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Data Provided: You may need to use the following physical constants:

Charge on electron:	-1.602×10^{-19} C
Free electron rest mass:	$m_0 = 9.110\times 10^{-31}$ kg
Speed of light in vacuum	$c = 2.998\times 10^{8}$ m s^{-1}
Planck's constant:	$h = 6.626\times 10^{-34}$ Js
Boltzmann's constant:	$k = 1.381\times 10^{-23}$ JK^{-1}
Melting point of ice:	0^{o}C = 273.2 K
Permittivity of free space:	$\varepsilon_0 = 8.854\times 10^{-12} Fm^{-1}$
Permeability of free space:	$\mu_0 = 4\pi \times 10^{-7} Hm^{-1}$

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DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2010-2011 (2 hours)

Semiconductors for Electronics and Devices 2

Answer **THREE** questions. **No marks will be awarded for solutions to a fourth question.** Solutions will be considered in the order that they are presented in the answer book. Trial answers will be ignored if they are clearly crossed out. **The numbers given after each section of a question indicate the relative weighting of that section.**

1. a. Starting from the Fermi-Dirac expression for the number of electrons in the conduction and valence band of a semiconductor, show that the temperature dependence of the intrinsic carrier density of a semiconductor, n_i, is of the form:

$$n_i \propto \exp\left(A/T\right)$$

where T is the temperature and A is a constant, related to the band gap, to be determined. State clearly any assumptions that you make. **(6)**

b. A semiconductor is doped uniformly with acceptor density, N_a and donor density, N_d, such that it is found to have an electron concentration of 10^{12}m^{-3} and a hole concentration of $4\times10^{20}\text{m}^{-3}$ at room temperature. If we know that $N_d = 6\times10^{20}\,\text{m}^{-3}$, determine the following:

(i) the intrinsic carrier concentration of the semiconductor at room temperature,

(ii) the value of N_a,

(iii) the mobility of the majority carrier, if the conductivity is known to be 3.2Sm^{-1}. **(6)**

c. Estimate the highest temperature that this semiconductor can operate without its conductivity changing significantly, making clear any assumptions that you make. (You may assume that the mobilities and the semiconductor band-gap energy, E_g=1.1eV, do not change significantly with temperature.) **(6)**

d. Explain qualitatively how the conductivity would be affected if the temperature was reduced below room temperature. **(2)**

2. **a.** Draw the equivalent circuit of a p-n semiconductor junction under illumination when it is connected to a resistive load as in a photovoltaic or solar cell. Show clearly the direction of conventional current flow.

Sketch and label the typical current-voltage characteristic of such a semiconductor junction when in the dark, and when under illumination. **(4)**

b. (i) Sketch and label the energy band diagram of the p-n junction above when in the dark, and when under illumination. Identify clearly the conduction band, valence band and Fermi level in both these cases.

(ii) Show also the voltage that is developed across the load when the p-n junction is under illumination.

(iii) What is the maximum voltage such a junction can theoretically deliver to an external load? **(6)**

c. (i) The active region of the p-n junction comprises a narrow band gap semiconductor, GaAs (E_g=1.42eV), surrounded by a wider band gap semiconductor AlGaAs (E_g=1.80eV).

What is the longest wavelength of light that could cause a photocurrent to flow in this semiconductor junction?

(ii) The junction is made up of a number of identical GaAs quantum wells with AlGaAs barriers, such that the longest wavelength that is detectable is 820nm. What is the dimension of the quantum wells? (Assume that in a quantum well with infinitely high and wide barriers the bound energy levels are given by $E_n=n^2h^2/8mL^2$, where the terms have their usual meaning, and that the electron and hole effective masses in GaAs are $0.06m_0$ and $0.45m_0$ respectively). **(8)**

d. As the width of the GaAs layer is reduced further, what in reality becomes the longest wavelength that causes a photocurrent in this junction and why? **(2)**

3. **a.** Sketch, label and discuss briefly the conduction mechanisms in an induced channel Metal Oxide Semiconductor Transistor (MOST). Identify all the significant parts of the device. **(4)**

b. Assuming that the change in drain current with drain voltage is in a MOST is given by:-

$$\frac{dI_d}{dV_d} = \frac{\mu_e C_g}{l^2}\left[V_g - V_T - V_d\right]$$

where the symbols have their usual meaning, derive expressions for

(i) the drain current in the unsaturated region,

(ii) the value of drain voltage when saturation of the drain current occurs, and the value of the saturation current, and

(iii) the transconductance in the saturated region. **(6)**

c. The MOST is operated as an amplifier in common source mode, with a standing drain current of 50mA and a 5kΩ load resistor. If the voltage gain of the amplifier is found to be 25, determine the voltage at the drain terminal and the transconductance of the device. **(4)**

d. A particular n-channel MOST is fabricated in silicon, which has a relative permittivity of 11.8, and has a gate capacitance of 0.2pF. The gate aspect ratio (length/width) is known to be 0.5. Given that the electron and hole mobility in silicon is $0.15m^2V^{-1}s^{-1}$ and $0.05m^2V^{-1}s^{-1}$ respectively, determine the gate dimensions and oxide thickness. **(6)**

4. **a.** Using the fact that force is equal to the rate of change in momentum, show that the conduction band effective mass of an electron can be represented by:-

$$m^* = \hbar^2\left(\frac{d^2E}{dk^2}\right)^{-1}$$

where the terms have their usual meaning. (Remember that momentum, $p=\hbar k$) **(6)**

b. InGaAs has a direct band gap energy of 0.75eV and at the centre of the first Brillouin zone, the conduction band can be assumed to be parabolic.

(i) If we assume that the effective mass of an electron at the zone centre is $0.04m_0$, deduce an expression for how the electron energy varies with the electron wavenumber, k in this region.

(ii) What happens to the shape of the energy versus momentum relationship, and hence the effective mass, as we move away from the Brillouin zone centre?

(8)

c. Sketch the approximate form of the electron and hole energy versus wavenumber for (i) a direct band gap semiconductor and (ii) for an indirect band gap semiconductor, labelling the conduction band, valence band and band gap.

From this diagram, explain how the recombination of electrons and holes determines why one material can be used to make lasers but not the other. **(6)**