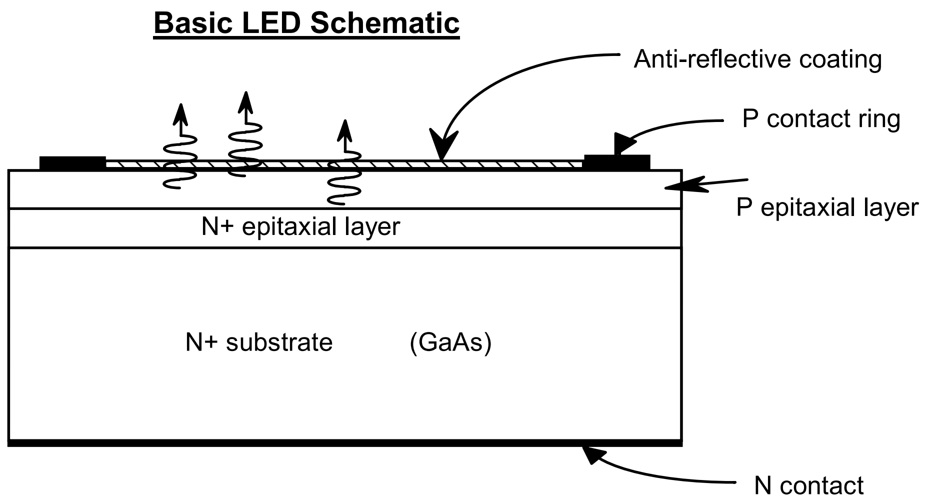
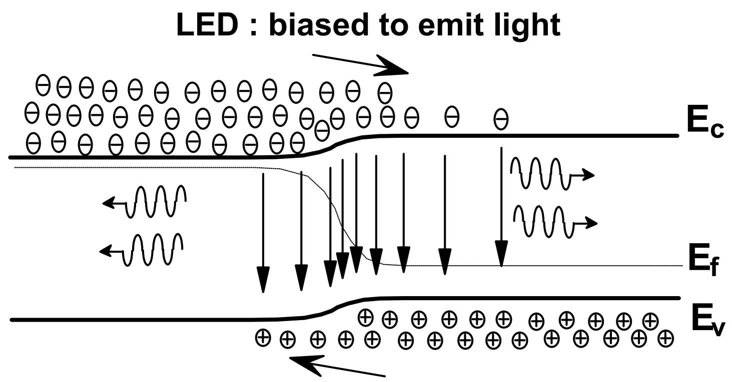
**3B6 Photonics Technology 2023 Crib**

1. (a) Bookwork. In its simplest form, a light emitting diode consists of a p-n semiconductor junction at which electrons and holes recombine to generate photons by spontaneous emission. The basic SELED structure is shown below.




All LEDs must have a junction, and therefore be compatible with P and N doping. Also indirect materials are likely to be inefficient at best.



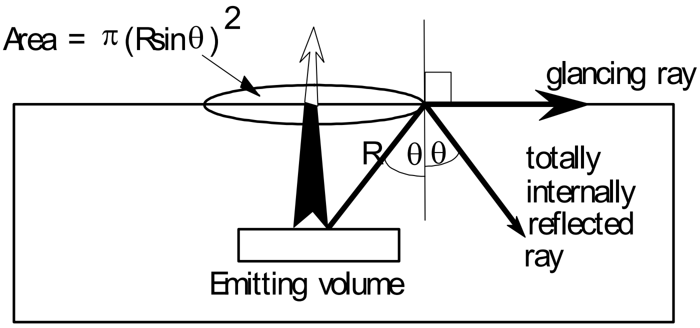

The optical output power, P, from the LED may be determined as a function of the current by considering the emission process. In a perfect system, one photon is generated by one electron. In a typical LED however only a fraction of the electrons which recombine generate a photon. Hence an efficiency, η is defined as the ratio of the number of photons generated per unit time to the number of electrons injected into the LED per unit time. Hence

P = photon energy × quantum efficiency × number of injected electrons

$$= \left(\frac{hc}{\lambda}\right)\eta\frac{I}{e}$$

The Quantum Efficiency, η, has two main parts, namely an Internal Quantum Efficiency, ηint, (defining the efficiency of generation of a photon following injection of an electron into an LED), and External Quantum Efficiency, ηext, (defining the efficiency of extracting generated photons from the LED in a well defined beam).

The internal efficiency is usually rather high (80-90%). However 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.

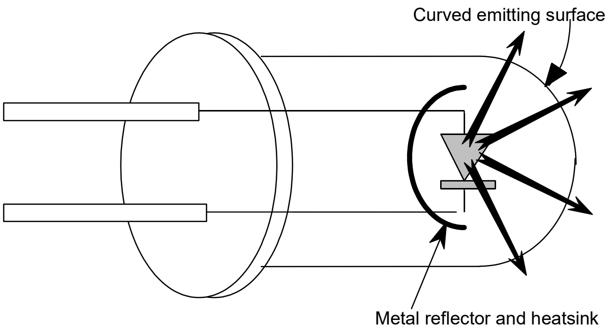



The proportion of light leaving a flat surfaced LED into air can be shown to be

$$\eta_{ext} = \frac{1}{4}\left(\frac{n_a}{n_s}\right)^2 \cdot \left[1 - \left(\frac{n_s - n_a}{n_s + n_a}\right)^2\right]$$

with a typical semiconductor refractive index of 4, this works out to a few %.

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.

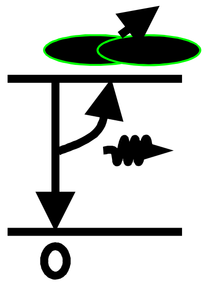



b) Heat dissipation problems can be severe in semiconductor optoelectronic light emitting devices. For example, at room temperature the thermal conductivity of GaAs is 44 W/(mK). A current density of 500 $A/mm^2$ will cause a 50°C rise in temperature for a standard LED device.

Light emitting diodes emitting at either 0.8 μm wavelengths (GaAs/GaAlAs devices) or at longer 1.3 μm wavelengths (InGaAsP material) suffer from saturation of the output optical power at high temperatures and drive levels. This is due to a variety of effects:

- Current leakage across the junction and the junction resistance both increase with drive and temperature.

- By increasing the current drive and operating temperature, increased charge carrier concentrations occur in the conduction band. This can lead to enhanced non-radiative recombination such as Auger recombination where one electron falling from the conduction band gives its energy to another electron in the conduction band rather than to generate a photon. As less light is generated the LED efficiency falls.



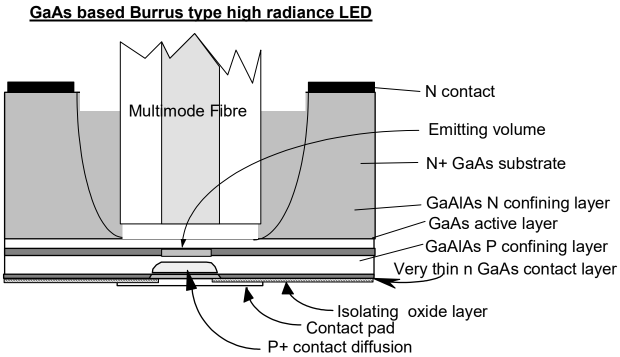
Temperature effects in LEDs with built-in heterostructures have been found to obey approximately the following relationships:

(a) The output power P(T) at a temperature T may be related to that at temperature $T_1$ and power $P(T_1)$ as $P(T)/P(T_1) = \exp[-(T - T_1)/T_o]$ where $T_o$ is a constant for a given device, and depends upon the LED structure. Typically $T_o$ is around 100 K for long (1.3 μm) wavelength devices.

(b) The output optical power ($P_T$) from an LED operating at a temperature T may be written as a function of operating time (t) as $P_T(t) = P_T(0) \exp(-\beta t)$

where $\beta = \beta_0 \exp(-E_a/kT)$. $E_a$ is the activation energy of the ageing process and is typically around 1 eV for long wavelength devices.k is Boltzmann's constant.The lifetime of an LED can therefore change by 60% for a 10°C change in temperature.

Heat effects can be reduced by better heatsinking. The 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.



(c) i) $1/\tau_s = 1/\tau_{rr} + 1/\tau_{nr}$ so

$\tau_s = 1 / (1/3 + 1/8) = 2.18$ ns

$\eta_{int} = (1/\tau_{rr})/(1/\tau_{rr} + 1/\tau_{nr})$

so $\eta_{int} = 1/3 / (1/3 + 1/8) = 0.73$

ii) $P_{out} = \eta \frac{hc}{\lambda}\frac{I}{e} \Rightarrow I = \frac{P_{out}}{\eta}\frac{\lambda e}{hc} \Rightarrow I = 23.5 \ mA$

$$V_{bg} = \frac{h\ c}{e\lambda} = 1.46 \ V$$

$$V_o = V_{bg} + IR = 1.46 \ V + 23.45 \times 10^{-3} \times (2 + 0.5) = 1.52 \ V$$

Overall efficiency (so called wallplug efficiency) = Optical power/supplied electrical power
= 1mW/23.45 x $10^{-3}$ x 1.52 = 2.8%

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

$$\frac{P(T)}{P(T_1)} = \frac{P(378)}{P(293)} = e^{-(\frac{T-T_1}{T_0})} = 0.466, \ \frac{I(T)}{I(T_1)} = \frac{1}{0.466} \Rightarrow I(T) = \frac{I(T_1)}{0.466} = 50.38 \ mA$$

$$V_{(T1)} == 1.46 \ V + 50.38 \times 10^{-3} \times (2 + 0.5) = 1.59 \ V$$

iv) $\Delta\lambda \sim 2kT\lambda^2/hc$

20 °C . $\Delta\lambda = 29.4$ nm

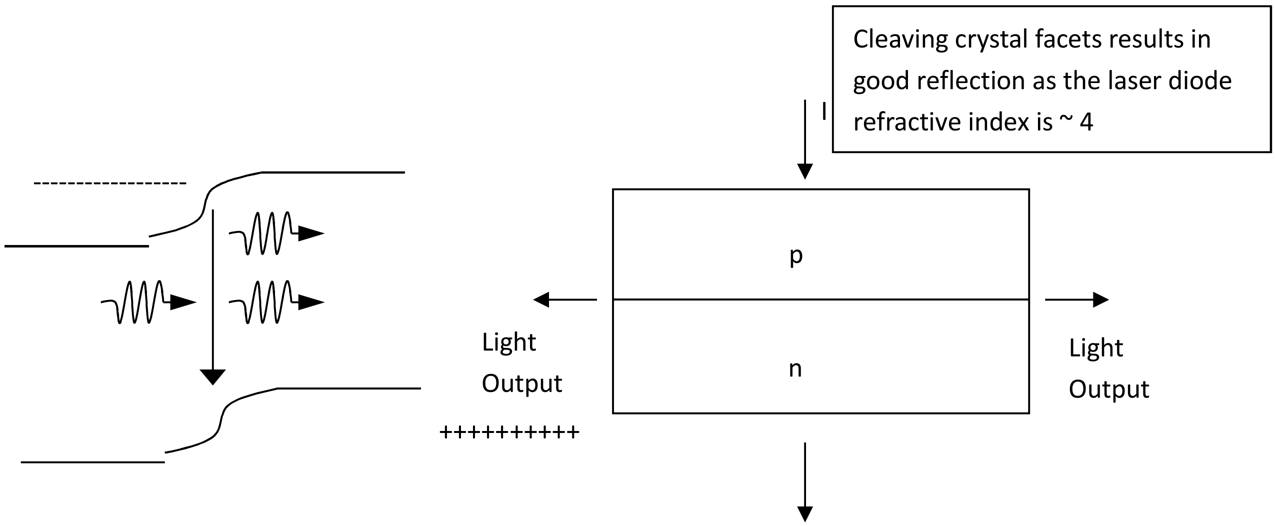
85 °C . $\Delta\lambda = 35.9$ nm

2. (a) In order for a system to lase, two main conditions must be achieved, (i) stimulated amplification must be stronger than absorption so that any optical signal is rapidly amplified in power, and (ii) some form of optical feedback must be provided so that lasing light generated can in part be fed back so that stimulated amplification can continue to occur, thus causing sustained stimulated emission and hence lasing output.

To achieve continual net stimulated amplification, there must be a larger numbers of free carriers in the upper level than the lower level so that a photon is more likely to stimulate the emission of another photon rather than be absorbed. This therefore requires a "population inversion" to be created as normally carriers gather at the lowest possible energy levels.

As a result of these requirements, in a typical laser system, much more care must be taken to ensure that the light does not scatter or "leak" out of the lasing region. It is also important to ensure that an optical cavity is bounded by reflectors, so that a lasing filament is formed which oscillates back and forth within the cavity, and that the generated light is confined to cause further stimulated emission. By using partial reflectors, some of the light is emitted from the cavity as the output from the laser.

(b) The diode injection laser is now the most common form of optical source used in fibre communication systems. 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/cm3) and hence steps are generally taken to ensure that the active light generating region is kept very small.

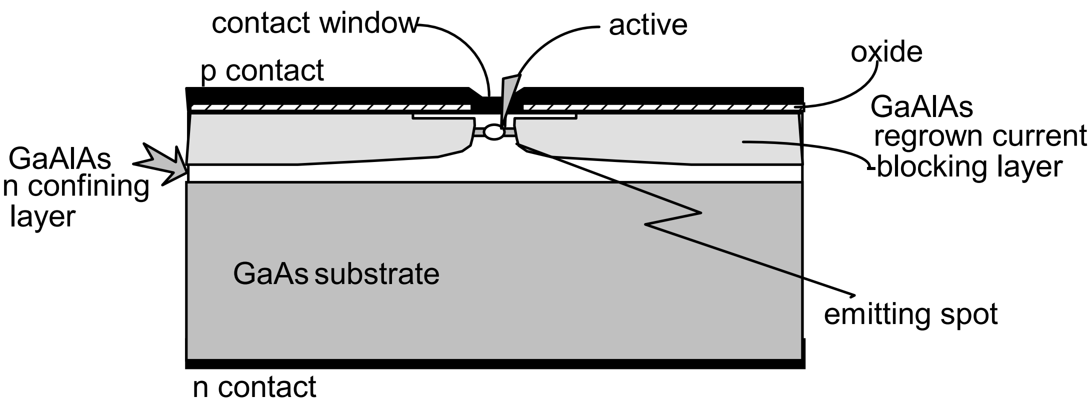
- A method is required to ensure that the photon density in the junction is maintained at a high level. This is generally done by cleaving the p-n diode in chip form so that dielectric mirrors are formed to reflect light back into the device. Typical reflectivities are 30%.

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.

At long wavelengths, no absorption or gain occurs, and at short wavelengths the material always absorbs, but near the wavelength corresponding to the bandgap increasing, forward bias will take the material from loss to gain.

To make the laser more efficient, it is important to confine both carriers (so that the threshold carrier concentration can be reached at moderate currents) and photons (so the photons are confined to the same volume where there is gain). This is done best in the buried heterostructure laser where the heterostructure provides both carrier confinement and optical waveguiding in both vertical and lateral operation.

**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 Ga0.4Al0.6As 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.

The formation of such a cavity, however, has a major effect on the form of optical spectrum generated. This can be understood by considering Fig. 2. If the 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.

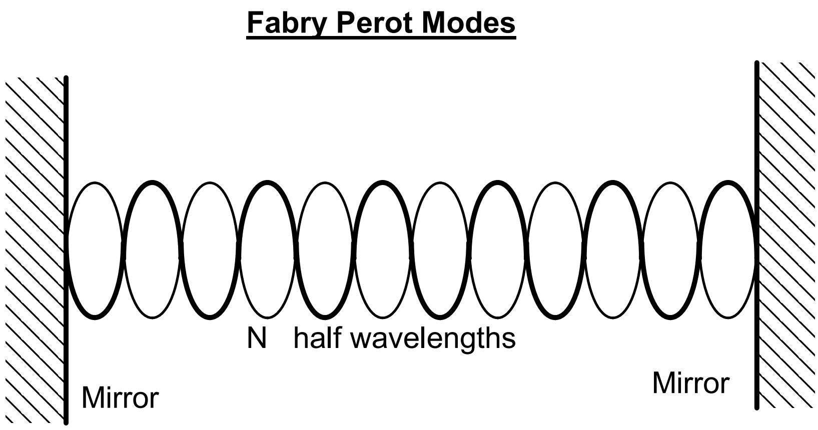



Fig. 2

It should be noted, however, that wavelengths are only generated if electronic transitions occur with the necessary energy spacing. However, a range of optical lasing modes can be generated simultaneously if a range of energy levels are available. By meeting both these requirements, lasing action is achieved.

(c) i) From diagram in (b) the lasing wavelength needs to sataisfy the condition that there is an integer number of half wavelengths in the cavity (NB L is optical length)

$$\lambda_m = 2L/m.$$

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.

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

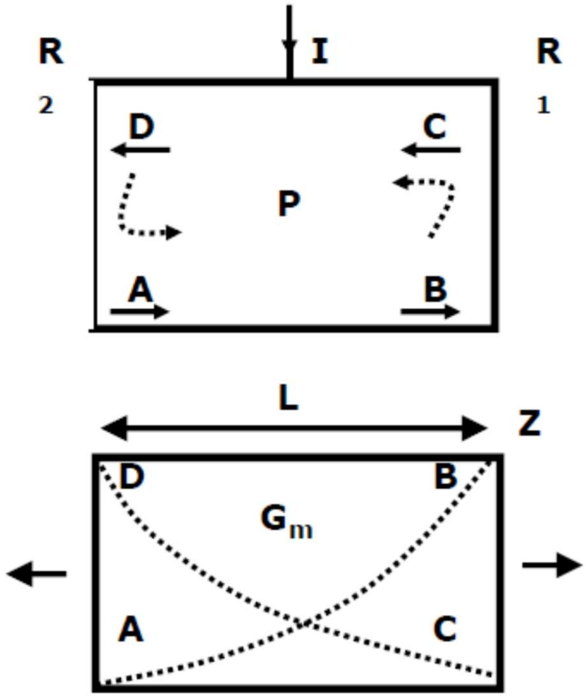
ii) $|\delta\lambda_m| = \lambda^2/2L = (1.3 \times 10^{-6})^2 / 2 \times 3.3 \times 400 \times 10^{-6} = 0.64$ nm

iii) 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.

$dP/dz = G_m P$

=>

$P(Z) = P(o)\exp(G_m z)$




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, $\alpha$, 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 light A starting at one facet will be incident on the opposite facet with an optical power

$B = \exp\{(G - \alpha)L\} A$

At that point part of the signal is reflected with a coefficient R and the signal then passes back amplified by 1 the same amount as above and again reflected by the initial facet. Lasing action will occur in the net round trip gain of the signal is unity i.e. if

$A. \exp\{(G - \alpha)L\}.R1\exp\{(G - \alpha)L\}.R2 = A$

$=> G = \alpha + (1/2L)\ln(1/(R1R2))$ [N.B. Gain/unit length]

Effective gain needed to overcome facet losses

$G = 15\ cm^{-1} + (1/2 \times 0.04)\ \ln(1/0.32^2) = 43.5\ cm^{-1}$

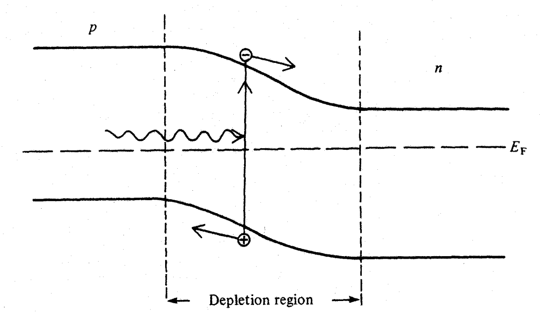
d) This value of G is equal to the ratio of photons lost as the signal travels a unit length. Hence the proportion of photons lost per unit time is simply the gain G times the speed of light in the laser material, $v_g$ (i.e. gain/length x length/time). As a result the average time for which one photon will remain in the cavity is given by

$$\tau_p = 1/Gv_g$$

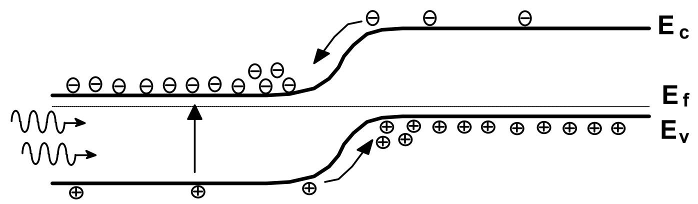
$$= 1/\{v_g\{\alpha + (1/2L)\ln(1/R_1R_2)\}\}$$

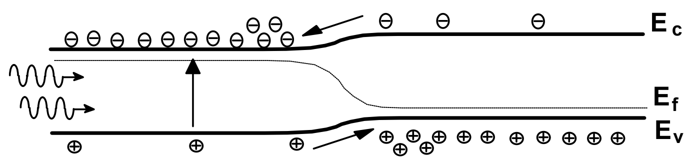
= (3.5/3 x $10^8$) x (1 / ( 4350 + (1/400x$10^{-6}$)ln(1/0.32)) = 2.53 ps

3. (a) The answer to this question can be primarily found from handout. A good answer should cover the following points: The photodiode is a reverse biased diode, made from an appropriate material, which converts an optical signal into an electrical form. The important design and device parameters for a photodiode are: 1. Responsivity in Amps per Watt (varies with wavelength) + linearity. 2. Sensitivity: ie minimum detectable power in Watts (varies with modulation frequency). 3. Sensitive area in m2. 4. Capacitance. 5. Dark current. 6. Bias requirement. 7. Speed of response etc.

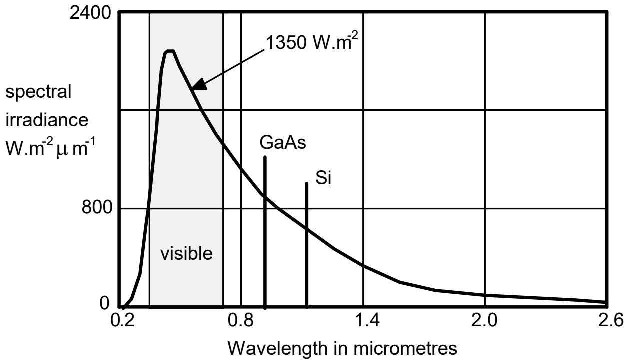



An important application of a pn diode is to convert optical energy to electrical energy in a solar cell. The solar cell operates without an external power supply and relies on optical power to generate both current and voltage (a photodiode generates current but relies on an applied voltage). A solar cell typically doesn't have to be fast and needs to collect as much sunlight as possible and so it has a large area. To generate power it operates in the bottom RH quadrant of the VI characteristic.




(b)




If a solar cell has bandgap energy Eg , any photons absorbed with energies > Eg will have their excess energy wasted, and of course any photons with energies < Eg 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. Silicon is quite good: GaAs is slightly better, but not usually worth the extra cost.

(c) For Material #1 – most photons will be absorbed but energy > Eg will have excess energy dissipated. For Material #2, it will absorb virtually all solar photons. Both materials have similar quantum efficiency. However, Material #2 will have a lower efficiency as most photons will have Eg much smaller than Eph. Hence Material #1 is the better material choice to be used in the solar cell.

(d) Appropriate credit will be given if the wrong material choice is made in part (b) and the below analysis is completed with incorrect data.

(i) $P = 2\ m^2 \times 1.2\ kW\ m^{-2} = 2.4\ kW$;

$I_{ph}=\eta eP/(hc/\lambda)$,

$I_{ph}=1546$ A

(ii) Calculate the maximum power that can be generated. Assuming the shape factor is 0.7.

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

Open circuit voltage

$$V_{oc} = \frac{nkT}{e} \ln \frac{I_{ph} + I_0}{I_0}$$

$$V_{oc} = \frac{1.1 \times 1.38 \times 10^{-23} \times 300}{1.602 \times 10^{-1}} \ln\left(\frac{1546 + 10 \times 10^{-6}}{10 \times 10^{-6}}\right) = 0.536V$$

$P=A\ I_{sc}\ V_{oc}= 0.7 \times 1546 \times 0.524 = 580$ W

(e) A good answer should cover the following points: 1. Use a material with a similar bandgap but with a higher quantum efficiency. 2. Use a solar cell with a larger illumination area. 3. Use a material with a higher shape factor.

4. (a) The ray is critically guided and propagates along the fiber by means of multiple internal reflections provided that the angle of incidence on to the core-cladding interface is greater than the critical angle. This requires that the angle of obliqueness to the fiber axis, $\theta = \pi/2 - \phi$ be less than $\theta_m = \pi/2 - \phi_c$, and that the angle of incidence, $\alpha$, of the incoming ray on to the end face of the fibre be less than a certain value, $\alpha_m$. In order to calculate $\theta_m$ and $\alpha_m$, we apply Snell's law at the fibre facet for the critical ray.

$$n_a \sin\alpha_m = n_1 \sin\theta_m = n_1 \cos\phi_c$$

We can then derive

$$\cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

and so $\sin\alpha_m = \dfrac{\sqrt{n_1^2 - n_2^2}}{n_a}$

The greater the value of $\alpha_m$, the greater is the proportion of the light incident on to the end face that can be collected by the fibre and propagated by total internal reflection. By analogy with the term used to define the light-gathering power of microscope objectives, $n_a \sin\alpha_m$ is known as the numerical aperture (NA) of the fiber. Thus,

$$NA = n_a \sin\alpha_m = \sqrt{n_1^2 - n_2^2} = \sqrt{2n\Delta n}$$

(b) Consider a diffuse light source such as an isotropic radiator (also known as a Lambertian source). The power radiated per unit solid angle for such a source at an angle $\theta$ to the normal of its surface is given by

$$I(\theta) = I_0 \cos\theta$$

The total power emitted by such a source is found by integrating over all forward directions ie

$$P_0 = \int_0^{\pi/2} 2\pi I_0 \cos\theta \sin\theta d\theta$$
$$= \pi I_0$$

The power that can be collected by a fibre is given by

$$P = \int_0^{\alpha_m} 2\pi I_0 \cos\theta \sin\theta d\theta$$
$$= \pi I_0 \sin^2\alpha_m$$

Thus the collection efficiency is given by

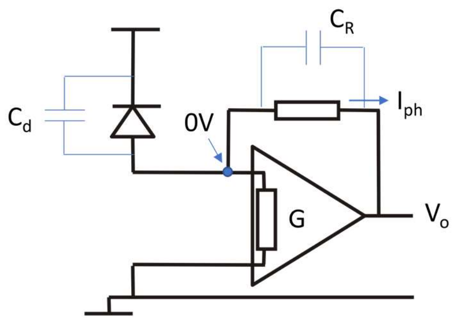
$$\frac{P}{P_0} = \sin^2\alpha_m = \frac{n_1^2 - n_2^2}{n_a^2}$$

When the outside medium is air, $n_a = 1$ and so the collection efficiency becomes $n_1^2 - n_2^2$

In order to maximise the fibre collection efficiency, it is necessary to maximize $n_1^2 - n_2^2$, and so cladding will be the glass with 1.51 refractive index while the core will be the one with 1.55

refractive index. The collection efficiency will be 12.24%.

(c) (i) Calculate the receiver bandwidth.




$$V_{out} = \frac{-I_{ph}R_f}{1 + j\omega(\frac{C_d}{G} + C_r)R_f}$$

$$f = \frac{1}{2\pi(\frac{C_d}{G} + C_r)R_f} = 7957.75\ \ MHz = 7.96\ \ GHz$$

(ii) Since SNR is thermal noise limited, shot noise can be ignored.

$$SNR = \frac{(\eta\frac{e\lambda P}{hc})^2}{4kTB/R_f} = 20\ \ dB = 100$$

$$=> \quad (\eta\frac{e\lambda P}{hc})^2 = 1.3178 \times 10^{-10}$$

$$=> \quad P = 1.1477 \times 10^{-2}\ \ mW = -19.4\ \ dBm$$

(d) (i) Assuming dispersion limited:

$\Delta t_{smf}$ = D L Δλ = 17 × L × 0.2 = 2.55L ps;

Bit period = 1 / (10×$10^9$) = 100 ps;

Output pulse width = 100 × 1.25 = 125 ps;

$t_0^2 - t_{in}^2 = \Delta t_{smf}^2$

$125^2 - 100^2 = (2.55L)^2$, L = 29.41 km.

Assuming attenuation limited:

Coupling efficiency 12.24% => -9.12 dB

-19.4 dBm = 0 dBm – 9.12 – 2 – 2 – 0.25L, L=25.12 km.

The link is attenuation limited.

(i) What is the maximum fibre transmission distance?

L=25.12 km