1 (a) Bookwork

(b) Bookwork.

(c) Direct bandgap semiconductor material. Active material often placed in a double heterostructure to improve carrier confinement. Important to have a good chance of radiative recombination of a carrier in the conduction band, hence $\tau_r < \tau_{nr}$

Blue GaN

Red GaAsP

Near IR (Al)GaAs

(d) (i) $\eta = \eta_{int}\, \eta_{ext} = 6\%$

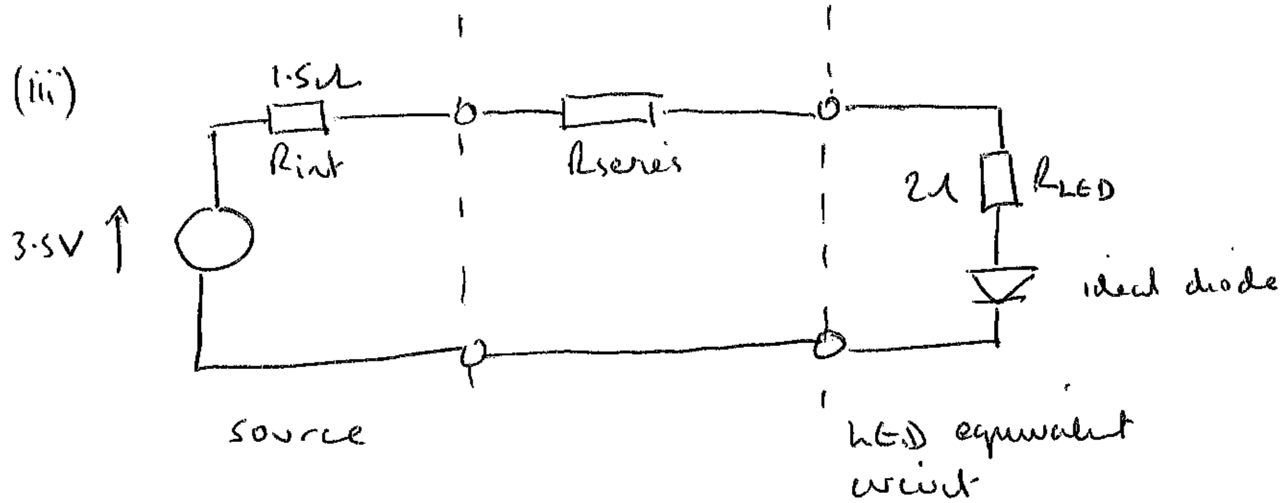
$\Rightarrow \eta_{ext} = \dfrac{0.06}{\eta_{int}}$

$$\eta_{int} = \frac{1/\tau_r}{1/\tau_r + 1/\tau_{nr}} = \frac{1}{1 + 1/2.5} = 0.714$$

$$\Rightarrow \eta_{ext} = \frac{0.06}{0.714} = 0.084 \text{ or } 8.4\%$$

(ii) Need to reduce the number of non-radiative recombination pathways which are primarily a result of defects in the s/c crystal and surface defects due to device processing. To increase τ_{nr}, efforts should be made to reduce the crystal defects & to improve device design & processing to minimise chance of surface defects (in a SELED, there is no etching required to form the device structure, so surface defect density is likely to be low.

(iii)



$$P = \eta \frac{hc}{e\lambda} I$$

$$I = \frac{e\lambda}{\eta hc} P = \frac{1.602\times10^{-19} \times 633\times10^{-9}}{0.06 \times 6.62\times10^{-34} \times 3\times10^{8}} \; 2.3\times10^{-3}$$

$$= 20.9 \text{ mA}$$

But $V = IR$

$$R_{int} + R_{series} + R_{led} = \frac{3.5}{20.9\times10^{-3}} = 167.5\,\Omega$$

$$R_{series} = 167.5 - 1.5 - 2$$

$$= 164\,\Omega$$

(iv)

$$\frac{P(T)}{P(T_1)} = e^{-\left(\frac{T - T_1}{T_0}\right)}$$

$$= e^{-\left(\frac{343-293}{100}\right)} = 0.607$$

$$\Rightarrow P(70°C) = 0.607 \times 2.3 \text{ mW}$$

$$= 1.40 \text{ mW}$$

(V) New $\eta_{int} = \frac{1}{1 + 1/5} = 0.833$

So new $\eta_{ext} = 0.084 \times 0.833 = 0.07$

So $\frac{0.07}{0.06} \times$ power produced for same current $\Rightarrow I_{ext} = 20.9 \times \frac{0.06}{0.07} = 17.9$ mA (for same power)

$R_{int} + R_{series} + R_{led} = \frac{3.5}{...}\,\Omega = 195.4\,\Omega \Rightarrow R_{series} = 191.9\,\Omega$

2 (a) bookwork

(b) bookwork → ~~to~~ needs discussion of both current & photon confinement

(c) (i) $P = \eta \frac{hc}{e\lambda}(I - I_{th})$

$$\Rightarrow I = I_{th} + \frac{e\lambda}{\eta hc} P$$

$$= 18\,mA + \frac{1.602 \times 10^{-19} \times 1.55 \times 10^{-6}}{0.63 \times 6.62 \times 10^{-34} \times 3 \times 10^{8}} 7\,mW$$

$$= 31.9\,mA$$

(ii) Assuming efficiency remains constant and that the main effect is a change in threshold

For $I_{th1} = 18\,mA$ $T_1 = 293\,K$.

$$\frac{I_{th1}}{I_{th2}} = \exp\left(\frac{T_1 - T_2}{T_0}\right)$$

Required $I - I_{th} = 31.9 - 18\,mA = 13.9\,mA$

So max $I_{th2} = 60\,mA - 13.9\,mA$
$= 46.1\,mA$

So $T_2 = T_1 - T_0 \ln\left(\frac{I_{th1}}{I_{th2}}\right)$

$$= 293\,K - 90 \ln\left(\frac{18}{46.1}\right)$$

$$= 104.6\,°C$$

(iii) Bookwork $\xrightarrow{\text{result}}$ $$\eta_d = \frac{\ln(1/R_1R_2)/2L}{\alpha + \ln(1/R_1R_2)/2L}$$

(iv) Assuming $R_1 = R_2$

$$\eta_d = 0.63 = \frac{\ln(1/R^2)/2L}{\alpha + \ln(1/R^2)/2L}$$

$$\alpha + \ln(1/R^2)/2L = \frac{1}{\eta_d}\ln\left(\frac{1}{R^2}\right)/2L$$

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

$$R = \exp\left(\frac{-\alpha L}{1/\eta_d - 1}\right)$$

$$= \exp\left(\frac{-7\times 0.08}{1/0.63 - 1}\right)$$

$$= 0.39.$$

(v) $$\Delta\lambda = \lambda^2/2nL = \frac{1.55^2}{2\times 3.3\times 800\times 10^{-6}} = 0.46\ nm$$

(d) A good answer should explain the basic trade offs → increasing reflectivity reduces facet losses & hence reduces threshold current, but will reduce the differential quantum efficiency also. Note can increase one facet reflectivity & reduce the other to optimise the threshold & useful (we usually only use light from one end of the laser) optical power – e.g. $R_1 = 0.95$, $R_2 = 0.3$.

Q3

(a) Material selection and bandgap considerations

(i) The photon energy corresponding to an optical wavelength of 1.9 μm is obtained from $E = hc / \lambda$.
Using $E(eV) \approx 1240 / \lambda(nm)$, with $\lambda = 1900$ nm, gives $E \approx 0.65$ eV. For efficient photodetection, the photon energy must be equal to or greater than the semiconductor bandgap. Therefore, the maximum allowable bandgap energy for this application is approximately 0.65 eV.

(ii) A suitable semiconductor material system is extended-wavelength InGaAs or InAsSb. These materials possess direct bandgaps that can be engineered to absorb radiation at 1.9 μm. In addition, III–V compound semiconductors offer relatively high carrier mobility and can be grown with high crystalline quality. With appropriate device design, such as barrier layers or heterostructures, they can operate reliably at elevated temperatures (up to 120 °C) while maintaining acceptable dark current and noise performance.

(b) Operation of a photoconductive detector

In a photoconductive detector, incident photons are absorbed within the semiconductor, generating electron–hole pairs. An externally applied electric field causes these free carriers to drift, increasing the electrical conductivity of the material. The resulting increase in current under illumination constitutes the detector signal.

The key parameters governing photoconductive operation are the carrier lifetime, mobility, and applied electric field. The carrier lifetime determines how long photogenerated carriers contribute to conduction before recombining. The mobility determines the carrier drift velocity for a given electric field. Together, these define the transit time required for carriers to traverse the device.

Photoconductive detectors can exhibit internal gain, because a single photogenerated carrier may circulate through the external circuit multiple times before recombination. This gain is absent in p–i–n photodiodes, which collect carriers once across a depletion region. As a result, photoconductors offer higher responsivity at the expense of increased noise and reduced speed compared to p–i–n detectors.

(c) Photoconductive gain, photocurrent, and noise

(i) The photoconductive gain G is defined as the ratio of carrier lifetime τ to the transit time $t_{transit}$:
$G = \tau / t_{transit}$.
The transit time is given by $t_{transit} = L^2 / (\mu V)$, where L is the device length, μ the carrier mobility, and V the applied voltage. Substituting the given values yields a transit time much shorter than the carrier lifetime, resulting in a gain significantly greater than unity.

(ii) The photocurrent is given by:
$I_{ph} = \eta G (q / h\nu) P$,
where η is the quantum efficiency, G the photoconductive gain, and P the incident optical power. This expression shows that the internal gain enhances the responsivity well beyond that of a unity-gain photodiode.

(iii) Assuming shot-noise-limited operation, the noise current is:
$i_n = \sqrt{2q I_{dark} B}$,
where I_{dark} is the dark current and B the electrical bandwidth. The signal-to-noise ratio is therefore:
$SNR = I_{ph} / i_n$,
which may be expressed in decibels as 20 log10(SNR).

(d) High-temperature effects and mitigation strategies

(i) At elevated temperatures, carrier mobility decreases due to increased phonon scattering, which reduces detector responsivity. Simultaneously, thermal generation of carriers increases the dark current, leading to higher shot noise. Both effects degrade the signal-to-noise ratio at high temperatures.

(ii) High-temperature performance can be improved by introducing wide-bandgap barrier layers to suppress thermally generated dark current, or by reducing the device length to shorten the carrier transit time. Additional approaches include improved surface passivation or modest cooling, though the latter increases system complexity.

Q4

(a) Dispersion mechanisms

Material dispersion arises from the wavelength dependence of the refractive index of the fibre material, which causes different spectral components of a pulse to propagate at different group velocities. Waveguide dispersion arises from the wavelength-dependent confinement of the guided mode within the fibre core. The total chromatic dispersion is the sum of these contributions and may be engineered to approach zero at a chosen wavelength by tailoring the fibre refractive index profile.

(b) Step-index fibre design

(i) To achieve total internal reflection, the glass with the higher refractive index (1.50) must be used as the core, and the lower refractive index glass (1.47) as the cladding.

(ii) The fibre remains single-mode when the normalised frequency V satisfies $V < 2.405$. Using $V = (2\pi a/\lambda)\,\mathrm{NA}$, where $\mathrm{NA} = \sqrt{n_{core}^2 - n_{clad}^2}$, the maximum allowable core radius can be calculated.

(iii) Operating close to the single-mode cutoff makes the fibre highly sensitive to bending and fabrication tolerances, which can cause mode leakage and excess loss.

(c) Receiver bandwidth and sensitivity

(i) The receiver bandwidth is limited by the RC time constant formed by the photodiode capacitance, stray capacitance, and the transimpedance resistor. A first-order estimate is given by $f_{3dB} \approx 1/(2\pi RC)$.

(ii) At high bandwidth and relatively low transimpedance resistance, thermal noise from the feedback resistor typically dominates over shot noise. This may be verified by comparing the respective noise current spectral densities.

(iii) The minimum detectable optical power is obtained by equating the signal current to the noise current required to achieve the specified SNR.

(d) System limitations and maximum link length

(i) Dispersion-limited transmission is determined by equating the chromatic-dispersion-induced pulse broadening to 25% of the bit period. The attenuation-limited distance is obtained from the optical power budget, including the required system margin.

(ii) The maximum transmission distance is given by the smaller of the dispersion-limited and attenuation-limited lengths.

(iii) The transmission distance may be extended by reducing the laser linewidth, employing dispersion compensation techniques, or using advanced modulation and coding schemes.