PART IIA 2005
3B6: Phototonic technology
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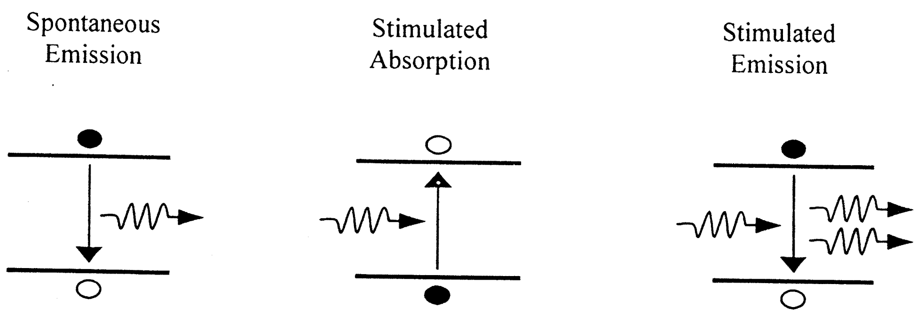
ANSWERS TO MODULE 3B6,

Datasheet: Photonic Technology

Question 1

(a) This is primarily a bookwork part of the question. A good answer should cover the following points:

There are three major types of electron/photon interactions in materials.



Spontaneous Emission: An electron in a high energy level falls losing energy which is emitted as a photon – the basis of operation of a light emitting diode.

Stimulated Absorption: An incident photon is absorbed in a material causing the excitation of an electron to a higher energy level – the basis of operation of a photodiode.

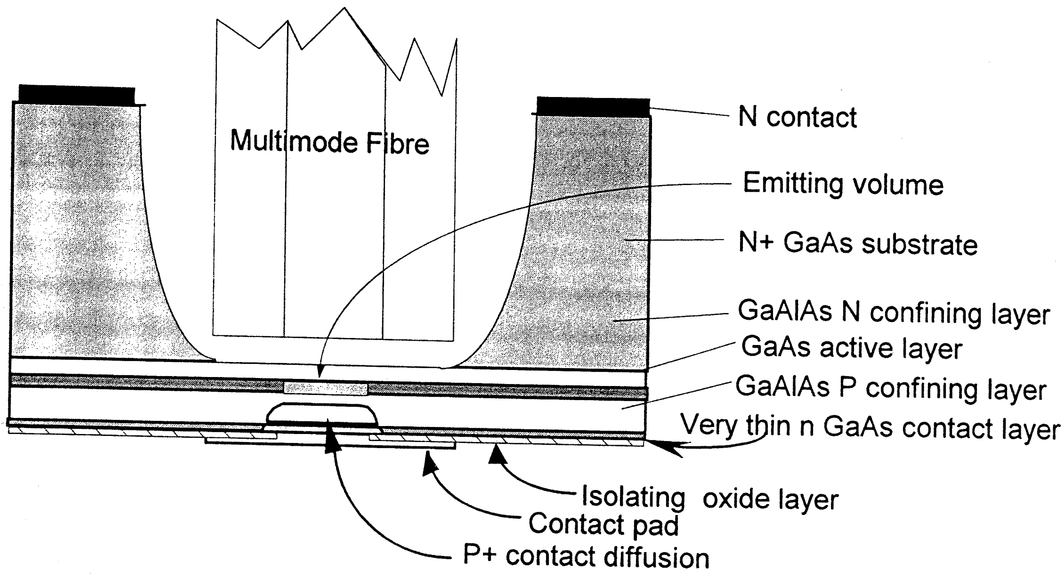
Stimulated Emission: A photon, incident upon an electron in a higher energy level causes the electron to fall to a lower level thus generating a second photon. This is therefore an amplifying action. Two photons are generated from one and in turn they can cause the generation of two further photons. Using this method high optical powers can be generated and this operation is the basis of lasing action. The generated photon has the same frequency and phase as the incident photon and therefore very pure monochromatic and coherent light is generated. This mechanism is at the heart of the operation of the laser.

[20%]

(b) (i) Again this is largely a bookwork section. A good answer would include the following points:

The SELED (sometime called Burrus) diode has much of the substrate etched away: this allows high coupling into a multimode fibre, sometimes a spherical micro-lens is interposed as well. In addition the heat generation is close to the p surface which can be bonded directly to a heatsink, and the contact metal also reflects some light back upwards into the fibre. Similar devices are made using the InP/GaInAsP materials system at longer wavelengths.

GaAs based Burrus type high radiance LED



[25%]

(ii) The wavelength of the LED is given by

$\lambda = hc/(eV_{band\text{-}gap}) = 851$ nm

The linewidth is given by $\Delta\lambda \sim \lambda^2 . 2kT/hc = 30$ nm

[15%]

(iii) The overall quantum efficiency is given by

$\eta = \eta_{int}\,\eta_{ext} = (1/\tau_{rr})/(1/\tau_{rr} + 1/\tau_{nr}).\ \eta_{ext}$

Therefore $\eta_{ext} = \eta\,/((1/\tau_{rr})/(1/\tau_{rr} + 1/\tau_{nr})) = 25$ %

[15%]

(iv) The variation of LED power with temperature is given by

$P(T)/P(T_1) = \exp[-(T - T_1)/T_0] = 0.53$ for a temperature change from 300 K to 350 K.

As a result, if the LED remains linear, the quantum efficiency reduces to 0.053, the change in current can be written as

$I_{350} - I_{300} = (hc/e\lambda)\ [(P_{350}/\eta_{350}) - (P_{300}/\eta_{300})] = 26$ mA

[15%]

(c) This is a largely bookwork section, where a good answer should describe how the heterostructures within an edge emitting LED act to confine the light within the LED and guide it so that the output irradiance is substantially larger than in the surface emitting version. However the output beam of the device is typically anistropic.

[10%]

Question 2

(a) (i) This is largely a bookwork question showing that in the electron rate equation the terms relate to the nett change in carrier concentration/second, the rate of depletion of carriers due to stimulated emission, that due to spontaneous emission and the rate of enhancement of carrier concentration due to current injection respectively. In the case of the photon rate equation the terms relate to the nett change in photon density within the laser of the lasing mode /second, the generation of photons due to stimulated emission, that in the lasing mode due to spontaneous emission and the rate of loss of photons from the cavity. The equations assume that the laser gain is linear, and the light is monochromatic. Confinement and temperature effects are neglected. A good answer should define the specific variables.

[20%]

(ii) In order to generate equations for the P/I and n/I characteristics at steady state, set dn/dt = dP/dt = 0 and assume that β is very small. Rewriting the photon rate equation,

$$0 = g(n - n_o)P - P/\tau_p$$

=>

$$P\{g(n - n_o) - 1/\tau_p\} = 0$$

As P may have values greater than 0 (and not less!),

$$g(n - n_o) - 1/\tau_p = 0$$

=>

$$n = n_o + 1/(g\tau_p)$$

However all the terms on the right hand side of the equation are constants. Therefore at steady state for all values of lasing photon density, the carrier concentration in the laser is constant. Let this value be called the threshold carrier density, n_{th}.

Below threshold, when P = 0 (there is no lasing light generated), the electron rate equation becomes simply, $n = I\tau_s/eV$.

As a result the threshold current, $I_{th} = eVn_{th}/\tau_s$.

Below threshold no nett stimulated emission is emitted but above threshold the light increases linearly with current.

Considering the steady state (ie dn/dt = 0) electron rate equation,

$$0 = -g(n - n_o)P - n/\tau_s + I/eV$$

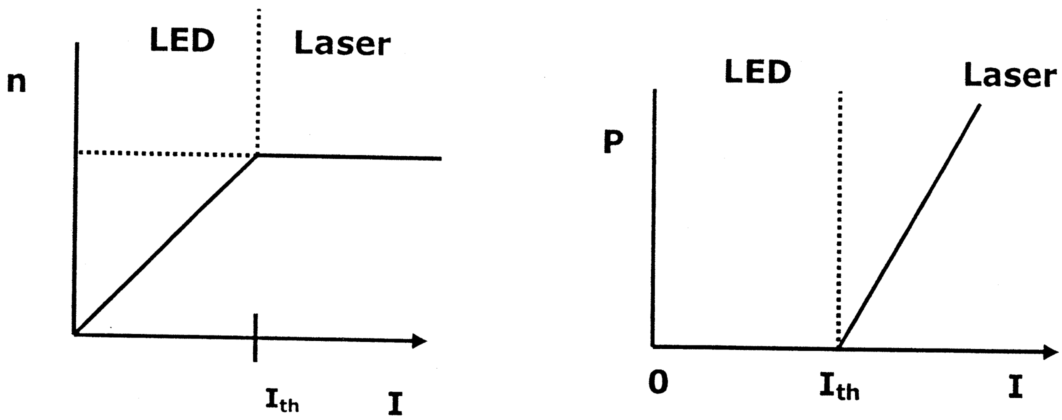
But $n = n_{th}$ for all $P > 0$, so in this regime,

$$P = \frac{\{I/eV - n_{th}/\tau_s\}}{g(n - n_o)}$$

Let $I_{th} = eVn_{th}/\tau_s$,

$$=> \quad P = \frac{\{I - I_{th}\}}{eV\,g(n_{th} - n_o)} = k(I - I_{th})$$

As a result the optical power generated by the laser may be shown to be proportional to the current above the threshold current.



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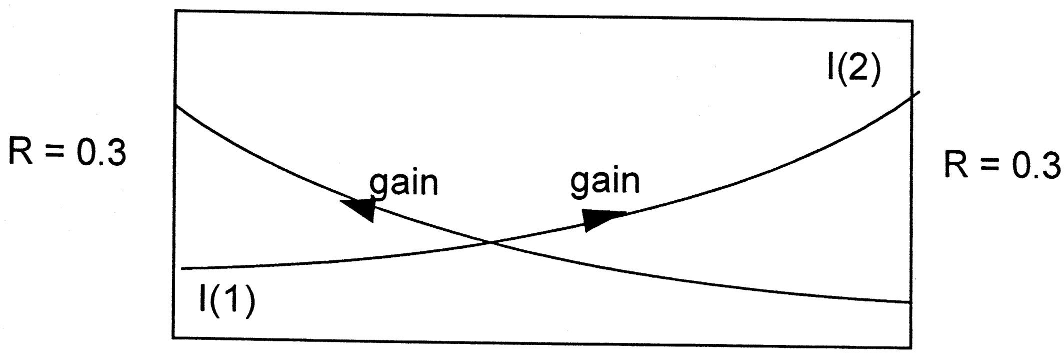
(b) The photon lifetime of the laser cavity can be readily determined by considering the amplification of laser light as it propagates along the laser cavity.

Laser round-trip gain matching



Assume that stimulated emission encounters a gain per unit length (due to stimulated amplification), G, and a loss per unit length due to scattering and absorption, α, as it passes along the laser. The gain G in practice creates extra photons to compensate for those photons lost as the signal travels over a distance of unit length.

Therefore the stimulated emission intensity I(1) starting at one facet will be incident on the opposite facet with an optical intensity

$$I(2) = \exp\{(G - \alpha)L\}\, I(1)$$

At that point part of the signal is reflected with a coefficient R and the signal then passes back amplified by the same amount as above and again reflected by the initial facet. Lasing action will occur if the nett round trip gain of the signal is unity i.e. if

$$\exp\{(G - \alpha)L\}.R.\exp\{(G - \alpha)L\}.R = 1$$

$$\Rightarrow \quad G = \alpha + (1/L)\ln(1/(R))$$

This value of G is equal to the ratio of photons lost as the signal travels a unit length and hence the proportion of photons lost per unit time is simply the gain G times the speed of light in the laser material, v_g. As a result the average time for which one photon will remain in the cavity is given by

$$\tau_p = 1/Gv_g$$

$$\tau_p = 1/[v_g\{\alpha + (1/L)\ln(1/R)\}]$$

[40%]

(c) Above threshold the differential efficiency is simply the proportion of photons leaving the cavity through the facets over the total number of photons, i.e.

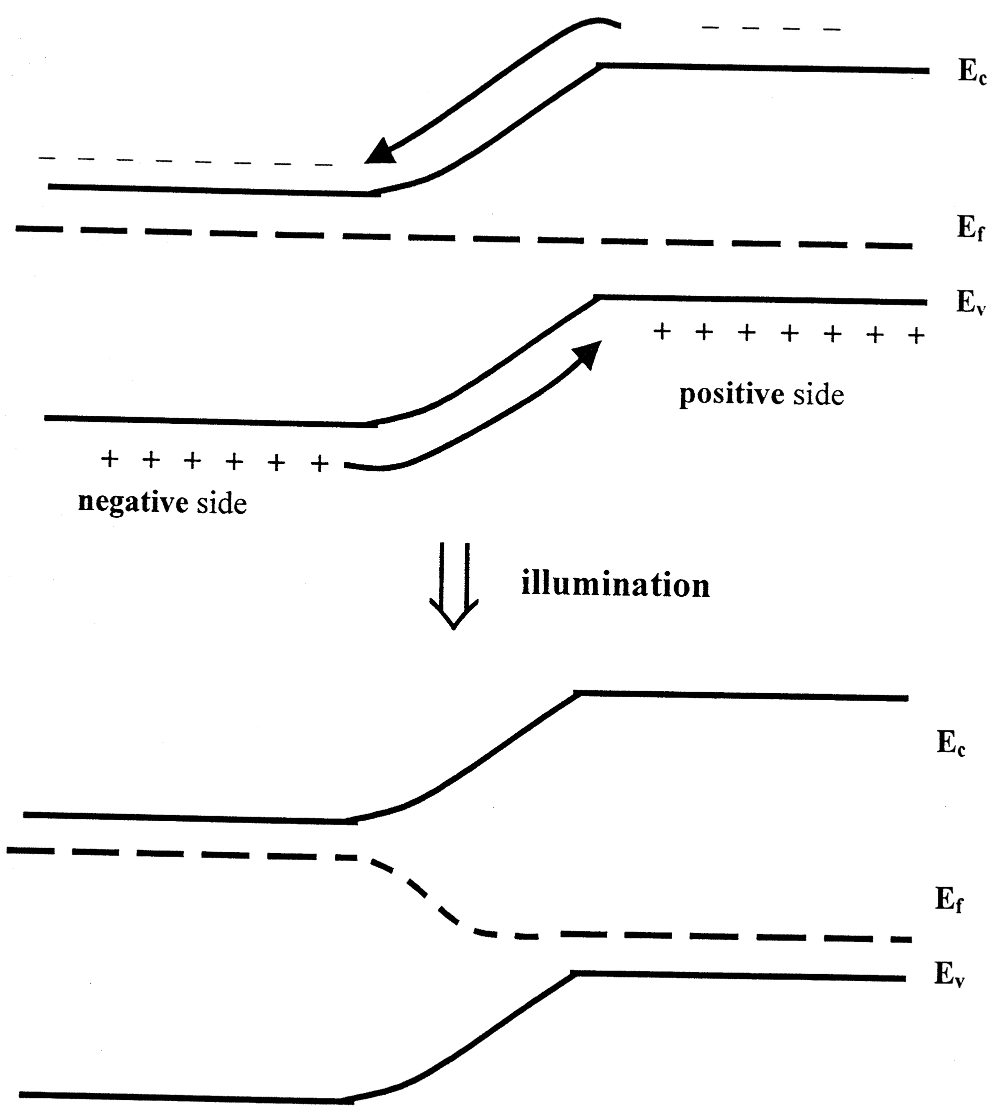
$$\eta_D = \frac{\ln(1/R)/(L)}{\alpha + \ln(1/(R))/(L)}$$

For maximum efficiency, minimise the cavity loss. Alternatively, reduce the cavity Q, though this will also lead to an increase in threshold current

[20%]

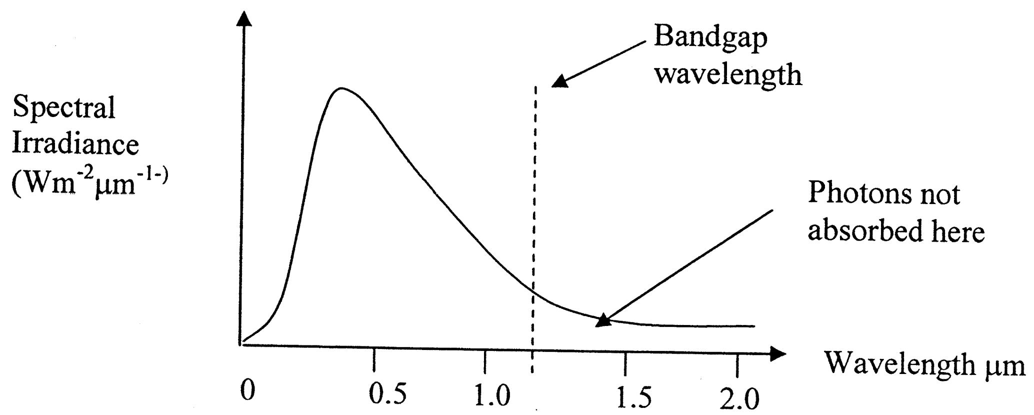
Question 3

(a) A bookwork question. The key points are as follows. Photogenerated electrons diffuse from the p side to the n side where they will accumulate (making it more negative). Holes on the n side diffuse from the p side (making it more positive). So



The bands become nearly flat ⇒ voltage (slightly less than bandgap voltage) is generated. So the solar cell can be considered as a current generator connected in parallel with a diode. **[20%]**

(b)



$$E_g = \left(\frac{hc}{\lambda_g}\right) = \frac{6.6\times10^{-34}\times3\times10^{8}}{1.1\times10^{-6}} = 1.8\times10^{-19} J$$

$$= 1.12 \text{ eV}$$

Any photon with an energy <E_g (ie with a wavelength > 1.1 μm) is not absorbed so all of the energy to the right of the dotted line in the graph is lost. All photons with energy > E_g (ie with wavelength < 1.1 μm) are absorbed and therefore produce carriers. However, energy is still wasted because the photon energy is > E_g. For example a photon with λ = 0.55 μm will lose half its energy to heat etc. Consequently the choice of bandgap wavelength is important. 1.1 μm is too great for maximum efficiency (0.8 μm is better). Material costs of higher bandgap materials (eg GaAs) don't usually justify higher efficiency c.f Si solar cells.

[25%]

(c) Open circuit $I_{ph} = I_0\left(\exp\left(\frac{eV_{oc}}{nkT}\right)-1\right)$

$$\frac{I_{ph}+I_0}{I_0} = \exp\left(\frac{eV_{oc}}{nkT}\right)$$

$$V_{oc} = \frac{nkT}{e} In\left(\frac{I_{ph}+I_0}{I_0}\right)$$

(i) $$I_{ph} = \frac{\eta e\lambda}{hc}p = \frac{0.0\times1.602\times10^{-19}\times1.0\times10^{-6}}{6.6\times10^{-34}\times3\times10^{8}}\times200\times10^{-3}$$ (photon energy is > Eg => all photons absorbed)

= 146 mA

[10%]

(ii)

$$\Rightarrow V_{oc} = \frac{1\times1.38\times10^{-23}\times300}{1.602\times10^{-19}}\ln\left(\frac{146\times10^{-3}+1\times10^{-6}}{1\times10^{-6}}\right)$$

= 307 mV

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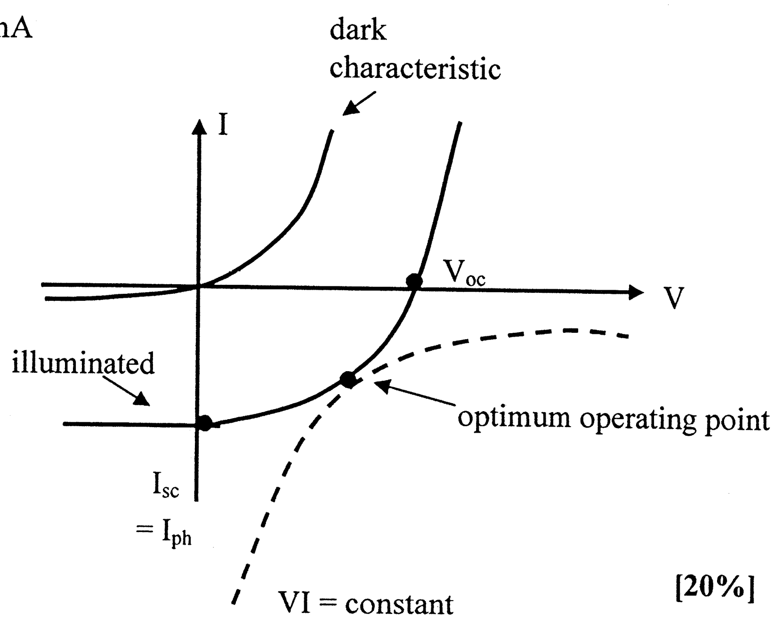
Short circuit current $I_{sc} = I_{ph}$ = 146 mA

(iii)

To generate power, solar cell must operate in lower RH quadrant. Optimum operate point is shown.



$P_{max} = V_{oc} I_{sc}$ A

= 0.307 x 0.146 x 0.65
= 29.2 mW

[20%]