

## Answers EE2 Semiconductor Devices (2008)

①

① a) Roles

b)  $n_m = 5 \times 10^{17} \text{ cm}^{-3}$  majority carrier concentration

$$p_m = \frac{n_i^2}{N_D} = \frac{(1.45 \times 10^{10} \text{ cm}^{-3})^2}{5 \times 10^{17} \text{ cm}^{-3}} = 420.5 \text{ cm}^{-3}$$

= minority carrier concentration.

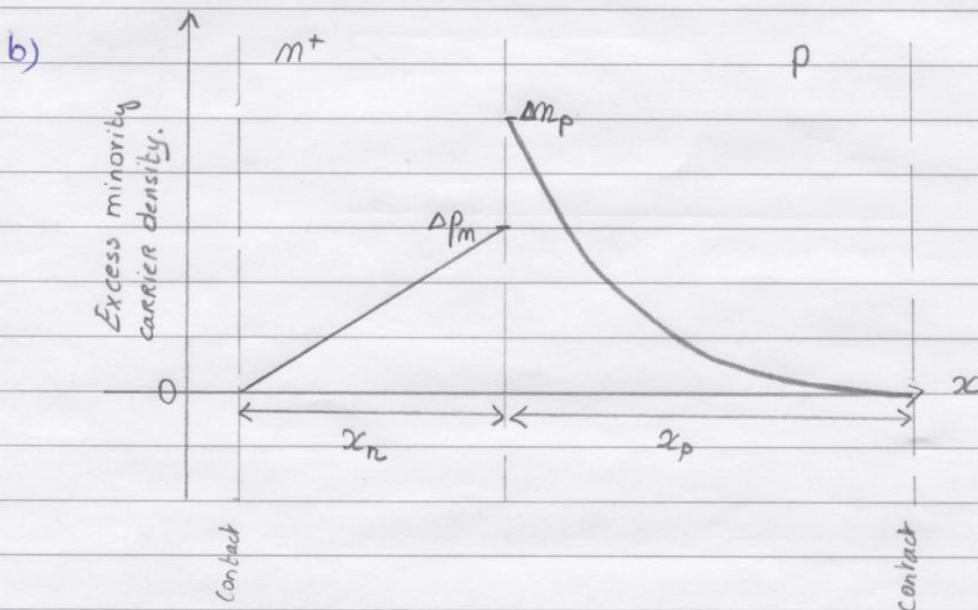
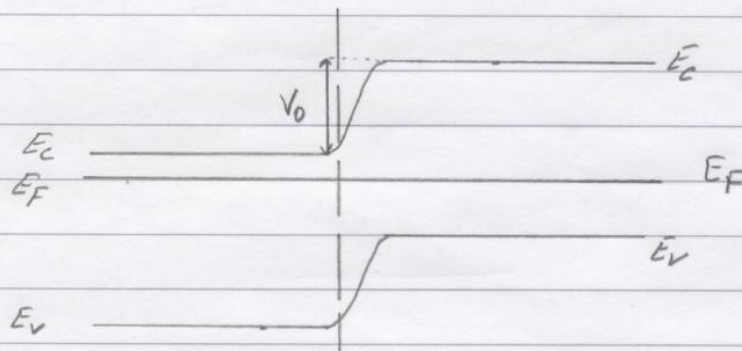
c) Drift is caused by an electric field  
Diffusion is a result of carrier gradients



Should be an exponentially decreasing curve that goes to zero @  $x=L$ .

e) The main cause of delay in a BJT is the charge in the base region. This charge needs to be completely removed before the collector current can become zero.

3 a) Energy band diagram



Note: • variation in  $m^+$  layer linear  
 • variation in  $p$  layer exponential.

$$\begin{aligned}
 Q_p &= \frac{e \cdot \Delta p_m \cdot x_n \cdot A}{2} = \frac{e (p_m' - p_{m0}) \cdot x_n \cdot A}{2} = \frac{A e x_n p_{n0}}{2} \left( \exp\left(\frac{V_{EB}}{V_T}\right) - 1 \right) \\
 &= \frac{e x_n n_i^2}{2 N_D} \left( \exp\left(\frac{V_{EB}}{V_T}\right) - 1 \right) \cdot A
 \end{aligned}$$

$$\begin{aligned}
 Q_n &= -e A \int_0^{x_p} \Delta n_p \exp\left(-\frac{x}{L_n}\right) dx \\
 &= e \cdot A \cdot \Delta p_p \cdot L_n \exp\left(-\frac{x}{L_n}\right) \Big|_0^{x_p}
 \end{aligned}$$

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$$Q_n \approx +e A (n_p' - n_{p0}) L_n (0 - 1)$$
$$= -\frac{e A n_i^2 L_n}{N_A} \left( \exp\left(\frac{V_{EB}}{V_T}\right) - 1 \right)$$

d) since  $n^+p$  junction  $I_{tot} \approx I_n$   
 $I_n = \frac{Q_n}{\tau_n}$  Recombination current.

$$I_n = -\frac{e A \Delta n_p L_n}{\tau_n}$$

$$J_n = \frac{I_n}{A} = \frac{-1.6 \cdot 10^{-19} \text{ C} \cdot 2 \cdot 10^{12} \text{ cm}^{-3} \cdot 500 \cdot 10^{-7} \text{ cm}}{0.1 \cdot 10^{-6} \text{ s}}$$
$$= -16 \cdot 10^{-5} \frac{\text{A}}{\text{cm}^2}$$

- e) i)  $I = 0 \text{ A}$  open circuit.  
ii)  $V_d > 0 \text{ V}$  forward bias voltage remains until excess charge is removed.

2E Electromagnetic Fields 2008 – Solutions

4. a) Key contributions were as follows:

i) Wilhelm Roentgen: Discovered X-rays

Heinrich Hertz: Discovered radio waves

[2]

ii) Alexander Graham Bell: Invented the telephone

Guglielmo Marconi: Invented the radio

John Logie Baird: Invented the television

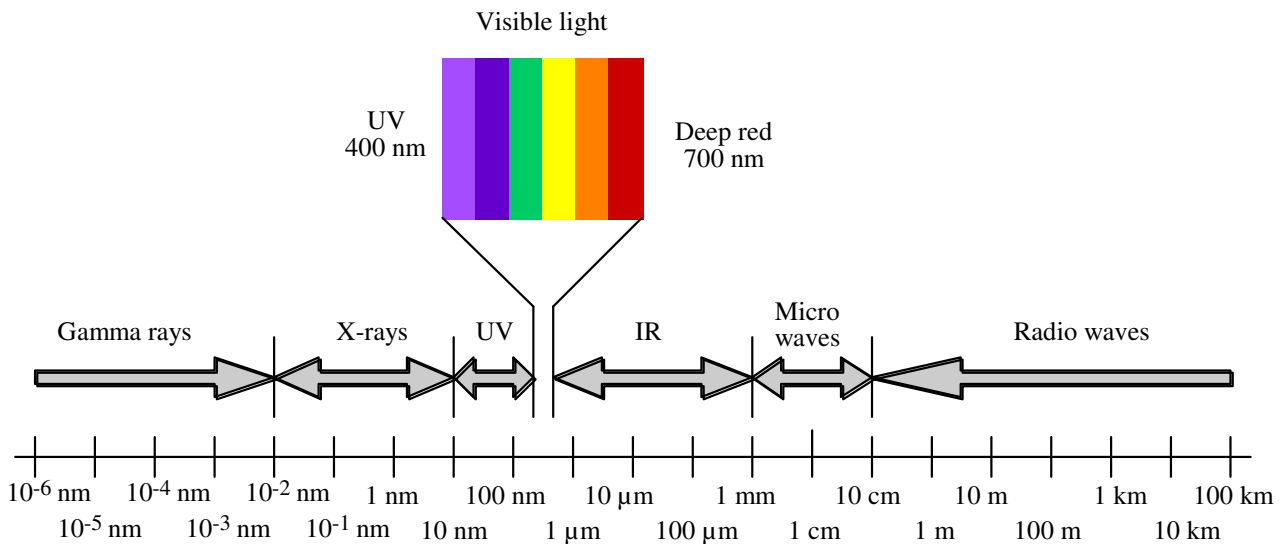
[3]

iii) John Tyndall: Demonstrated light guidance by total internal reflection in a water jet

Charles Kao and George Hockham: Proposed low loss optical fibre communications

[2]

b)



[1 mark for each band = 7]

c) Radio waves – main difficulty is diffraction; overcome using phased arrays

[2]

Microwaves – main difficulty is attenuation; overcome by avoiding water absorption frequency.

[2]

Light waves – main difficulty is scattering; overcome by confinement inside an optical fibre.

[2]

5. a) The phase velocity is the velocity of a single travelling wave.

The group velocity is the velocity of a group of waves, which can represent a modulated carrier and hence describe information propagation.

[3]

The two constituent waves with frequencies  $\omega + \Delta\omega$  and  $\omega - \Delta\omega$  must have corresponding propagation constants  $k + \Delta k$  and  $k - \Delta k$ . The combined signal can therefore be written as:

$$A(z, t) = A_0 \{ \exp\{j[(\omega + \Delta\omega)t - (k + \Delta k)z]\} + \exp\{j[(\omega - \Delta\omega)t - (k - \Delta k)z]\} \} \text{ or}$$

$$A(z, t) = A_0 \{ \exp[j(\Delta\omega t - \Delta k z)] + \exp[-j(\Delta\omega t - \Delta k z)] \} \exp[j(\omega t - kz)] \text{ or}$$

$$A(z, t) = 2A_0 \cos(\Delta\omega t - \Delta k z) \exp[j(\omega t - kz)]$$

This result describes a carrier with a modulating envelope in the form of a travelling sinusoidal wave. The velocity of the envelope is  $v_g = \Delta\omega/\Delta k$ .

[3]

b) If the dispersion characteristic of the ionosphere is  $\omega = \sqrt{[\omega_p^2 + c^2 k^2]}$ , then:

$$v_{ph} = \omega/k = \sqrt{[(\omega_p^2/k^2) + c^2]} \text{ and}$$

[3]

$$v_g = d\omega/dk = c^2/\sqrt{[(\omega_p^2/k^2) + c^2]}$$

[3]

For the atmosphere, which has  $\omega_p = 0$ ,  $\omega = ck$ , so:

$$v_{ph} = \omega/k = c$$

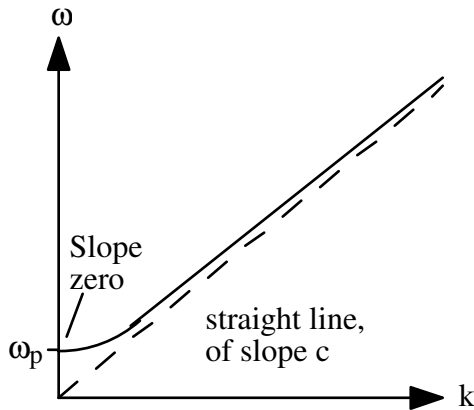
[3]

$$v_g = d\omega/dk = c$$

[3]

c) The dispersion diagram is as shown below. Since  $v_g$  tends to zero when  $\omega$  tends to  $\omega_p$ , there can be no transmission of information in this frequency range.

[3]



[3]

d) Rewriting the equation for the dispersion characteristic, we get:  $\omega^2 = \omega_p^2 + c^2 k^2$

Hence  $k = (1/c) \sqrt{(\omega^2 - \omega_p^2)}$ .

If  $\omega < \omega_p$ , this result can be written as  $k = \pm j(1/c) \sqrt{(\omega_p^2 - \omega^2)} = \pm jk'$

[3]

A wave solution  $A(z, t) = A_0 \exp[j(\omega t - kz)]$  then becomes  $A(z, t) = A_0 \exp(j\omega t) \exp(\pm k' z)$ , i.e. an exponentially decaying wave.

The significance of this result is that waves with angular frequencies less than  $\omega_p$  will not be able to penetrate the ionosphere; instead, they will be reflected (as Marconi found).