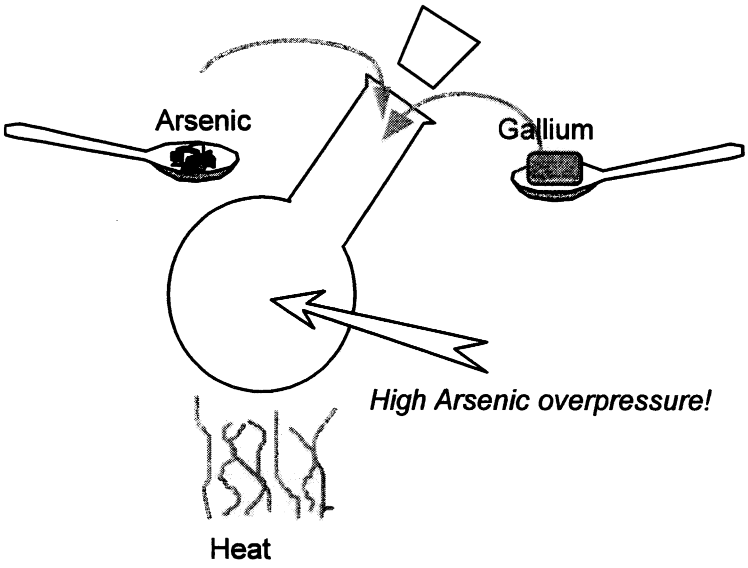
Question 1

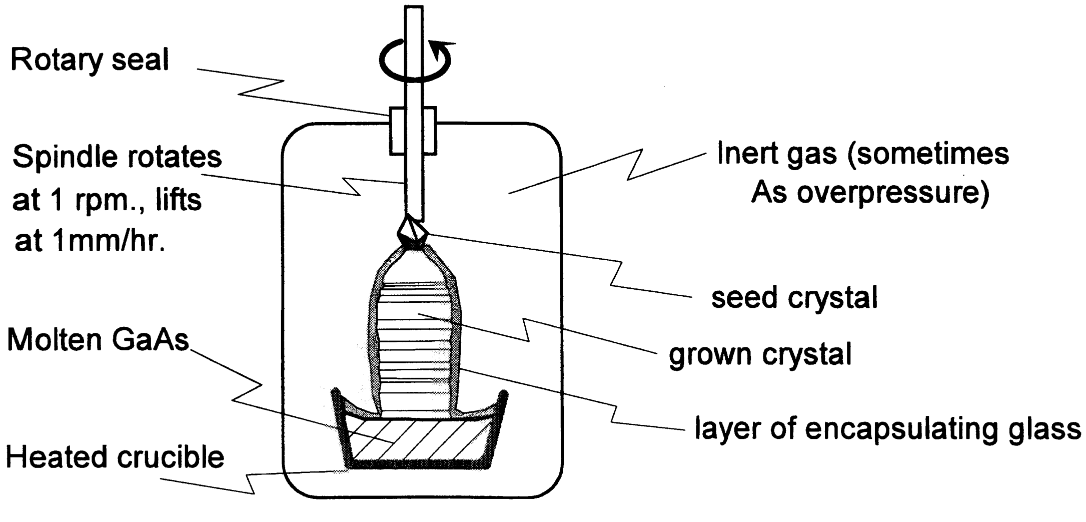
This question primarily involves bookwork answers

(a) This part of the question should explain the formation of the polycrystalline material and then pure crystal growth using LEC. Start from 'high purity' metallic elements, weigh them into equi-atomic numbers, and heat them in a closed pot with an arsenic overpressure. Stir, and allow to cool into a polycrystalline boule.



Polycrystalline material as initially made will need refining to reduce atomic impurity levels, and re-casting with a seed crystal to give a large single crystal.

Although the quality tends to be a little worse than for the Bridgeman technique, the **Liquid Encapsulated Czochralski** tends to be used for large wafer sides. Here a seed crystal is gradually removed from a melt, causing crystal growth to follow, impurities being left in the melt. Good answers should highlight the use of over pressure and encapsulation to maintain good material quality. [30%]


"LEC" growth of GaAs (and InP) crystals

(b) After growth, the large crystal has to be first checked for orientation, then fixed to a saw, and a few test wafers produced and checked for doping level, mobility, etch pit density, and then the rest of the boule sawn up, or rejected and recycled as appropriate. A good answer should describe these tests in some detail and the key crystal planes that are of particular interest for photonic components, some answers will describe off-angle cleaving which is often used for good epitaxial growth.

Wafers are typically checked for:

(i) Doping type and mobility, usually Hall effect. Typical substrate carrier density is 10^{21}cm^{-3} but this is likely to be heavily compensated, and the atomic doping level will be much higher.

(ii) Resistivity (and hence doping density): various techniques such as 'four point probes' etc.

(iii) Etch pit density, which correlates with dislocation density. The Etch pit density for laser quality GaAs: 1000 cm^{-2} - 200 cm^{-2} [30%]

(c) A good answer should provide descriptions of at least three main epitaxial growth techniques (LPE, MOCVD or MBE) although some answers might include tipping furnaces.

The simplest way of growing GaAs is from liquid Ga saturated with As and slowly cooling, in a tipping furnace. For high power single heterostructure lasers and some simple LEDs the tipping furnace works very well. Adding an appropriate weight of Al to the melt allows GaAlAs to be grown, and clearly dopants may be added to choice.

More complex laser structures need multiple different layers, and hence multiple gallium melts. Most frequently this is done with a high purity graphite 'boat' constructed with a slider so that a series of melts may be positioned over the substrate for lengths of time to give the required thickness - liquid phase epitaxy.

Such furnaces work well, particularly for large volume applications where basic devices are required, though their use for laser diodes has diminished following the development of other techniques. The main limitations are thickness control of thin layers, and the growth of large numbers of layers. Layers 0.1 μm thick are possible with an accuracy of about ± 10%, which might typically take about 1 second. If the furnace cooling rate is reduced to slow down growth, nucleation or initiation of growth is poor, and poor morphology results. The limitations of LPE have led to Molecular beam epitaxy (or MBE) being used, particularly in research laboratories. Here excellent quantum well growth is possible, this being used in many CD laser devices.

A major difficulty with MBE is that the equipment is very expensive (£1 million+) and the growth rate of good quality semiconductor is low (usually less than 1 μm/hour) so it is not an attractive method for commercial production. In principle the materials to be grown should be almost unlimited, but the large difference between Ga and As vapour pressure imposes considerable restrictions on the conditions for GaAs growth.

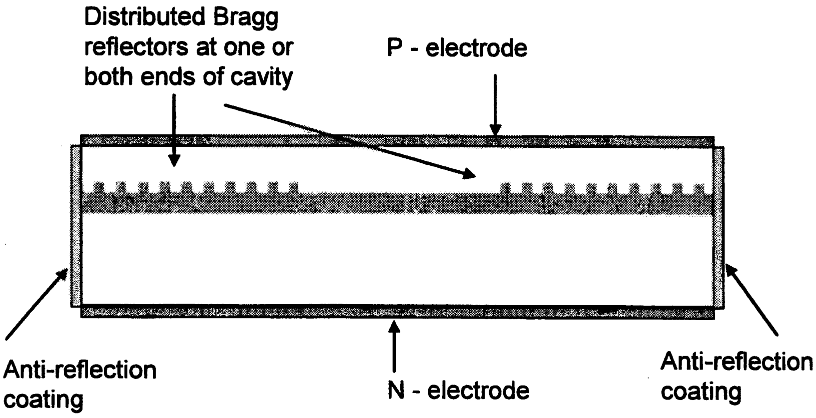
In MOCVD (Metal Organic Chemical Vapour Deposition - also known as Metal Organic Vapour Phase Epitaxy, MOVPE) growth is achieved from the gas phase, with the addition of dopant sources and a great many control components, such a system is capable of completing several laser layer structures in 24 hours. In less critical applications multiple wafers may be grown simultaneously. Each wafer will give over 10,000 standard lasers, so such systems are capable of meeting present and immediate future needs. In general, GaInAsP based materials are easier to grow than good quality GaAlAs materials because the Al in the latter is very reactive, and so the whole system has to have oxygen and water vapour levels reduced to a few parts per billion in the reactor carrier gas. Perhaps the biggest problem with use of MOCVD in manufacturing is the exhaust: the growth process is inefficient in its use of AsH_3, PH_3 etc so that although the epitaxial layers on a wafer only contain milligrams of As and P, the growth system may consume 100s of grams per run, which has to be extracted efficiently from the exhaust gas, and stored and recycled safely. MBE is more efficient in its use of source materials.

A good answer might describe hybrid techniques for example involving metalorganics in a high vacuum directed beam growth system (MOMBE or CBE).

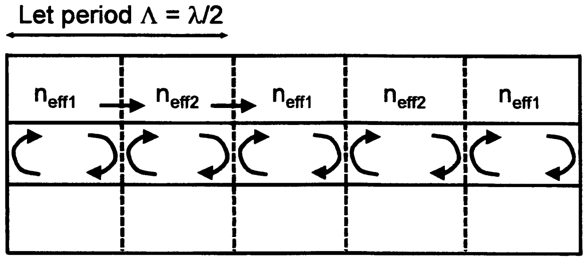
In general for basic CD lasers, MBE is often used though LPE systems are very cost effective and have high speed throughput. MOCVD systems are particularly heavily used in long wavelength applications. [40%]

Question 2

(a) A Bragg reflector can be implemented by periodically varying the refractive index profile along the length of the cavity. The schematic diagram shows a cross-section of a laser diode with electrodes on the top and bottom. The local effective refractive index is changed by varying the thickness of a higher refractive index material in the epitaxial structure.



The period of the refractive index modulation is equal to an integer multiple of half wavelengths so is of order hundreds of nanometers. This is fabricated by creating a mask pattern either by means of holography where a very simple diffraction pattern is generated or by direct e-beam writing. The exposed area is selectively etched. A material of different refractive index is then grown on top before completing the fabrication process in the normal manner with waveguides and contact electrodes.



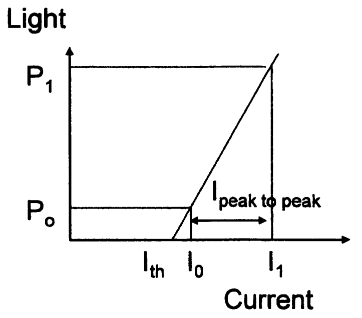
The resulting periodic structure with interfaces between regions of relatively high and low effective refractive index leads to multiple reflections. Constructive addition of reflections occurs at the grating wavelength. [30%]

(b) (i) Both first and second order Bragg gratings are feasible. First order gratings are more challenging in terms of lithographic resolution. Second order gratings require a frequency component at the first order, but this is feasible using typical etch profiles.

(ii) A quarter wavelength phase shift ensures single frequency operation in distributed feedback lasers where the grating forms the complete laser cavity. However e-beam lithography techniques may be required and this is a slower fabrication process than using holography. Laser performance may also be affected by impaired dynamics due to spatial hole burning.

(iii) Facet reflections are critical to the spectral properties of distributed Bragg grating lasers. Ideally no reflection is wanted at the facet by a grating and so an antireflection coating is required. If just one grating is used at one end of the cavity, a second reflection is required to form the cavity, and so a cleaved facet or a high reflectivity coating may be used. [30%]

(c) (i) Defining the variables by means of an LI curve with constant slope



Considering first the extinction ratio $P_1/P_0 = 10\text{dB} = 10$ in linear units

$P_1/P_0 = 10 = (I_1 - I_{th}) / (I_0 - I_{th}) = (I_1 - I_{th}) / (I_1 - I_{peak\ to\ peak} - I_{th})$

$\Rightarrow I_1 - I_{th} = 10\ (I_1 - I_{peak\ to\ peak} - I_{th})$

$\Rightarrow\ I_{th} = I_1 - 10/9 \times I_{peak\ to\ peak}$

Threshold current also depends on temperature: $I_{th} = I_o \exp\{T/T_o\}$
so the maximum value of threshold current will occur at higher specification 85°C

$I_{th}\ (85°\text{C}) = 90 - 10/9 \times 50 = \underline{35\text{mA}}$

$I_{th}(25°\text{C}) = I_{th}(85°\text{C}) = \exp\{\ ([273+20] - [273+85])/80\ \} = \underline{15.5\text{mA}}$ [20%]

(ii) The slope efficiency may reduce at higher temperatures due to a reduction in the injection efficiency. This may arise from temperature dependent leakage currents. A detuning of the gain wavelength from the grating peak may also reduce the efficiency at high temperature. [10%]

(iii) Feedback circuits may be implemented to control the modulation current and the dc bias current to the laser. A photodiode within the package at the rear facet will monitor the output power. An integrated value may be used to set the DC current, while an ac coupled modulated photocurrent may be used to monitor and control the modulation current, and therefore the extinction ratio. [10%]

Question 3

(a) The transparency current density in a diode laser quantifies the current density required for the laser active layer to be lossless. The threshold current density is the current density required to achieve laser oscillation, and therefore ensures sufficient gain in the laser active layer to equal the sum of the waveguide and cavity losses. [10%]

(b) The parameters in the given equation represent:

J_{th}	the threshold current density
J_o	the transparency current density
v_g	the speed of light within the laser cavity
e	electron charge
d	thickness of the active layer
g	the gain constant for the laser active layer
τ_s	the carrier lifetime
α	waveguide scattering losses
$R_{r/f}$	the reflectivity of the rear/front facets
L	the length of the cavity

There are two key types of optical loss in a laser cavity, the waveguide loss which is normalised relative to length, and facet loss, which for the case of Fabry Perot lasers, is inversely dependent on length. It is therefore possible to isolate the waveguide loss by cleaving diodes to a range of cavity lengths and plot parameters such as efficiency and threshold current as a function of inverse length to estimate waveguide losses. It is worth noting that there is variation in such an analysis due to uncertainties in parameters, and so a large number of samples are required. [30%]

(c) (i) The slope efficiency is defined by the product of the internal and external efficiencies where the internal injection efficiency $\eta_i = 100\%$ and the required slope efficiency $dL/dI = 1W/A$.

$dL/dI = \eta_i \eta_e hf/e$

$\Rightarrow \eta_e = e/hf = \lambda/1.24 = 0.98/1.24 = 0.79$

External efficiency is also defined by ratio of mirror loss to total losses

$\eta_e = \alpha_{mirror} / (\alpha_{mirror} + \alpha_{guide})$

$\Rightarrow \eta_e \alpha_{guide} = \alpha_{mirror} (1 - \eta_e)$

$\Rightarrow \alpha_{mirror} = \alpha_{guide}/(1/\eta_e - 1) \quad = \quad 18.85/cm$

Length $= 1/(2\alpha_{mirror}) \log_e(1/R_rR_f) = \underline{1280\ \mu m}$ [25%]

(ii) To estimate the current density required, the expression given for J_{th} may be used. However carrier lifetime is not known. Noting that for below or at threshold for steady state conditions the carrier rate equation in the standard equation list will reduce to:

$J/ed = N/\tau_s$

So may estimate the carrier lifetime from knowing the transparency current and transparency carrier densities:

$\tau_s = N_o ed / J_o = 0.16ns$

Noting that speed of light in waveguide $v_g = 3\text{x}10^{10}/3.4$ cm/s
Now estimating the contributions to the threshold current density equation by substituting in the known variables:

Transparency current density = 1000 A/cm^2

Waveguide loss dependent term $(v_g ed/g\tau_s)\ \alpha$ = 441.18 A/cm^2

Length dependent term $(\log_e\{1/R_r R_f\} v_g ed/2g\tau_s)\ L^{-1}$ = 1662.90 A/cm^2

⇒ Threshold current density = 1000 + 441.18 + 1662.90 = 3104.07 A/cm^2

Waveguide area = length . width = $1280\text{x}10^{-4}.\ 3\text{x}10^{-4}$ = $3.84\text{x}10^{-5}$ cm^2

⇒ operating current density = $3104.07 + 0.200 / 3.84\text{x}10^{-5}$ = $\underline{8.31\ \text{kA/cm}^2}$ [25%]

(iii) Operating current = $8310\ .\ 3.84\text{x}10^{-5}$ = 320mA

Diode voltage = $hf/q = 1.24/\lambda = 1.24/0.98 = 1.27$V

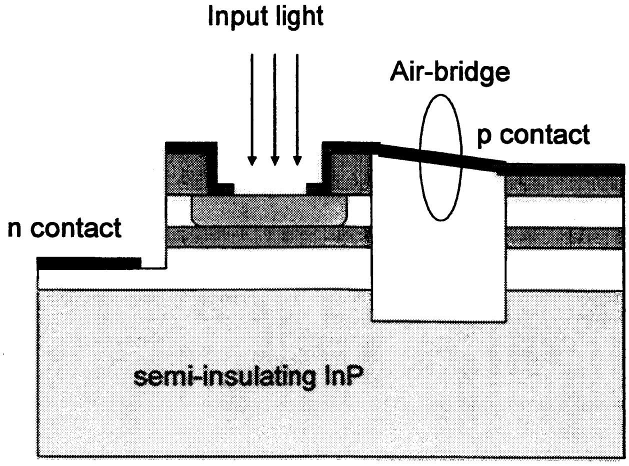
Electrical input power therefore $I(IR+V)$=0.50W

So wall plug efficiency = 0.20/0.50 = $\underline{40\%}$

The rest of the remaining input power will dissipate thermally [10%]

Question 4

(a) An example structure for a high speed photodiode for operation at 1.5μm wavelength could be a double heterostructure p-i-n structure shown schematically below



To ensure high speed operation, the active area would be minimised for reduced capacitance, the thickness of the active absorbing region reduced for fast sweep-out. To ensure fast electrical connection, n and p electrodes might be brought closely together, and an air bridge implemented to further reduce capacitance.

High speed design however can impact responsitivity as the area of the aperture needs to be large for efficient coupling, and the active layer would need to be sufficiently thick to efficiently absorb the incoming optical signal. [20%]

(b) (i) The capacitance can be reduced through improvements to the electrode design through reduced area and by using a thicker insulator layer [10%]

(ii) The normalised frequency dependent responsivity from the standard equation list:
$H(\omega) = 1/(1+j\omega RC)(1+j\omega\tau)$
Note that the transit time is not known so first evaluate this from the capacitance and measured cut off frequency.
Angular 3dB cut off frequency $\omega_{3dB} = 2\pi x10^9 = 6.28x10^9$rad/s
RC time constant $RC = 50.2x10^{-12} = 10^{-10}$s
Half frequency point may be estimated by equating the real and imaginary impedances in the denominator

$$1 - \omega_{3dB}{}^2 RC\tau = \omega_{3dB} RC + \omega_{3dB}\tau$$

$$\Rightarrow \tau = (1 - \omega_{3dB} RC) / (\omega_{3dB}{}^2 RC + \omega_{3dB}) = 36.3\text{ps}$$

Now consider the reduced capacitance value of 0.5pF and solve for ω_{3dB} as a quadratic equation

$$RC\tau\, \omega_{3dB}{}^2 + (RC+\tau)\, \omega_{3dB} - 1 = 0$$

$$\Rightarrow 9.08x10^{-22}\, \omega_{3dB}{}^2 + 6.13x10^{-11}\, \omega_{3dB} - 1 = 0$$

$$\Rightarrow \omega_{3dB} = (-6.13x10^{-11} \pm 8.60x10^{-11})/(2.9.08x10^{-22})$$

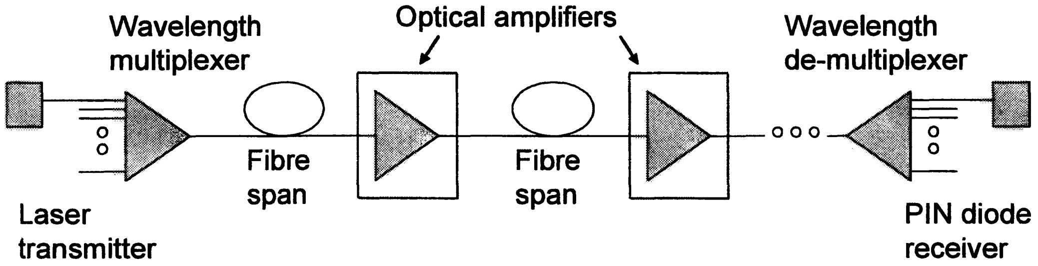
giving one positive root

$$\omega_{3dB} = 1.36x10^{10} \text{ rad/s}$$

$\Rightarrow f_{3dB} = \underline{2.16\text{GHz}}$ [30%]

(iii) The cut-off frequency is now largely limited by the carrier sweep-out time, so this might be further improved through thinning the active layer for example. [10%]

(c) A long haul wavelength multiplexed communications link with optical amplification at regular intervals will take the form



The above additional components are therefore required and these will each impair signal quality as follows:

Single frequency lasers	Signal to noise ratio degradation from relative intensity noise in the laser
Wavelength multiplexers	Signal loss and also crosstalk from additional wavelength channels
Optical fibre	Signal loss, inter-symbol distortion due to e.g. dispersion
Optical amplifiers	Degradation in signal to noise ratio due to amplifier amplified spontaneous emission
Wavelength de-multiplexers	Signal loss and also crosstalk from additional wavelength channels
Receivers	Shot noise in the p-i-n diode, thermal noise in the receiver, beat noise due to ASE and additional channels

[30%]