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

Charge on electron:	-1.602×10^{-19} C
Free electron rest mass:	$m_0 = 9.110\times10^{-31}$ kg
Speed of light in vacuum	$c = 2.998\times10^{8}$ m s^{-1}
Planck's constant:	$h = 6.626\times10^{-34}$ Js
Boltzmann's constant:	$k = 1.381\times10^{-23}$ JK^{-1}
Melting point of ice:	0^{o}C = 273.2 K
Permittivity of free space:	$\varepsilon_0 = 8.854\times10^{-12}\,\mathrm{Fm}^{-1}$
Permeability of free space:	$\mu_0 = 4\pi\times10^{-7}\,\mathrm{Hm}^{-1}$

The University of Sheffield

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2005-2006 (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.** 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 thermistor made from intrinsic silicon has a resistance of 2.5kΩ at 20°C dropping to 1% of this resistance at 100°C.

Estimate the band gap energy, E_g, of the material, assuming that the mobilities and E_g do not change significantly over the temperature range. **(5)**

c. Supposing that the intrinsic silicon is lightly doped n-type, such that E_F, the Fermi level moves from its intrinsic position by an energy cE_g, where c is a constant, derive an expression for the ratio of the electron density in the doped semiconductor to that in the original intrinsic material. **(5)**

d. In a particular case, the light n-doping changes the conductivity of the silicon at 20°C by a factor of 10^6. Estimate the corresponding change in the Fermi level, assuming that μ_e=0.13m^2 V^{-1} s^{-1}, μ_h=0.05m^2 V^{-1} s^{-1}. **(4)**

2. a. Sketch the energy band diagram of a semiconductor p-n junction when no dc bias is applied under the following conditions:

(i) in the dark, and

(ii) under illumination by short wavelength light.

Show clearly the conduction band, valence band and Fermi level in both cases. What is the maximum voltage such a junction can theoretically deliver to an external load? **(6)**

b. Draw the equivalent circuit of such a 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.

Explain qualitatively why the load is chosen such that less than the maximum voltage of the junction is dropped across it. **(4)**

c. The active region of the p-n junction comprises a narrow band gap semiconductor, InGaAs (E_g=0.75eV), surrounded by a wider band gap semiconductor InP (E_g=1.35eV).

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

The thickness of the InGaAs layer is now known to be 10nm. How does this change the answer above? (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 InGaAs are $0.04m_0$ and $0.45m_0$ respectively). **(6)**

d. As the width of the InGaAs layer is reduced further, what in reality becomes the longest wavelength that causes a photocurrent in this junction and why? **(4)**

3. **a.** Sketch and discuss briefly the conduction mechanisms in an induced channel Metal Oxide Semiconductor Transistor (MOST). **(6)**

b. Assuming that the I-V characteristics in the unsaturated region are given by:-

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

where the symbols have their usual meaning, state the condition for current saturation to occur. From this, derive expressions for the drain current and transconductance in the saturated region. **(5)**

c. A particular n-channel MOST is operated via a 1kΩ load resistor from a 40V supply rail and biased such that the saturated drain current is 25mA.

Assuming a channel length of 25μm and an electron mobility of $0.15\text{m}^2\ \text{V}^{-1}\ \text{s}^{-1}$, estimate the gate capacitance. **(4)**

d. Find the device transconductance under the conditions described in part **(c)** above and estimate the small signal voltage gain in the common emitter mode. **(5)**

4. **a.** Show that from the energy versus momentum relationship, 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. GaAs has a direct band gap energy of 1.42eV and at the centre of the first Brillouin zone, the conduction band can be assumed to be parabolic. If we assume that the effective mass of an electron at the zone centre is $0.06m_0$, deduce an expression for how the electron energy varies with the electron wavenumber, k. **(6)**

c. GaAs (E_g=1.42eV) is a direct band gap semiconductor while GaP (E_g=2.2eV) is an indirect band gap semiconductor. Assuming that the hole effective mass is about five times that of the electron effective mass in both materials, sketch the approximate form of the electron and hole energy versus wavenumber for both materials, labelling the conduction band, valence band and band gap.

From this diagram, explain why one material can be used to make lasers but not the other. **(8)**

JPRD / CHT