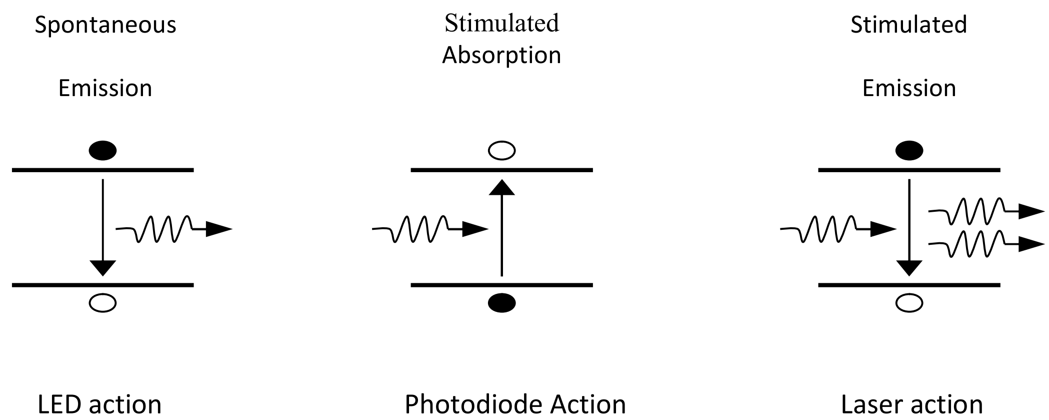
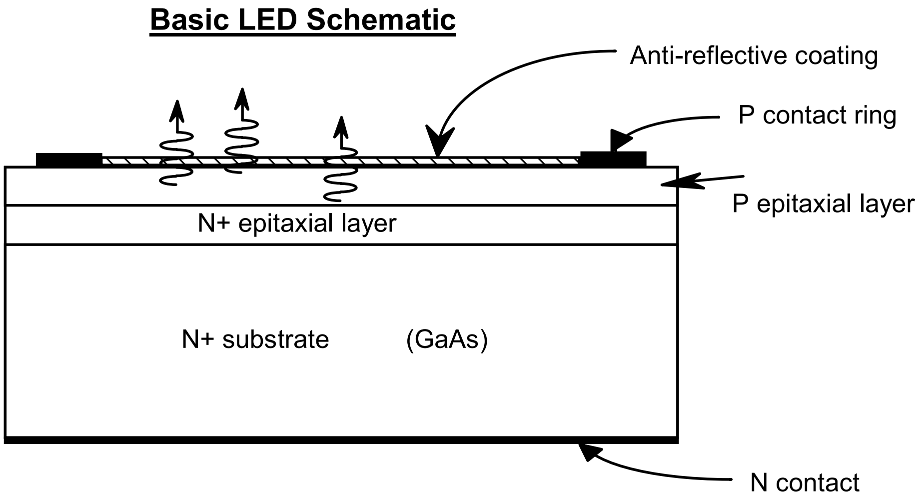
Q1: This was the most popular question and had a high average mark. It began with a qualitative question on photon-semiconductor interactions, which was well answered. Most could describe the SELED structure but almost nobody stated that the most important way to improve the efficiency was by increasing the external quantum efficiency by reducing the number of reflections at the device surface, instead concentrating on increasing the already good internal quantum efficiency. The quantitative questions linewidth, efficiency, drive voltage and lifetime were answered well.

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

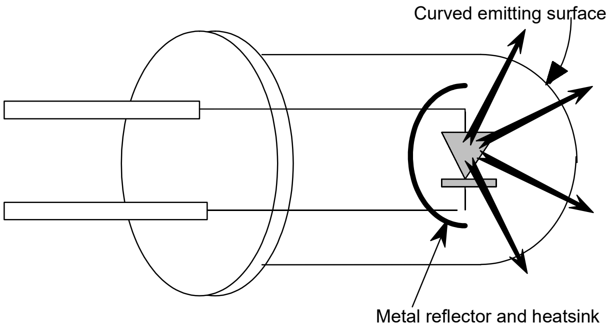


- **Spontaneous Emission**
  An electron in a high energy level falls, losing energy which is emitted as a photon – the basis of operation of a light emitting diode.
- **Stimulated Absorption**
  An incident photon is absorbed in a material, causing the excitation of an electron to a higher energy level – 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. It is used in optical amplifiers and, most commonly, in lasers (in combination with optical feedback).

(b) (i)



Light generated within the LED and leaving the chip as a ray normal to the surface is subject to partial reflection due to the refractive index change. Rays at angles greater than the critical angle will be subject to total internal reflection. Plastic encapsulated LEDs reduce this loss by the lower refractive index change at the semiconductor/plastic boundary, and by the curved surface of the plastic where emitted rays are all reasonably close to the local normal.



(ii) $\lambda = \frac{hc}{E_g} = 887.41\, nm\,,\ \Delta\lambda = 2\lambda^2 \frac{kT}{hc} = 32.04\, nm$

(iii) $\eta_{int} = \frac{\frac{1}{\tau_{rr}}}{\frac{1}{\tau_{rr}}+\frac{1}{\tau_{nr}}} = \frac{\tau_{nr}}{\tau_{nr}+\tau_{rr}} \Rightarrow\ \eta_{int} = 0.625$

$\eta = \eta_{int}\eta_{ext} \Rightarrow \eta_{ext} = \frac{\eta}{\eta_{int}} = 0.048\ \Longrightarrow\ \eta = 4.8\%$

(iv) $P_{out} = \eta \frac{hc}{\lambda}\frac{I}{e} \Rightarrow I = \frac{P_{out}}{\eta}\frac{\lambda e}{hc}\ \Rightarrow I = 238.1\, mA$

$V_{bg} = \frac{E_g}{e} = 1.4\, V$

$V_o = V_{bg} + IR_T = 1.4\, V + 238.1\ \times 10^{-3} \times 12 = 4.257\, V$

(v) drop in optical power due to temperature increase to be counterbalanced by increase of driving current

$$\frac{P(T)}{P(T_1)} = \frac{P(343)}{P(293)} = e^{-(\frac{T-T_1}{T_0})} = 0.573, \frac{I(T)}{I(T_1)} = \frac{1}{0.573} = 1.7429 \Rightarrow \Delta I = 0.7429 \cdot I(T_1) \Rightarrow \Delta V = 0.7429 \cdot I(T_1) \cdot R_T$$

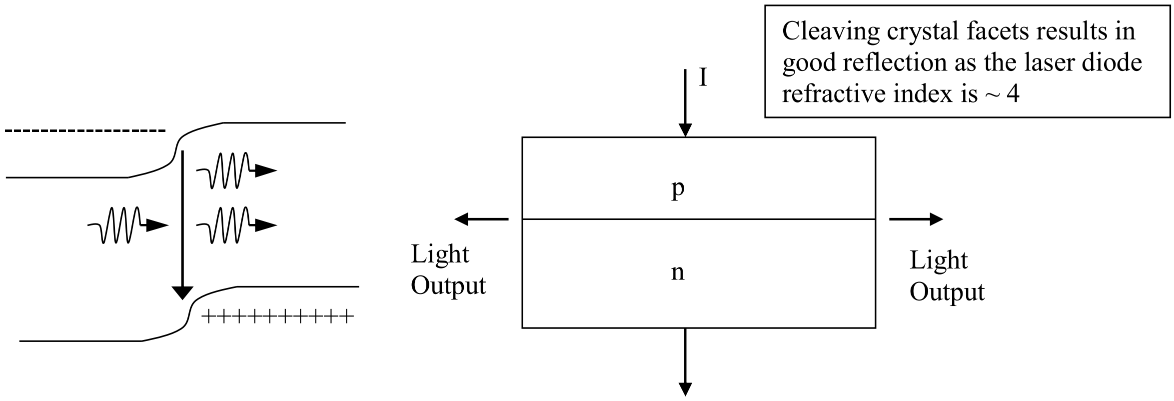
$$\Rightarrow \Delta V_0 = 2.122\ V$$

Q2: This question was attempted by the great majority of students. Overall, it was answered relatively well. The first qualitative part, on the requirements for lasing, was generally well answered. The quantitative parts, on mode spacing, mirror reflectivity and temperature dependence were quite well answered, though most students didn't answer the part on how to improve device efficiency effectively.

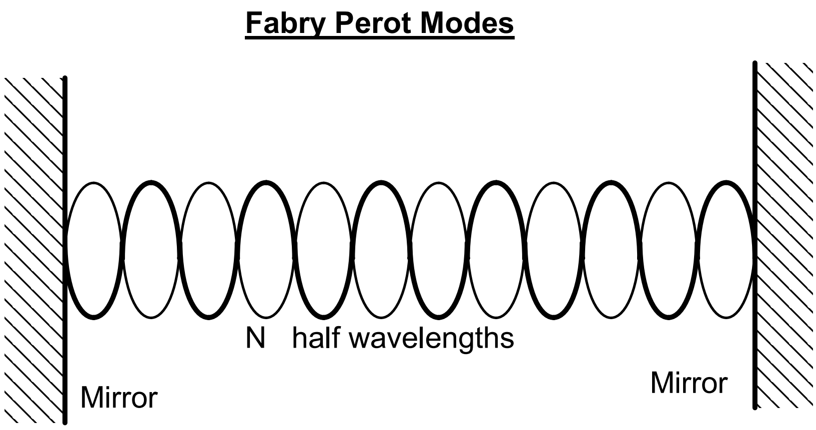
(a) In order to attain lasing action the following situations must be produced:

- A state must be obtained whereby more electrons exist in the higher electron energy level than the lower (population inversion). Such a condition may be achieved by driving a p-n junction at voltage greater than the bandgap. Here electrons will be injected directly into the conduction band and holes into the valence band so that at the junction, an incident photon is more likely to cause recombination rather than the excitation of a valence electron into the conduction band. Driving a p-n junction at such a high forward bias level can lead to very high power dissipation (10 MW/cm^3) and hence steps are generally taken to ensure that the active light generating region is kept very small.
- A method is required to ensure that the photon density in the junction is maintained at a high level. This is generally done by cleaving the p-n diode in chip form so that dielectric mirrors are formed to reflect light back into the device. Typical reflectivities are 30%.

Having a combination of a high concentration of electrons in the conduction band, holes in the valence band and photons in the diode cavity, stimulated emission is more likely than absorption and hence laser action occurs.



(b) (i) A Fabry Perot laser cavity is formed by two mirrors with power reflection set a distance, L, apart, the optical filament will oscillate at such a wavelength that nodes occur at both reflectors.



As a result, a series of different wavelengths λ_m can be supported by such a cavity where

$\lambda_m = 2L/m$.

where m is an integer. In essence, a series of optical modes that can be generated are given by

$\nu = mc/(2L)$

so that the spacing in frequency between adjacent modes, $\Delta\nu_m$, is c/2L. Note L is the optical length (so the physical length x the refractive index)

As $\nu = c/\lambda$, $|\delta\nu| = (c/\lambda^2)|\delta\lambda|$ => $|\delta\lambda_m| = (\lambda^2/c)|\delta\nu_m| = \lambda^2/c \times c/2L = \lambda^2/2L$

So $|\delta\lambda_m| = (1.3 \times 10^{-6})^2/2 \times 3.6 \times 250 \times 10^{-6} = 0.94$ nm

(ii) G is equal to the ratio of photons lost as the signal travels a unit length. 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 (i.e. gain/length x length/time). As a result the average time for which one photon will remain in the cavity is given by

$$\tau_p = 1/Gv_g$$

$= 1/\{v_g\{\alpha + (1/2L)\ln(1/R_1R_2)\}\}$ - fine to quote from data sheet

The output power from the laser may be determined readily in terms of the laser cavity photon density, P, noting that the light output from the laser is that equivalent to a loss per unit length of

$$(1/2L)\ln(1/(R_1R_2)).$$

As a result the proportion of photons leaving the cavity per unit time is given by

$$(1/2L)\ln(1/(R_1R_2)).v_g$$

=> the output power from one facet, P_{out}, is given by,

$$P_{out} = \underbrace{(1/2)}_{\text{Proportion out of one facet if both facets identical}}\underbrace{(hc/\lambda)}_{\text{Energy of one photon}}\underbrace{(PV)}_{\text{Total number of Photons in laser Density x volume}}\quad (v_g/2L).\ln(1/(R_1R_2))$$

$$=> \qquad P_{out} = \frac{hcPVv_g \ln(1/(R_1R_2))}{4\lambda L}$$

Hence above threshold the differential quantum efficiency is simply the proportion of photons leaving the cavity through the facets over the total number of photons, ie

$$\eta_D = \frac{\ln(1/(R_1R_2))/(2L)}{\alpha + \ln(1/(R_1R_2))/(2L)}$$

$$ln\left(\frac{1}{R^2}\right) = \frac{2\alpha L\eta}{(1-\eta)}$$

= 1.5, so R= 0.472 or 47.2%

(iii) $J_{th}(T) = J_0\exp(T/T_0)$ => $I_{th}(T_2)= I_{th}(T_1)\exp(T_2-T_1)/T_0$ => $I_{th}(50°C)=30\times\exp(30/90)=41.9$mA

$t_{life}= K\exp(E_a/kT)$ => $t_{life}(T_1)/ t_{life}(T_2)=\exp(E_a/k(1/T_1-1/T_2))$

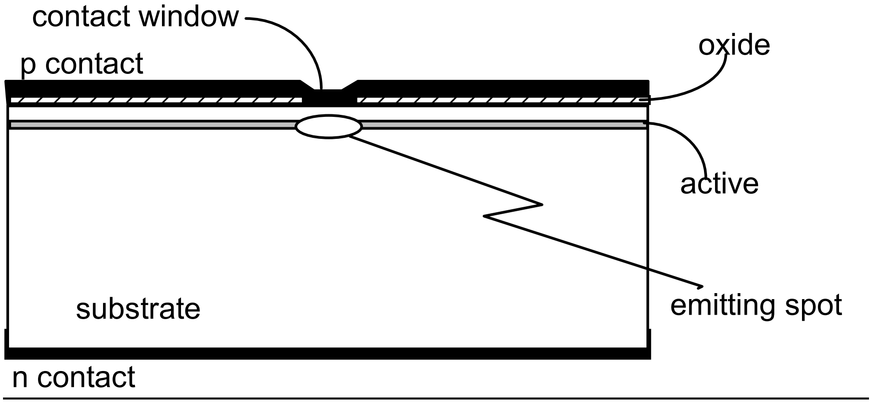
$E_a = 0.7 \times E_g = 0.7 \times 6.63 \times 10^{-34} \times 3 \times 10^8 / 1.3 \times 10^{-6} = 1.07 \times 10^{-19}$ J

$t_{life}(50°C)/ t_{life}(20°C)=\exp((1.07 \times 10^{-19}\ \text{J} /1.34\times10^{-23})(1/323-1/293))= 0.079$

$t_{life}(50°C) = 0.079 \times 25 = 1.98$ years

(c) In order to get a low threshold current, and hence high efficiency, we need to confine the current to as small an area as possible across the width of the chip, eg a typical laser with the whole chip area pumped, might have a threshold current density of 1000 A/cm^2 (10 A/mm^2) on a chip 0.5 mm long and 0.2 mm wide. In other words a current of 1 Amp. However, typically we might confine the current to a region between 1 and 2 μm wide, which will reduce the operating threshold current to 10 mA: much more compatible with high speed drive electronics. We also need the light to be confined to the area of the gain, and so need a waveguide structure which is aligned with the gain.

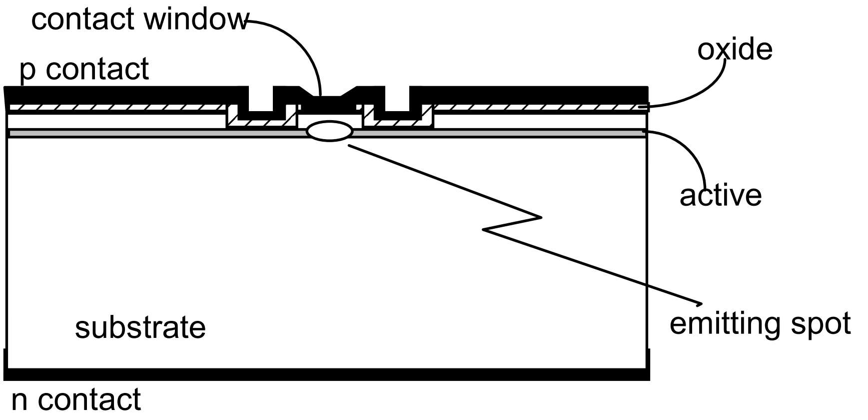
Stripe laser schematic end view



The stripe laser is simple, but current leaks out sideways, and there is no strong lateral waveguiding mechanism.

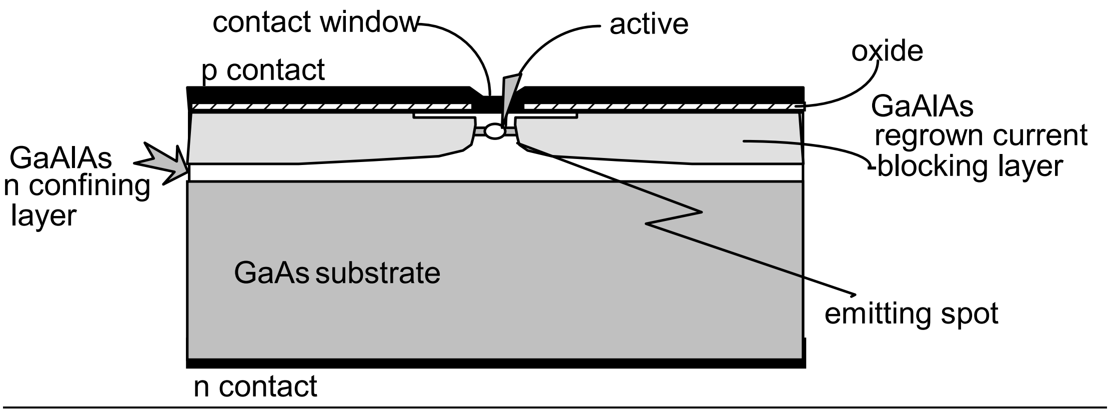
The two main FP laser structures are shown below. The buried heterostructure laser is the most efficient but is more difficult / expensive to make than the ridge laser.

Ridge laser schematic end view



The ridge laser has reasonable current confinement, and the shaped surface provides a weak but adequate lateral waveguide. This design is very widely used for telecommunications.

Buried heterostructure laser schematic end view



The Buried Heterostructure laser has excellent current confinement and waveguiding, but is difficult and expensive to make, and is not quite as reliable as the ridge laser. The current confining layers are of $Ga_{0.4}Al_{0.6}As$ doped with germanium, which gives a high resistivity. These structures are actually more popular with InP / GaInAsP materials, where good quality semi-insulating semiconductor cannot be grown, so in this case the current blocking layer consists of a p-n-p sandwich of InP, which together with the n InP of the substrate gives an n-p-n-p or "thyristor" structure which always has one reverse biased junction and blocks current under low bias conditions. It is however more expensive to make than the ridge waveguide structure as it needs at least two separate epitaxial growths.

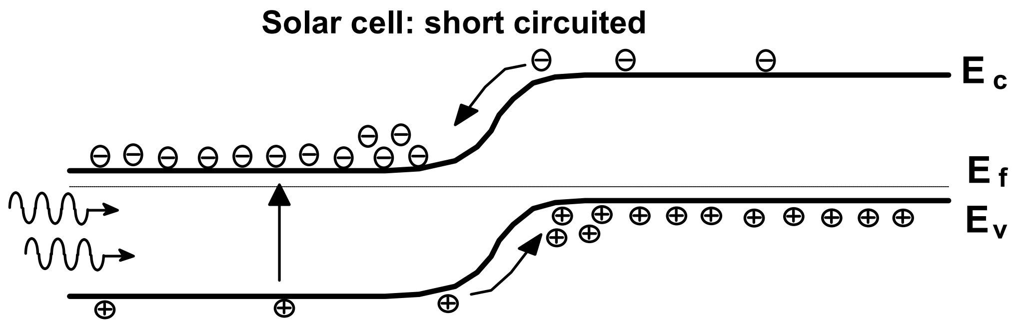
Q3: This was the least popular question but has the highest average mark. Most students were able to do the bandgap calculation and explain why the material would not be able to detect light at the specified wavelength. Most were able to calculate the minimum molar fraction of Indium that would fulfil this requirement. Most were able to describe the operation of a solar cell with the aid of band diagrams, though not all gave a complete answer. Most were able sketch the graph of the spectra irradiance of solar radiation against wavelength but some failed to correctly discuss the choice of optimum bandgap wavelength for a solar cell to maximise its efficiency. Most were able to explain whether the material would not be a good choice for a solar cell deployed on the satellite.

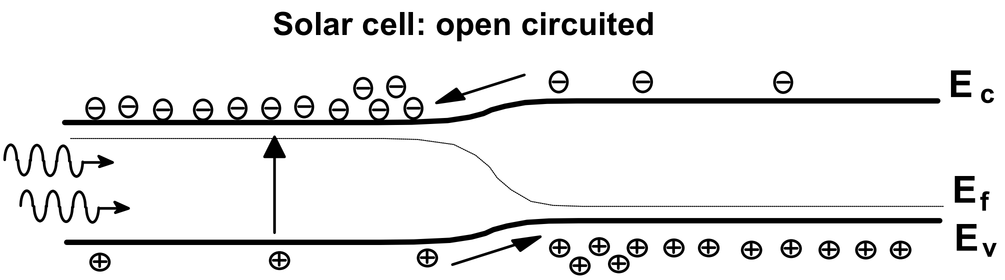
(a) (i) $E_g < E_g^{max} = \frac{hc}{\lambda} = 15.06 \times 10^{-20}\, W = 0.941\, eV$. So photon energy is less than the bandgap energy and cannot promote an electron from the valence to the conduction band of the GaAs.

(ii) $E_g^{max} = 1.424 - 1.52x + 0.39x^2, \Rightarrow x = 0.349$

(b) (i) The solar cell operates without an external power supply and relies on optical power to generate *both* current and voltage (a photodiode generates current but relies on an applied voltage).

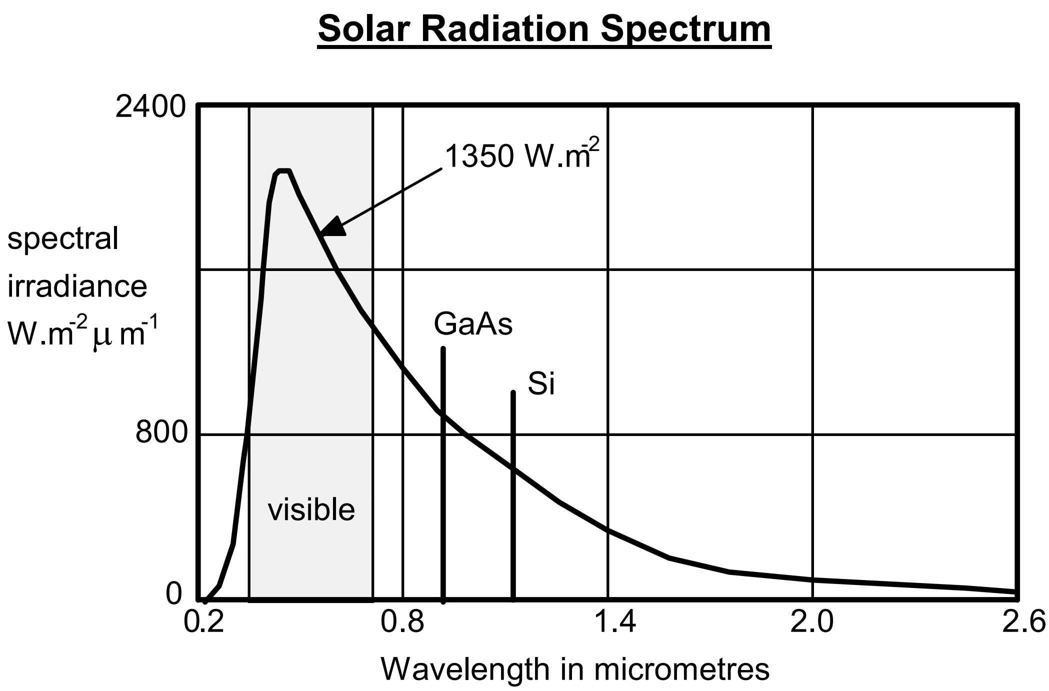
From the p side of a junction, diffusing electrons which reach the junction will be accelerated across it to the n side, where they will tend to accumulate, causing it to become more negative. Exactly the same thing happens for holes from the n side, crossing to the p side and making it more positive.





To a reasonable approximation, all the photogenerated holes on the n side reach the junction, and likewise the electrons on the p side. Their accumulations will make the p side more positive, and the n side more negative, until the bands become flat, which will be at a voltage somewhat less than the bandgap voltage. Up to this point, the solar cell may be regarded as a current generator connected in parallel with an ordinary diode (which it is composed of itself)

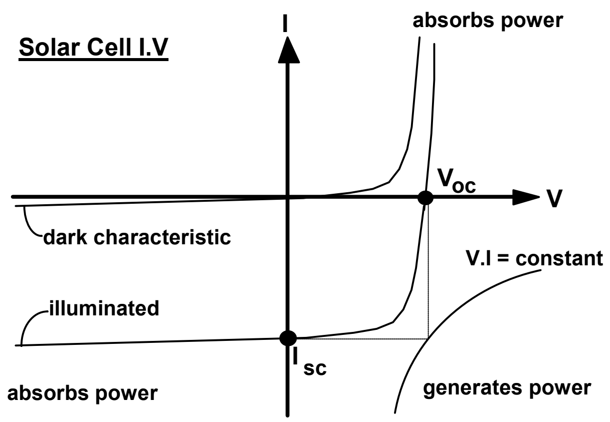
(ii) If a solar cell has bandgap energy E_g , any photons absorbed with energies > E_g will have theri excess energy wasted, and of course any photons with energies < E_g will not generate holes and electrons at all. The optimum bandgap for a solar cell therefore depends on the wavelength-intensity curve of solar radiation. Given the material has a bandgap wavelength of 1320nm, it will detect most of the light in the spectrum, but given much of the light is at much shorter wavelengths, there will be a lot of the energy wasted as heat. Silicon will be better and GaAs more so. GaAs is much more expensive but it is probably worth the extra cost given the expense of a satellite launch.



(c) (i) $I_{sc} = I_{ph} = \eta_q \frac{P\lambda e}{hc} = 833.08\, mA$

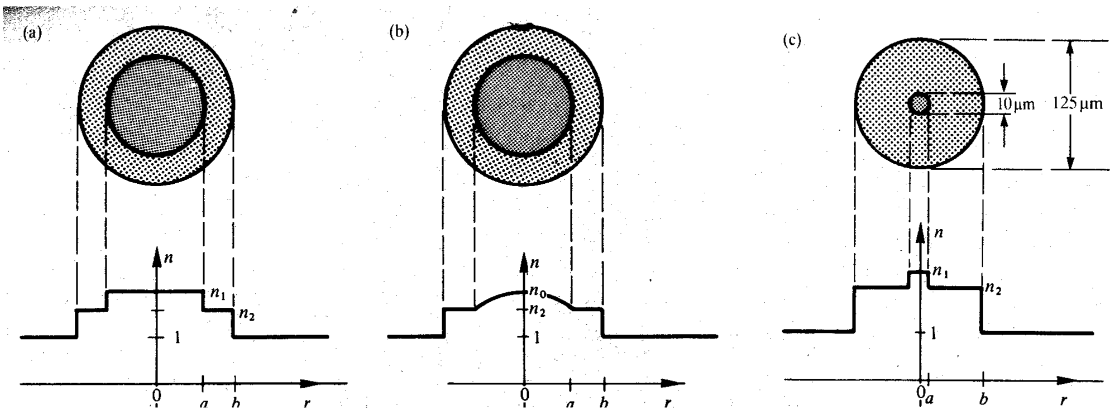
$$V_{oc} = \frac{nkT}{e}\ln(1 + \frac{I_{ph}}{I_o}) \Rightarrow V_{oc} = 0.438\, V$$

(ii) $P = \eta_{sf}\, I_{sc}V_{oc} = 219.04\, mW$



Q4: This was quite a popular question with moderately high average mark. The qualitative introductory questions were generally well answered, but the weaker students struggled. Answers to identify the best glass for a high-capacity optical fibre of a communications link were quite digital, with candidates either getting completely right or mistaking high NA for high-capacity. Most were able to calculate the maximum value of the spectral linewidth, and correctly determine the link is attenuation limited. Some students struggled on how best to improve the link length to national distances.

(a) There are three main types of optical fibre, namely step index (SI) multimode fibre, graded index multimode fibre and step index single mode fibre. The refractive index profiles are shown below. There are two main types of multimode fibre. Each of these has a core diameter typically in excess of 50μm. Step index multimode fibre is relatively cheap, easy to handle and to join together, but it does suffer from high dispersion, and therefore limited bandwidth. Graded index multimode fibre is the most expensive type but it combines the other advantages of SI multimode fibre with greatly reduced dispersion. This is the predominant fibre type used in in-building (up to 550m) applications. Finally, SI single mode fibre has a core diameter <10μm – resulting in only one mode being allowed. This means that dispersion is low but the fibres are quite difficult to handle. Because of the low dispersion, it is the only choice for long distance transmission (>2km – 10,000km).



(b) (i) core: n_{co}=1.535, cladding n_{cladd}=1.520

(ii) $NA = \sqrt{n_{co}^2 - n_{clad}^2} = 0.214,\ N \sim \frac{V^2}{2}, V = \frac{2\pi a}{\lambda} NA \Rightarrow N \sim 782$

(iii) intermodal dispersion : $\frac{\Delta t}{L} = \frac{n_{co}}{c\, n_{cl}}(n_{co} - n_{cl}) \Rightarrow \frac{\Delta t}{L} = 50.49 \frac{ns}{km}$

Output pulse width: $\Delta t_{\mathrm{out}} = \sqrt{\Delta t_{\mathrm{in}}^2 + (\frac{\Delta t}{L} \times 1\ km)^2} \Rightarrow \Delta t_{\mathrm{out}} = 58.73\ \mathrm{ns}$

(c) (i) $t_{out} = 1.3 \times t_{in}, t_{out}^2 = t_{in}^2 + \Delta t^2 \Rightarrow \Delta t_{max}^2 = 0.69\, t_{in}^2, \Rightarrow \Delta t_{max} = 0.83\, t_{in} = \frac{0.83}{R} =$ $83.06\, ps$

$\Delta\lambda_{max} = \frac{\Delta t_{max}}{D\, L} = 0.04\, nm$

(ii) attenuation limit

Received power at length Lmax

$$P_{Rx}(dBm) = P_{Tx}(dBm) - Tot_{Loss}(dB) - Mod\ Penalty\ (dB) - Margin\ (dB)$$

Total link loss includes attenuation (0.22 dB/km × L), and splice losses (0.5 dB)

Minimum power at the receiver is equal to receiver sensitivity (-24 dBm)

$$-24 = 5 - 0.22 \times L_{max} - 2 - 0.5 - 3 = -0.5 - 0.22 \times L_{max}$$
$$\Rightarrow L_{max} = 106.8\ km$$

This is less than the dispersion limit of 120km and so link is attenuation limited.

(iii) To do this both dispersion and attenuation limit need to be extended.

Dispersion – reduce modulated linewidth of laser by using e.g. a DFB, though 0.04nm is close to Fourier limited at 10Gb/s. Use dispersion compensating fibre if necessary to overcome the dispersion of the standard SMF

Attenuation. The fibre dispersion is already low so only option is to boost power, perhaps at launch but more likely by periodically amplifying using an EDFA