\dfrac{p'_n(0)}{W_b}} = \frac{W_b^2}{2D_p} \qquad [1]$$

Main mistakes were made by using diffusion length L_p in the base rather than using the base width that is smaller than L_p. Another common mistake was to draw a non-linear variation and try to work out the difficult formulae or using the long material approximation.

General note:

Overall the exam went well for the majority of students. However, there was a large proportion of students who might not have revised the subject in an appropriate way, expecting to gain sufficient marks on the other topic such that they can get away with low marks in this one. These students did quite poorly whilst the exam was not at all difficult.