**OLLSCOIL NA hÉIREANN, CORCAIGH**
THE NATIONAL UNIVERSITY OF IRELAND, CORK

COLÁISTE NA hOLLSCOILE, CORCAIGH
UNIVERSITY COLLEGE, CORK

**SUMMER EXAMINATIONS, 2011**

**B.E. DEGREE (ELECTRICAL & ELECTRONIC)**
**M.Eng.Sc. (MICROELECTRONIC DESIGN)**

OPTICAL ELECTRONICS
EE4007

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Time Allowed: *3 hours*

FOUR QUESTIONS TO BE ANSWERED, AT LEAST TWO FROM EACH SECTION.
USE SEPARATE ANSWER BOOKS FOR EACH SECTION

The use of approved calculators is permitted.
The use of Log Tables and Graph paper are permitted.

*Physical Constants:*

Free electron mass, $m_0$ = 9×$10^{-31}$ kg
Planck's constant, h = 6.626×$10^{-34}$ J s
Electronic charge, q = 1.602×$10^{-19}$ C
Boltzmann's constant, $k_B$ = 1.38×$10^{-23}$ J $K^{-1}$
Room temperature = 300 K
Speed of light in free space, $c$ = 3×$10^8$ m $s^{-1}$
Permittivity of free space, $\epsilon_0$ = 8.854 × $10^{-12}$ F $m^{-1}$

## SECTION A

1. (a) Using diagrams where appropriate, explain how a light emitting diode (LED) operates. Your answer should include a discussion the principles of operation a diode, and for the LED the relationship between light output power and voltage and current. It should also explain where the energy being carried away in the form of emitted light came from, with reference to the band structure of the material in the junction. [*8 marks*]

   (b) A high brightness green LED using an InGaN active region is forward biased to give a current of 350 mA with a drive voltage of 3.4 V. Using a so-called integrating sphere all the light emitted can be detected and in this case a power of 40 mW at a wavelength of 530 nm was measured.

      i. What is the external efficiency of this device? [*4 marks*]

      ii. What is the wall plug efficiency? [*2 marks*]

      iii. Explain the difference between the two values calculated above. [*2 marks*]

   (c) The InGaN active region normally is a quantum well sandwiched between layers of GaN. Due to the piezoelectric nature of the material and the strain in the well the conduction and valance band profile looks as shown in the figure below, ignoring the effects of band bending due to any applied bias. For this figure sketch the form of the ground (lowest energy) state electron and hole wavefunctions and suggest what will happen to the wavelength of emission and the quantum efficiency of an LED as the well width is varied. Explain clearly your reasoning in all parts you your answer. [*4 marks*]

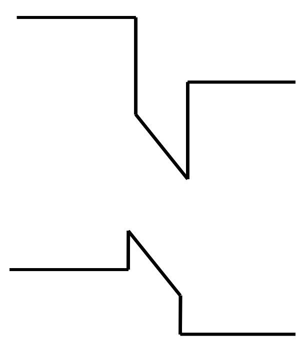

Figure 1: InGaN/GaN Quantum Well

2. (a) Schrödinger's Equation is given by:

$$-\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi = E\Psi$$

For this equation describe what is meant by $\Psi$ and give an equation in classical physics that it is equivalent to. [*3 marks*]

(b) Use Schrödinger's Equation to obtain an equation for the electron energy levels in a quantum well (QW) with infinite barriers.

[*6 marks*]

(c) Assuming that the potential barriers for both electron and hole energy levels in a GaAs QW are infinite, estimate the wavelength of emission of a QW LED if the width of the well is 6 nm.
GaAs Electron Effective mass: $0.063m_0$
GaAs Hole Effective mass: $0.51m_0$
GaAs Bandgap: $1.424$ eV

[*4 marks*]

(d) In reality the GaAs quantum well is surrounded by AlGaAs barriers which will have finite barrier heights. Describe the boundary conditions required to obtain a solution and suggest how the actual wavelength of emission might compare to that estimated in part (c).

[*3 marks*]

(e) A ”superlattice” is a structure where a large number of quantum wells are grown, separated by thin layers of the barrier material. A series of 100 GaAs quantum wells, with a thickness of 5 nm, are separated by thin AlGaAs barriers, also with a thickness of 5 nm. For this structure explain what you would expect to happen as a result of the very thin barriers between the quantum wells and suggest a method for solving this using Schrödinger's Equation

[*4 marks*]

3. (a) i. For a homojunction semiconductor laser, derive an expression for the minimum possible operating voltage as a function of the laser wavelength.

ii. Use this expression to estimate that minimum voltage for a GaN laser operating at 420 nm.

[*8 marks*]

(b) Semiconductor lasers are used in optical data storage systems.

i. Briefly describe how a laser can read information stored on a DVD-ROM.

ii. State two key advantages of a semiconductor laser over other laser types for this application.

iii. Why can Blu-ray discs hold substantially more information than a DVD?

[*8 marks*]

(c) A 300 $\mu$m $\times$ 300 $\mu$m chip of an InP - InGaAsP ($E_{g(InP)} = 1.34\,eV$; $E_{g(InGaAsP)} = 0.9\,eV$) double heterostructure with cleaved edges is irradiated continuously with intense light from:

i. A $CO_2$ laser with an operating wavelength of 10.6 $\mu$m

ii. A Nd-YAG laser with an operating wavelength of 1.06 $\mu$m

Explain what you would expect to observe from the surfaces and edges of the semiconductor chip in each case.

[*4 marks*]

## SECTION B

4. A point-to-point optical fibre link is to be designed to cover a total distance of 265 $km$. The required link margin is 12 $dB$ with a receiver sensitivity of -24 $dBm$, and the single mode fibre used has an attenuation of 0.18 $dB.km^{-1}$. Assume the maximum laser output power is 3.4 $mW$, with negligible coupling and isolator losses.

   (a) For the conditions described, what is the maximum length link achievable using a single strand of this fibre? [*5 marks*]

   (b) How many optical amplifiers are required to make the 265 $km$ link feasible? (EDFA gain is 5 $dB$, splice loss is 0.25 $dB$ per splice) [*5 marks*]

   (c) If the data-rate for the link is 1.25 $Gb.s^{-1}$, what is the average number of photons per bit arriving at the receiver? (Assume $\lambda = 1.55\mu$ m.) [*5 marks*]

   (d) To cover the 265 $km$ with a single fibre, without regeneration, the laser power can be increased to 10 $mW$ without complication. What would the receiver sensitivity need to be in this case to meet the original design criteria? (fibre attenuation unchanged, all other losses negligible) [*5 marks*]

5. (a) Draw a generic photodiode I-V curve showing the effects of increasing illumination intensity.

   [*4 marks*]

   (b) Describe, with the aid of diagrams, the operation of the resonant cavity enhanced (RCE) photodiode, paying particular attention to quantum efficiency, speed of response and spectral response.

   [*8 marks*]

   (c) Describe in detail an experimental set-up that can be used to measure the spectral response of a p-i-n photodiode. Draw a clear diagram of the set-up and state clearly all assumptions you have made, particularly in relation to the calibration of the measurement.

   [*8 marks*]

6. (a) What is meant by the term *internal quantum efficiency* in the context of semiconductor photodiodes? [*4 marks*]

   (b) A particular photodiode has a responsivity of 0.6 A/W at 633 nm. What is its quantum efficiency at this wavelength? [*5 marks*]

   (c) A silicon p-i-n photodiode is illuminated by 75 nW of light having a wavelength of 800 nm. The quantum efficiency of the device is 68% and its dark current is considered negligible. Calculate the *rms* photocurrent and the *rms* shot noise current if the bandwidth is 8 MHz. [*11 marks*]