



The
University
Of
Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2015-16 (3.0 hours)

EEE6212 Semiconductor Materials

Answer **FOUR** questions. **No marks will be awarded for solutions to a fifth 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. The elements silicon (Si), phosphorus (P) and gallium (Ga) have numbers 14, 15 and 31 in the periodic table of the elements. The lattice parameters are very similar ($a_{\text{Si}}=0.357\text{nm}$, $a_{\text{GaP}}=0.357\text{nm}$). Explain the similarities and differences between the crystalline semiconductor materials Si and GaP qualitatively with respect to the following aspects:

- i) crystal structure;
- ii) F_{002} structure factor;
- iii) covalence bonding /ionicity;
- iv) size of bandgap;
- v) type of bandgap;
- vi) average atomic number;
- vii) density.

(7)

- b. Sketch a three-dimensional view of the unit cell of a gallium phosphide crystal with all atoms in the cell.

Label the origin and the directions of the basic unit cell vectors.

Mark the $[111]$ and the $[\bar{1}11]$ directions.

Calculate for a lattice parameter of $a=0.357\text{nm}$

- (i) the atomic number density in units of atoms/nm^3 ,
- (ii) the atomic areal density of the (011) surface in atoms/nm^2 ,
- (iii) the spacings of the $\{111\}$ lattice planes.

(7)

- c. Silicon carbide (SiC) exists in hundreds of different crystal modifications many of which are related in terms of stacking sequences and called polytypes. β -SiC (also called 3C-SiC) is cubic with zinc blende structure and has a lattice constant of $a_{\text{cub}}=0.436\text{nm}$. α -SiC (also called 6H-SiC) is hexagonal with lattice parameters of $a_{\text{hex}}=0.308\text{nm}$ and $c_{\text{hex}}=1.512\text{nm}$, where 3 wurtzite-type units are stacked on top of each other along the c-axis but rotated with respect to each other about the c- axis. Calculate and compare the Si-C bond lengths in α -SiC and β -SiC.

(6)

2. a. Tetragonal crystals can be found as minerals in nature (e.g. rutile, anatase, zircon) and in strained semiconductor thin films. Name all possible symmetry elements of a tetragonal crystal (apart from the identity operation). For each, identify where they are and how many there are. (6)
- b. (i) Draw a three-dimensional sketch of the wurtzite lattice and label it.
 (ii) How many atoms are there effectively per unit cell?
 (iii) State their relative coordinates.
 (iv) In your sketch, indicate all tetragonal interstices commencing in the (x,y) -plane and pointing upwards (along z -direction). Which of them are occupied by atoms? (5)
- c. All possible unit cells can be divided into 7 crystal systems according to their shape, which comes from underlying point symmetry. These can be further divided into Bravais lattices and space groups. While most semiconductors are either cubic or hexagonal in bulk form, during epitaxy the unit cells can adopt different shapes of reduced symmetry.
 (i) Define what a Bravais lattice is.
 (ii) Explain the four types of space centering.
 (iii) Explain why there are not $7 \times 4 = 28$ Bravais lattices, but only 14.
 (iv) Why is there no tetragonal C lattice? (4)
- d. Dislocations are common extended defects in semiconductors.
 (i) Define what the Burgers vector \underline{b} and line direction \underline{u} are.
 (ii) Sketch an edge dislocation and include \underline{b} and \underline{u} in your sketch.
 (iii) Using your sketch, explain how the scalar product $\underline{b} \cdot \underline{g}$ can be used in dark-field imaging with reciprocal lattice vector \underline{g} to determine the Burgers vector direction. (5)

3. a. Give an example of and provide a suitable sketch for types of lattice defects in zero, one, two and three dimensions of space and label it properly. (8)
- b. The electron density in a heavily p-doped semiconductor at low temperature may be written as

$$p = \sqrt{\frac{1}{2} N_v N_a} \exp [-(E_a - E_v)/(2k_B T)] \quad (\text{equation 1})$$

where N_v , N_a are the number densities at and E_v , E_a the energy levels of the upper valence and the acceptor level, respectively, k_B the Boltzmann constant and T the absolute temperature. Describe how you can extract the magnitude of the energy of the acceptor level relative to the valence band edge using a series of conductivity measurements. (5)

- c. Provide a sketch of the cross-section through a p-channel MOSFET device used for high-speed switching or high-frequency amplification.

- (i) Name all terminals.
- (ii) Indicate the sign and strength of doping levels in all relevant regions.
- (iii) Explain the role of channel length and width and gate oxide type and thickness.
- (iv) Explain the difference between enhancement and depletion mode and give an application example of each. (7)

4. a. Consider the force imposed on an electron by the electric field in a crystal.
- (i) From this derive an expression for its drift velocity.
 - (ii) Define mobility and describe how the mobility of a semiconductor may be increased by the choice of material and synthesis methods. (5)
- b. Write down Shockley's equation for the current of a diode, defining all parameters used. Sketch and label a typical diode characteristic and name its three important regions. (6)
- c. With the help of a suitably labelled sketch, explain the difference between a type-I and a type-II band alignment between two semiconductors. Which is better for application as light-emitting device, and why? (4)
- d. The relationship between the lifetime τ of an excited electron state and electron density n is often modelled as
- $$1/\tau = A + Bn + Cn^2 \quad (\text{equation 2})$$
- (i) Explain the physical meaning of equation (2) and what the parameters A, B and C describe.
 - (ii) Which of the terms describes optical emission? (5)

5. a. (i) Identify both physical principles that the function of every LASER system relies on.
 (ii) Describe one possible technical implementation of each.
 (iii) Explain why you need more than just two energy levels to make a LASER. (6)
- b. Using schematic diagrams describe absorption, spontaneous and stimulated emission processes in a semiconductor, and define their rates. (6)
- c. (i) Define the external quantum efficiency of a photo detector as function of photocurrent, incident power P_{opt} and detector area A . Define all parameters you use.
 (ii) Consider that the incident light intensity falls off exponentially within the detector with distance z from its surface and that the generation rate for electron-hole pairs is given by the expression

$$g(z) = (1-R)P_{\text{opt}}/(Ahf) \exp(-\alpha z) \quad (\text{equation 3})$$

where R is the reflectivity of the surface and α the absorption coefficient. From this, calculate the photocurrent by depth integration over the depletion region width d .

- (iii) Insert this into your expression for the external quantum efficiency.
 (iv) Interpret the results in terms of optimal choice of material reflectivity and thickness. (8)

6. a. The Density of States (DOS) is a key concept in solid state physics.
- (i) Explain in words what is meant by it.
 - (ii) Sketch and compare the DOS for a bulk semiconductor and for a quantum dot.
 - (iii) Which is more suitable for applications in optoelectronics? Give reasons for your decision, taking into account both the form of the DOS and commenting on the absolute number of carriers available.
- (5)
- b. (i) Sketch and label the amplitudes of the electron wavefunctions for the four lowest energies of an electron confined in an infinitely deep quantum well.
- (ii) Derive an explicit expression for the energy levels, starting from the model that considers bound particles as standing waves.
- (iii) Calculate and compare the ground level ($n=1$) confinement energies in meV of electrons and holes in GaAs quantum wells of width $l=10\text{nm}$ and $l=3\text{nm}$, assuming the following constants:
- Planck's constant: $h=6.6261 \times 10^{-34} \text{ Js}$, $\hbar=h/(2\pi)$,
- elementary charge: $e=1.6022 \times 10^{-19} \text{ As}$,
- electron rest mass: $m_0=9.1095 \times 10^{-31} \text{ kg}$,
- effective masses: $m_e^*=0.063m_0$, $m_{hh}^*=0.51m_0$, $m_{lh}^*=0.082m_0$.
- (7)
- c. (i) Define what an exciton is.
- (ii) Sketch an excitonic transition in a direct-gap semiconductor and write down an equation for the line energy observed in photoluminescence that includes the bandgap, ground level energies of electron and hole and exciton binding energy.
- (iii) Calculate and compare the excitonic binding energies for the ground states ($n=1$) in the two following semiconductors, using the Rydberg constant of $R_y=13.6\text{eV}$:
- GaAs with $m_e^*=0.063m_0$, $m_{hh}^*=0.51m_0$, relative permittivity: $\epsilon_r=14.4$;
- Si with $m_e^*=0.98m_0$, $m_{hh}^*=0.49m_0$, relative permittivity: $\epsilon_r=11.7$.
- Assume the phonon energy is given by $E_{\text{phonon}}=k_B T$ where $k_B=1.38 \times 10^{-23} \text{ J/K}$ is the Boltzmann constant, $e=1.6022 \times 10^{-19} \text{ As}$ the elementary charge.
- (iv) Decide whether the excitons will be stable at room temperature.
- (8)

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