PART IIA 2006
3B6: Phototonic technology
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PHOTONICS TECHNOLOGY, 3B6,

Datasheet: Photonic Technology Data Sheet

Q1 (a) The answer is primarily bookwork and should highlight the direct dependence of emission wavelength on material bandgap. The material composition itself therefore must be selected for specific applications.

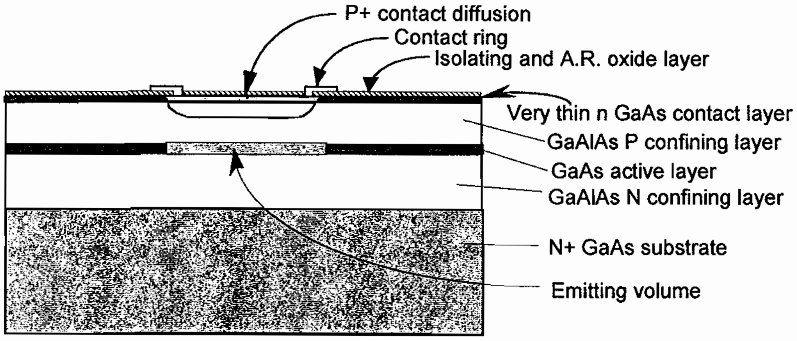
A good answer could include descriptions of the use of compound materials to allow engineering of emission wavelength.

The answer should explain the impact that direct and indirect bandgap materials have on emission efficiency and hence how direct bandgap materials are preferred. [10%]

(b) This again is primarily bookwork. A good answer should provide detailed descriptions of surface- and edge-emitting light emitting diodes. This might include:

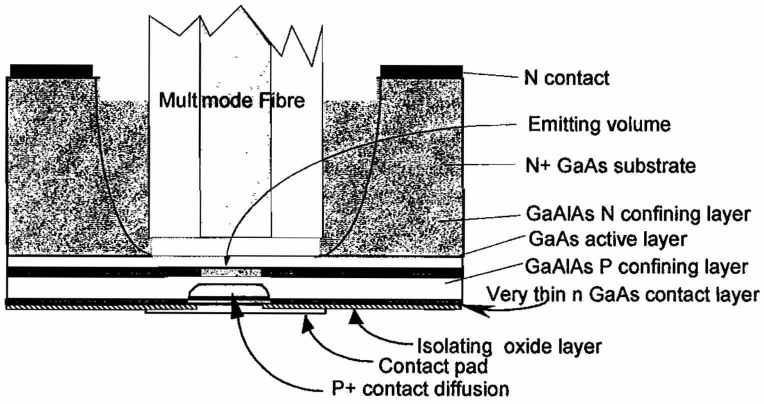
1 SURFACE EMITTING LED STRUCTURES

GaAs based double heterostructure LED



A good answer should explain the basic principles of the structure and perhaps comment on the different materials used for short and long wavelengths, and the Burrus structure.

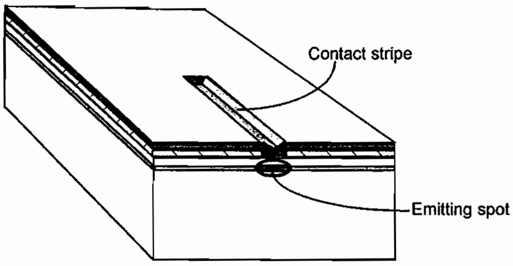
GaAs based Burrus type high radiance LED

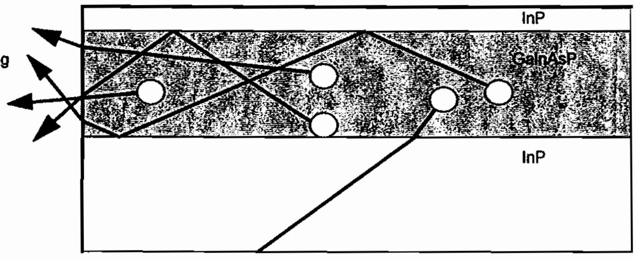


The Burrus diode has much of the substrate etched away: this allows high coupling into a multimode fibre, sometimes a spherical micro-lens is interposed as well. In addition, the heat generation is close to the p surface which can be bonded directly to a heatsink and the contact metal also reflects some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

2 EDGE EMITTING LEDS

A typical answer should explain the structure of the device, detailing the action of the heterostructure.





The answer should include typical advantages and disadvantages of the light emitting diodes for example that the surface emitting device generates well defined circular beams and is easy to use while the edge emitting device has much greater radiance, and is better at coupling light into single mode fibres. [30%]

(c) (i) The light emitting diode equation can be shown to be

$$I = e P \lambda / (h c \eta_i \eta_e)$$

The circuit equation is V = forward voltage + I x R

$$= [hc/e\lambda] + e P \lambda / (h c \eta_i \eta_e) \times R$$

$$= \underline{1.61\ \mathrm{V}}$$

[20%]

(ii) The light emitting efficiency may be shown to be

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

$$\Rightarrow \tau_{nr} = \tau_{rr} \eta_i / (1 - \eta_i) = 4.67\ \mathrm{ns}$$

The overall response time, $\tau = 1/ ((1 / \tau_{rr}) + (1 / \tau_{nr})) = 1.4$ ns

$\Rightarrow$ The bit rate $B = 1/(1.4\,\tau) = \underline{510\ \mathrm{MHz}}$ [20%]

(iii) The linewidth is assumed to be dominated by thermal effects so that the range of emission energies is given by

$$\Delta E = 2kT = h|\Delta f| = (hc/ \lambda^2).|\Delta\lambda|$$

$$\Rightarrow T = hc.\ |\Delta\lambda|/(2k\,\lambda^2) = 399\ \mathrm{K}\ \text{or}\ \underline{126\ ^{\circ}\mathrm{C}}$$

[20%]

Q2 (a) This is primarily a bookwork question.

In describing conditions for diode lasing, a typical answer should indicate that 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 the lasing light generated, can in part be fed back so that stimulated amplification can continue to occur, thus causing sustained emission and hence lasing output.

In order to achieve good power efficiency, good confinement of current injection and minimisation of unwanted optical losses must be achieved. A good answer will list some structures that can be used in laser diodes to achieve this.

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.

The formation of such a cavity, however, has a major effect on the form of optical spectrum generated.

The question concerning the dependence of laser diode performance on temperature again requires largely bookwork. As temperature strongly affects the recombination in a pn junction, it will affect the current required to ensure the high electron charge density necessary in the conduction band for lasing operation. For example, if the temperature increases, the normal time for a carrier to exist in the conduction band before spontaneously falling to the valence band reduces and more current is needed to maintain required charge levels for lasing. The threshold current can be shown to vary with temperature as

$$J_{th}(T) = J_o \exp(T/T_o)$$

where T_o is typically 150 K for GaAs lasers and 70 K for InGaAsP lasers. For small variations in temperature (20°C), η_D may be regarded as constant. The slope efficiency of the device is relatively unaffected as this is dominated by features which are less affected by temperature. At elevated temperatures however, this also does reduce. [20%]

(b) (i) The output power equation for the laser diode can be written as

$$P = hc\eta_D(I - I_{th})/(e\lambda)$$

$\Rightarrow$ the operating current, $I = I_{th} + Pe\lambda(hc\eta_D) = \underline{30\text{ mA}}$ [15%]

(ii) Let $I_{th1} = 20$ mA at $T_1 = 293$ K

$$\Rightarrow I_{th1}/I_{th2} = \exp\{(T_1 - T_2)/T_o\}$$

$$\Rightarrow T_2 = T_1 + T_o \ln(30/20) = 293 + 100 \ln(3/2) = 333\text{ K} = \underline{60\,^{o}\text{C}}$$ [20%]

(iii) This is a bookwork question.

Assume that in a Fabry Perot laser diode, 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.

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 if the net round trip gain of the signal is unity ie if

$$A.\exp\{(G - \alpha)L\}.R_1.\exp\{(G - \alpha)L\}.\,R_2 = A$$

$$\Rightarrow G = \alpha + (1/(2L))1n(/R_1R_2))$$

The gain overcomes the internal losses and the facet losses. As the latter represent useful output power, the differential quantum efficiency is the facet loss over the total loss, ie

$$\eta_D = (1/(2L))1n(1/R_1R_2)) / [\alpha + (1/(2L))1n(1/R_1R_2))]$$ [20%]

(iv) Assume that there are no leakage currents to degrade quantum efficiency, and $\eta_D = 60\%$

But $\eta_D = \alpha_f / (\alpha_f + \alpha)$ where α_f is the facet losses.

$$\Rightarrow \alpha_f = \eta_D\, \alpha/(1 - \eta_D) = 7.5\ /\text{cm}$$

But $\alpha_f = (1/(2L)).\ln(1/(R_1R_2))$

$$\Rightarrow R = R_1 = R_2 = \exp(-\alpha_f L) = \underline{47\%}$$ [15%]

(v) A good answer should explain the basic trade-offs, that as reflectivity increases, the threshold current decreases, but the differential quantum efficiency and modulation bandwidth reduces also. [10%]

Q.3. (a) Bookwork but should include a discussion of

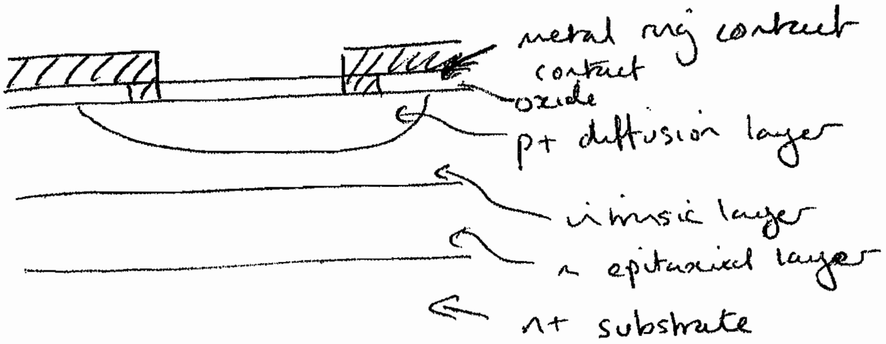
(i) capacitance

(ii) drift - including limit of saturation drift velocity

(iii) diffusion

A good answer would discuss trade off between capacitance and length of drift region (ie drift transit time)

(b)



If correctly designed + biassed, the intrinsic region eliminates diffusion transport processes.

(c) $E_g(eV) = \frac{hc}{e\lambda_{gap}} \Rightarrow \lambda_{gap} = \frac{hc}{eE_g}$

For GaAs $\lambda_{gap} = \frac{6.62\times10^{-34} \times 3\times10^{8}}{1.602\times10^{-19} \times 1.424}$

$= 871 nm$

Photon energy is less than bandgap so it is not possible to photogenerate carriers. $\Rightarrow$ Need to reduce bandgap energy.

For $\lambda = 1300nm$

$E_g(max) = \frac{6.62\times10^{-34} \times 3\times10^{8}}{1.602\times10^{-19} \times 1300\times10^{-9}} = 0.9536 \text{ eV}$

So $0.9536 = 1.424 - 1.50x + 0.4x^2$

Rearranging $0.4x^2 - 1.50x + 0.4704 = 0$

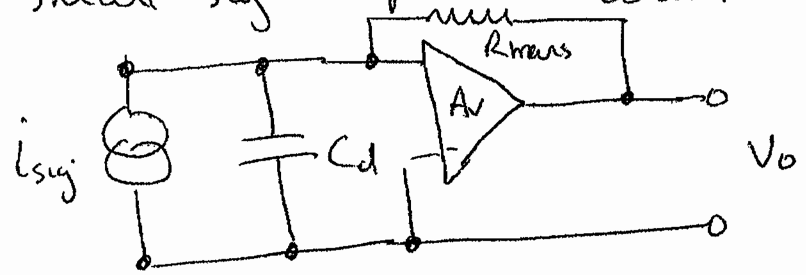
$$x = \frac{1.50 \pm \sqrt{1.50^2 - 4\times0.4\times0.4704}}{0.8}$$

$$= \frac{1.50 \pm 1.223}{0.8}$$

$$= 0.345 \text{ or } 3.405$$

non physical (can't have $x>1$)

(d) (i) Small signal equivalent circuit



$$\frac{V_o}{i_{sig}} = \frac{R_{trans}}{1 + s\,R_{trans}C/A_v}$$

$$\Rightarrow \omega_{3dB} = \frac{1}{R_{trans}C/A_v}$$

$$= \frac{1}{200\times40\times10^{-12}/100}$$

$$= 1.25\times10^{10} \text{ rad/s}$$

$$f_{3dB} = \frac{\omega}{2\pi} = 2.0 \text{ GHz}$$

(ii) At receiver sensitivity condition we require

$$\frac{\langle i_{sig}\rangle^2}{\langle i_n\rangle^2} = 22\text{dB} = 10^{2.2} = 158.5$$

$$i_{sig} = \frac{\eta e}{hc/\lambda} P_{sig} = \frac{0.9\times1.602\times10^{-19}}{6.62\times10^{-34}\times3\times10^{8}/1300\times10^{-9}} P_{sig}$$

$$= 0.944\, P_{sig}$$

$$\langle i_n \rangle^2 = \frac{4kTB}{R}$$

worst case temperature

$$= \frac{4 \times 1.38 \times 10^{-23} \times 398 \times 2 \times 10^{9}}{200}$$

$$= 0.2197 \times 10^{-12} \; A^2$$

At 125°C & assuming thermal noise processes dominate

$$\Rightarrow \quad \frac{(0.944\, P_{sig})^2}{0.2197 \times 10^{-12}} = 158.5$$

$$\Rightarrow \quad \underset{\text{(ie sensitivity)}}{P_{sig}} = \sqrt{\frac{158.5 \times 0.2197 \times 10^{-12}}{0.944^2}}$$

$$= 6.25 \text{ pW}$$

$$= 10 \log \left(\frac{6.25 \times 10^{-6}}{1 \times 10^{-3}} \right) = -22 \text{ dBm}$$

4 (a) Bookwork but should include

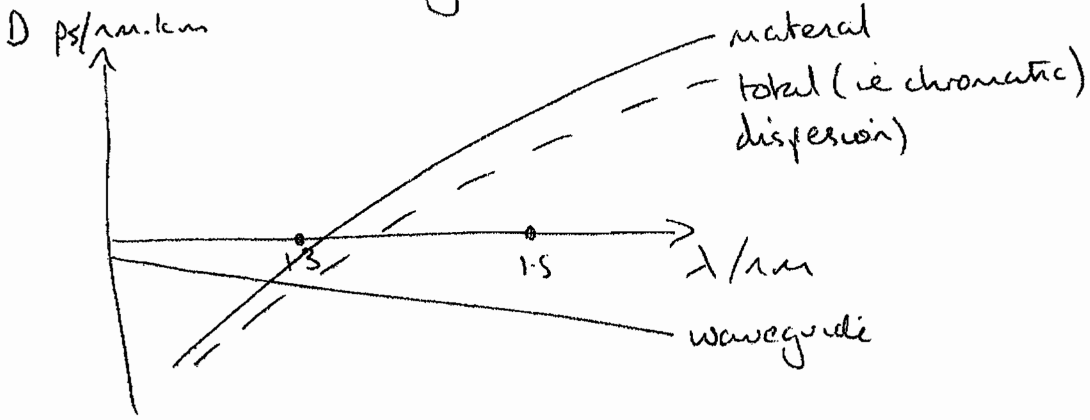
- low loss (< dB/km)
- low dispersion
- high tolerance to atmospheric conditions, e-m interference,

(b) Again bookwork but should discuss

- intermodal dispersion
- material dispersion
- waveguide dispersion

In long haul systems, single mode fibre will be used so there is no intermodal dispersion.

Both material and waveguide dispersion are wavelength dependent so dispersion, at usual comms wavelengths, is shown schematically as:



(c) (i) Bit period $T = \frac{1}{2.5\times10^9} = 400ps$

Dispersion equation $\Delta t_{out}^2 = \Delta t_{in}^2 + \Delta t_{disp}^2$ (i)

$\Delta t_{in} = 400ps$

$\text{Max } \Delta t_{out} = 1.4\,\Delta t_{in} = 560ps$

$$\Delta t_{disp} = D L \Delta\lambda$$

$$= 16 \times 100 \times \Delta\lambda = 1600\,\Delta\lambda \quad (ps)$$

(NB L in km, $\Delta\lambda$ in nm)

from (i) $\Rightarrow$ $\Delta t_{disp}^2 = \Delta t_{out}^2 - \Delta t_{in}^2$

$$= 560^2 - 400^2$$

$$\Delta t_{disp} = 391.9 \text{ ps}$$

$$= 1600\,\Delta\lambda$$

$$\Rightarrow \Delta\lambda = \frac{391.9}{1600}$$

$$= 0.245 \text{ nm}$$

(ii) Power budget

Power launched		+ 3dBm
Losses		
Splice	2 × 0.5dB	−1.0dB
Fibre	0.3 × L	− 0.3L dB
Margin	3dB	− 3dB
Receiver Sensitivity		−20dBm

So power budget = 23dB

= Splice + Fibre losses + Margin

$\Rightarrow$ Fibre losses = 0.3L = 23dB − 1dB − 3dB = 19dB

$$\Rightarrow L_{max} = \frac{19}{0.3} = 63.3 \text{ km}$$

$\Rightarrow$ link is attenuation limited at 63.3 km

(iii) To overcome the attenuation limit it is necessary to use optical amplifiers. The best amplifier for the purpose is the EDFA as it has high gain & low noise. An operating wavelength in the range 1530 – 1560 nm means that there is no need to change the link wavelength. Fibre amplifier gains in the range of 30 km would mean that ~100 km amplifier spacing is necessary.

To achieve link lengths of the order of 1000s km, dispersion must be managed. Consequently dispersion compensating fibre (DCF) should be used to counterbalance the dispersion of the link fibre.

PART II A 2006 3B6

Numerical Answers

Q.1 (c) (i) 1.6 V, (ii) 510 MHz, (iii) 399 K
Q.2 (b) (i) 30 mA, (ii) 333 K, (iv) 47 %
Q.3 (c) 0.345, (d) (i) 2.0 GHz, (ii) -22 dBm
Q.4 (c) (i) 0.245 nm, (ii) 63.3 km (attenuation limited)