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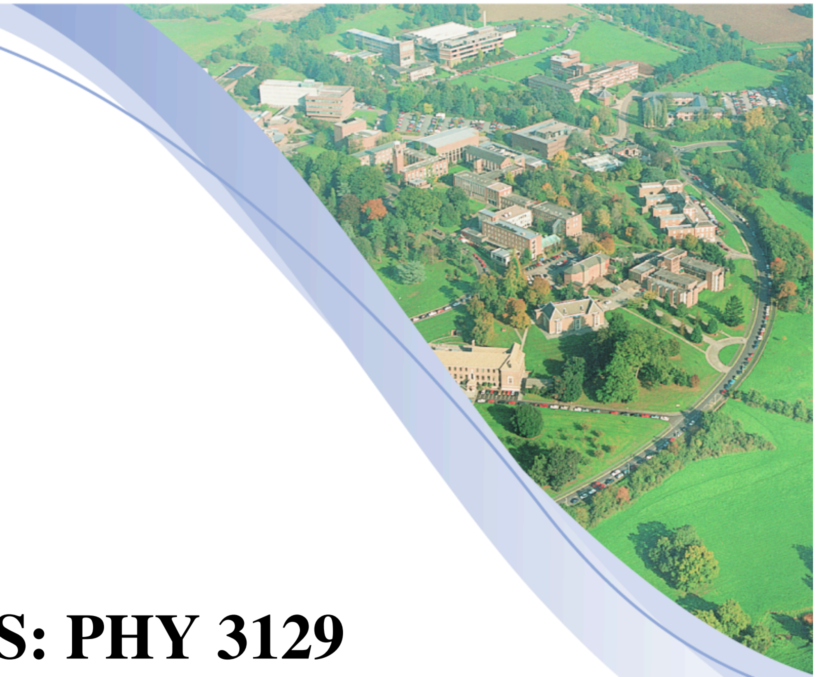

DEVICE PHYSICS: PHY 3129

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Lectures 21 & 22

1. Model solutions to past paper questions

Question 1 example I

(i) With the aid of diagrams describe the ordered states of **nematic**, **smectic** and **cholesteric** liquid crystals. Explain what is meant by the **director**. **[4]**

A nematic liquid crystal may experience elastic deformations known as splay, twist and bend. Sketch the form of these deformations. **[3]**

With the aid of diagrams describe the operation of the 90° twisted nematic liquid crystal cell and how it might be lit. **[8]**

(ii) The condition for a wave front to propagate in a planar waveguide may be written as

$$\frac{2\pi n_1 d \cos\theta}{\lambda_0} = m\pi + \phi(\theta)$$

where n_1 is the refractive index within the guide, λ_0 is the wavelength in free space, θ is the angle of incidence at the edge of the guide, m is the mode number, d is the thickness of the core region, and ϕ is the phase shift incurred from a single reflection. Sketch the form of the right and left hand sides of the above equation as a function of θ for the first few values of m and mark the solutions to the equation on your sketch. **[4]**

Explain what is meant by the term "cut-off" and obtain an expression for the number of guided modes. **[4]**

When will the waveguide support only a single mode? Obtain a limit on the thickness of the guide for the case that n_1=1.55, n_2=0.8 μm, and the refractive index of the surrounding medium n_0=1.52. **[3]**

Sketch the form of the intensity distribution associated with the $LP_{0,1}$ and $LP_{2,1}$ linearly polarised modes in a multimode optical fiber. **[4]**

Question 1 example II

1. (i) Display devices may take many different forms.

Explain what is meant by an **emissive** and a **passive** display device. **[2]**

Explain what is meant by **photoluminescence** and **cathodoluminescence**

[2]

With the aid of a diagram explain how Stokes shifting can prevent emitted light from being reabsorbed within the same medium. **[6]**

With the aid of a diagram describe the principle of operation of the cathode ray tube, and suggest how a display device with a full range of colour may be obtained. **[5]**

(ii) Fiber optic cables are increasingly used in communications systems.

Suggest one advantage and one disadvantage of fiber optic technology in comparison with wireless technology. **[2]**

State three further applications of optical fibers **[3]**

Describe how fiber optic cable is made. **[3]**

An optical fiber has a core and cladding with refractive indices of 1.52 and 1.5 respectively. Derive the condition for total internal reflection to occur at the core-cladding interface. **[3]**

Hence calculate the minimum angle of incidence at the core-cladding interface that will allow light to be guided within the fiber. **[1]**

State three sources of loss in single mode fibers. **[3]**

Question 2 example I

2. (i) Cost and weight are important factors in the selection of a display device. List five other factors that might be important. **[5]**

With the aid of diagrams explain the principle of operation of the cathode ray tube and explain how colour may be obtained. Describe the process by which light is emitted. **[3,2]**

Explain how placing a light-emitting diode with broad-band output in a thin planar cavity can be used to select colour, and estimate the maximum cavity spacing required to select a single spectral component from the visible spectrum. **[5]**

(ii) With help of diagrams explain the difference in the construction of a MOSFET with an induced electron inversion layer and a MESFET with a conducting channel of electrons. **[5,5]**

Explain qualitatively why the gate−channel capacitance of the MOSFET becomes constant at large gate voltages while the capacitance of the MESFET is always gate voltage dependent. **[5]**

Question 3 example I

3. (i) The core and cladding of an optical fibre have refractive indices of n_1 = 1.5 and n_2 = 1.48 respectively.

With the aid of a diagram, derive an expression for the maximum acceptance angle of the fibre, and define the **numerical aperture**. Calculate the value of the maximum acceptance angle of the fibre when it is immersed in a fluid with a refractive index of 1.3. **[6]**

Describe two other ways in which light may be coupled to an optical fibre. **[4]**

Describe three ways in which two fibres may be joined together so that light is transferred efficiently from one to the other. **[3]**

Give two reasons why poorly made joints might be troublesome in a digital communications system. **[2]**

(ii) Briefly describe the concept of the quasi-Fermi level for excess carriers in semiconductors. **[3]**

Sketch the band diagrams of a p-n junction:

a) in equilibrium,

b) with a forward bias applied.

Indicate on these diagrams the position of the Fermi level and quasi-Fermi levels of the charge carriers. **[4,4]**

At temperature $T = 300$ K the current density in a p-n junction diode for reverse biases is 2×10^{-11} A cm^{-2}. Estimate the current density of this diode at a forward bias of 0.1 V.

[4]

Question 3 example II

3. (i) The saturation current in a MOS transistor is given by the following relation:

$$I_D = \frac{W \mu_{\mathrm{n}} C_{\mathrm{ox}}}{2L}\left(V_{\mathrm{GS}} - V_{\mathrm{T}}\right)^2.$$

Describe the meaning of the terms in this relation. **[3]**

Briefly explain the reasons for the continual decrease in the size of transistors in integrated circuits. What is the advantage of **constant voltage scaling** compared with **full scaling**? **[2,2]**

Assume that in the constant voltage scaling all the dimensions are decreased by 10 times. Explain how this scaling will change (a) the capacitance of a MOSFET; (b) its saturation current; (c) the dissipated power; (d) the switching time.

[2,2,2,2]

(ii) Explain what is meant by a **meridional** and a **skew** ray within an optical fibre. **[2]**
With the aid of a diagram describe the operation of an optical fibre amplifier as might be found in an optical communications system. **[5]**

The chromatic dispersion $\Delta\tau$ accumulated over a distance L in a medium of refractive index n by a pulse of light with centre wavelength λ_0 in free space and bandwidth $\Delta\lambda_0$ is given by the expression

$$\Delta\tau = \frac{\lambda_0}{c}\frac{d^2 n}{d\lambda_0^2} L \Delta\lambda_0$$

The wavelength dependence of the refractive index of fused silica may be described by the polynomial expansion

$$n = a_0 + a_1\lambda_0 + a_2\lambda_0^2 + a_3\lambda_0^3$$

where $a_0 = 1.504$, $a_1 = -1.4 \times 10^5$ m^{-1}, $a_2 = 1.3 \times 10^{11}$ m^{-2} and $a_3 = -4.5 \times 10^{16}$ m^{-3}. Data are encoded as a series of bandwidth limited pulses with width 10 ps and centre wavelength of $\lambda_0 = 850$ nm. Use the uncertainty principle to estimate the value of $\Delta\lambda_0$. If the bit rate is 10 GHz, estimate how far the pulses may travel in the fused silica before dispersion causes the data to be lost. **[4,4]**

Question 3 example III

3. (i) Explain qualitatively why at equilibrium the built-in potential in a pn junction does not result in a voltage drop across the junction. **[4]**

How is the magnitude of the built-in potential affected by an increase of:

(a) the doping concentrations and .

(b) temperature T .

(c) intrinsic carrier concentration . **[2,2,2]**

Sketch the distribution of the electric field across the depletion region of a pn junction, and explain qualitatively how the width of the depletion region depends on the built-in potential V_{bi} and the doping concentrations N_d and N_a.**[3,2]**

(ii) Name three sources of loss in optical fibers. **[3]**

Explain what is meant by **intermodal** dispersion in a multimode optical fiber. Estimate its value in a fiber of 10 km length with core and cladding refractive index of 1.53 and 1.51 respectively. **[6]**

Describe three types of dispersion that occur in single mode fibers. **[6]**

Question 3 example IV

3 (i) In the Haynes-Shockley experiment electrons are injected at probe A and detected by probe B which is separated from A by a distance of 10 μm. An electric field of 10 V m^{-1} is applied between the probes.

If the mobility of electrons is 0.1 $m^2 V^{-1} s^{-1}$, what is the delay time between the pulses at A and B? **[5]**

Explain qualitatively how the diffusion coefficient of electrons and their recombination time are determined in the Haynes-Shockley experiment. **[5,5]**

(ii) State three applications of optical fibres. **[3]**

Describe the different stages in the fabrication of a fibre optic cable. **[6]**

Describe three ways in which light may be coupled into a planar waveguide, and draw a diagram to illustrate your answer in each case. **[6]**

Question 4 example I

4. Briefly describe the construction of a metal-semiconductor field-effect transistor (MESFET) and the principle of its operation. **[4,4]**

For a MESFET based on an n-type semiconductor, sketch the energy band diagram $\varepsilon(x)$ of the structure at equilibrium. Indicate on the diagram the Fermi level F, electron affinity χ and work function ϕ in the semiconductor. **[3,1,1,1]**

Briefly explain how the band structure is modified when a negative voltage V_g is applied between the gate and the conducting channel. **[2]**

Sketch I-V characteristics of a MESFET with an n-type channel at different gate voltages. Indicate the linear and saturation regimes and briefly explain their origin.

[3,3,3]

Measurements of the capacitance of an n-GaAs MESFET with a gate of 20 μm x 1000 μm area show that it is equal to 40 pF when the gate voltage V_g= -1 V is applied. Assuming that the relative permittivity of GaAs is 13 and the built-in potential is 0.8 eV, find the donor concentration in the doped layer. **[5]**

Question 4 example II

4. (i) Sketch the construction of a **n-p-n bipolar junction transistor** Indicate the sign of the voltages applied to its terminals with respect to the base, and the currents which are important for transistor operation. **[3,3,3]**

Sketch the band diagram of this transistor in the active mode. **[4]**

Define the base transport factor B and indicate its maximum value. Explain how B can be increased by choosing the correct material for the transistor and optimising its design. **[4,4]**

Define the emitter efficiency γ_e. **[4]**

Using the above definitions of B and γ_e, show that the current gain of a transistor in the common-base circuit is $\alpha = B\,\gamma_e$. **[5]**

Question 4 example III

4. (i) With the aid of sketches of the physical structure and the energy band structure, explain the construction and principle of operation of a MOSFET with an induced electron inversion layer. **[4, 4]**

(ii) Sketch how the low-frequency capacitance depends upon the gate voltage for a MOS capacitor with a *p*-type substrate, and indicate the regions where the capacitance is equal firstly to the value of the oxide capacitance , and secondly to the flat-band capacitance . **[6, 3, 3]**

Explain how and why this graph will change when capacitance measurements are performed at high frequency. **[6]**

Estimate the capacitance of a Si MOSFET with a gate of dimensions 3 μm x 25 μm, oxide thickness of 0.1 μm and dielectric constant of = 3.7. **[4]**