

Model solutions to Q1 and Q2

Q1a: Explain the similarities and differences between the semiconductor materials germanium (Ge) and gallium arsenide (GaAs) 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) lattice parameter;
- (viii) density.

8 points

Solution:

Ge has diamond structure, GaAs has zinc blende (sphalerite structure).

As a consequence $F_{002}=0$ for Ge (which is purely covalent) while it is small but finite for GaAs (which is slightly ionic in bond character);

Ge has a small indirect bandgap (0.66eV), GaAs has a medium, direct bandgap (1.42eV).

The average atomic number is the same ($\langle Z \rangle = 32 = \frac{1}{2}(31+33)$).

Lattice parameter and density are very similar (to roughly within 0.1% !).

density ? \rightarrow

Q1b: Sketch a three-dimensional view of the unit cell of a gallium arsenide crystal with all atoms in the cell. Label the directions of the basic unit cell vectors. Mark the [110] and the $[\bar{1}10]$ directions.

Calculate for a lattice parameter of $a=0.5653\text{nm}$

- (i) the atomic number density in units of atoms/ nm^3 ,
- (ii) the atomic areal density of the (001) surface in atoms/ nm^2 ,
- (iii) the spacings of the {113} lattice planes.

7 points

Solution:

Sketch of a typical sphalerite unit cell with 8 atoms within the cubic unit cell (2 points).

Correct axes labels with right-handedness and consistent markings of directions given another point each.

- (i) $n=8/a^3=44.3 \text{ nm}^{-3}$
- (ii) $N=2/a^2=6.26 \text{ nm}^{-2}$
- (iii) $d_{113}=a/\sqrt{(1^2+1^2+3^2)}=a/\sqrt{11}\approx 0.17\text{nm}$

Q1c: Calculate and compare the Ga-N bond lengths in cubic gallium nitride ($a_{\text{cub}}=0.452\text{nm}$) and hexagonal gallium nitride ($a_{\text{hex}}=0.319\text{nm}$, $c_{\text{hex}}=0.519\text{nm}$).

5 points

Solution:

sphalerite: 4 bonds in a straight line make up the body diagonal of the cube,

hence $d_{\text{bond}} = \frac{1}{4} \sqrt{3} a_{\text{cub}} = 0.196\text{nm}$.

wurtzite: bond length along the (0001) direction is given by the displacement of the two hexagonal sub-lattices,

i.e. $\frac{3}{8} c_{\text{hex}} = 0.195\text{nm}$.

These values are identical within error of 0.7%!

Q2a: The electron density in a strongly n-doped semiconductor at moderately low temperatures may be written as

$$n = \sqrt{\frac{1}{2} N_c N_d} \exp [-(E_c - E_d)/(2k_B T)] \quad (\text{equation 1})$$

Describe how you can measure the distance of the energy level of the donor below the conduction band edge using a series of conductivity measurements.

5 points

Solution:

In general, conductivity is $\sigma = e(n\mu_n + p\mu_p)$ where for n -doping only the 1st term counts, i.e. $\sigma \approx en\mu_n$. As the elementary charge e and the mobility μ are constants for a given material, σ has the same temperature dependence as given in the expression for the electron density, so

$$\sigma \propto \exp [-(E_c - E_d)/(2k_B T)],$$

$$\text{Hence, } \ln \sigma \propto -(E_c - E_d)/(2k_B T),$$

i.e. a plot of $\ln \sigma$ vs. $1/T$ should have a slope of $-(E_c - E_d)/(2k_B)$.

NB: In a decadic plot, where $\ln \sigma = 2.3 \log \sigma$, the slope of $\log \sigma$ vs. $1/T$ is given by $-(E_c - E_d)/(4.6k_B)$.

Q2b: Provide a sketch of the cross-section through a typical n-channel MOSFET device. Name all terminals. Indicate the sign and strength of doping levels in all relevant regions. Explain what the critical device dimensions are and why.

6 points

Solution:

The cross-sectional sketch gives 1 point. Correct identification of source, gate and drain contacts gives 1 point. Correct doping levels (substrate: p, source: n⁺, drain: n) gives 1 point. Critical device dimensions are:

- i) channel length (-> speed and ultimately transition frequency),
- ii) width (-> current),
- iii) gate oxide dielectric constant & thickness (-> capacitance)

more elaborate alternative solutions for the second half would involve the width/length aspect ratio but are not necessary:

The MOSFET gate works like a plate capacitor whose capacitance is given by $C = \epsilon_0 \epsilon_r A/t$, where ϵ_0 = electric field constant, ϵ_r = dielectric constant, A = area and t = oxide thickness. This means the specific capacitance per unit area is $C_{ox} = C/A = \epsilon_0 \epsilon_r / t$ and hence the drain current $I_D \propto \mu \epsilon W/(tL)$. Thus, for large drain currents materials with high carrier mobility, high dielectric constant, thinner oxides and improved aspect ratios will be needed. In order to enable higher frequency operation (faster switching), the total capacitance C needs to be reduced as well, which only agrees with the previous aim if the area $A = W \times L$ is reduced (as ϵ/t is to be increased); i.e. the MOSFET will have to become much smaller in footprint. If both W and L are reduced by factors of n , then W/D does not change so I_D stays constant but C is reduced by $1/n^2$ and thus f increased by n^2 . Hence both ϵ/t increase (C/A increase) and $W \times L$ decrease (C decrease) will be necessary.

The transition frequency of the MOSFET is $f_t = g_m / (2\pi C)$ where $C = C_{GS} + C_{GD}$.

As $g_m \propto i_D \propto \mu C_{ox} W/L$ and $C \propto C_{ox} W \times L$ we get $f_t \propto \mu / L^2$ which indicates the need for higher mobility materials and much shorter transistor gates.

Q2c: With the help of a suitable sketch, explain the difference between a type-I and a type-II band alignment between two semiconductors. Which is better for optoelectronic applications, and why?

5 points

Solution:

In a type-I alignment, conduction and valence band offsets are anti-correlated, in a type-II alignment they are correlated (2 points for proper sketches). As a result, in type-I band alignment electrons and holes are both located in the same material, namely that with the smaller bandgap, while in type-II the electrons are located in one and the holes in the other material. In result, radiative recombination in type-II semiconductors are much less likely, so the optical output is reduced. Type-I alignment is thus preferred for optoelectronic devices.

Q2d: Name the two physical principles that the function of a LASER relies on, and the corresponding components to be found in all LASER systems.

4 points

Solution:

Pumping (optically, electrically or by HF coupling) creates a population inversion in a system with at least three energy levels where the topmost is long-lived, which is necessary for stimulated, coherent emission.

Then a cavity with mirrors (one partially transparent or with a hole to couple out the light) acts as a resonator which provides optical feedback to amplify the radiation.

not clear what the components refer to, LASER system could include electronic driver and lens.

EEE6112 exam

Model solutions to Q1-3 green: modifications made after internal reviewer comments

Q1a: The elements gallium (Ga), germanium (Ge) and arsenic (As) have numbers 31, 32 and 33 in the periodic table of the elements. Explain the similarities and differences between the semiconductor materials Ge and GaAs with respect to the following aspects:

- (i) crystal structure;
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i.e. $\frac{3}{8} c_{\text{hex}} = 0.195\text{nm}$.

These values are identical within error of 0.7%!

Q2a: Name all possible symmetry elements of a cubic crystal (apart from the identity operation). For each, identify where they are and how many there are.

6 points

Solution:

3 tetrads (4 or C_4) perpendicular to the faces,

4 triads (3 or C_3) along the body diagonals,

6 diads (2 or C_2) through the midpoints of opposite edges,

9 mirror planes (m), 3x parallel to x,y,z through middle of faces ($\{200\}$), plus another 6x $\{110\}$ type planes

Q2b: (i) Draw a sketch of the diamond lattice.

(ii) How many atoms are there per unit cell?

(iii) In your sketch, indicate all tetragonal interstices. Which of them are occupied by atoms?

5 points

Solution:

2 points for a correct sketch of the unit cell with all 8 atoms. Each corner atom has an interstitial tetrahedron related to it, bounded by the corner atom and its 3 nearest-neighbour atoms in the middle of the adjacent faces. Only 4 of the 8 interstices are occupied, in an alternating way (5th point only if correctly identified in sketch).

Q2c: All possible unit cells can be divided into 7 crystal systems, 14 Bravais lattices and 230 space groups of increasing symmetry. 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 crystal system is.
- (ii) Define what a Bravais lattice is.
- (iii) Explain what space centering means.
- (iv) Explain why there are fewer than twenty Bravais lattices.
- (v) Why is there no tetragonal F lattice?

5 points

Solution:

Crystal system = order of unit cells according to their shape, which comes from underlying point symmetry.

Bravais lattice = lattice type classification due to combinations of point symmetry (7 lattice systems) with 4 space centerings (primitive P, base centred C, body centred I, face centred F) for all but the trigonal/rhombohedral system.

Space centering = gives spatial position of different, second atom within unit cell, if it exists

There are only 14 instead of $7 \times 4 = 28$ Bravais lattices because half of the combinations of crystal and centering can be represented by other combinations where the unit cell actually has a lower symmetry.

There is no tetragonal *F* lattice because this can also be described by a smaller tetragonal *I* lattice, rotated by 45° around the *c*-axis.

Q2d: Dislocations are common extended defects in semiconductors. Define what the Burgers vector is and use it to explain the difference between an edge and a screw dislocation.

4 points

Solution:

Need to define the line direction \underline{u} (as the line or lattice plane that defines the end of the row of atomic displacements) and the Burgers vector \underline{b} (as vector that describes the closure fault when a complete circuit around the dislocation core is made) . Then, for an edge dislocation we get $\underline{b} \perp \underline{u}$, while for a screw dislocation $\underline{b} \parallel \underline{u}$.

Q3a: The electron density in a heavily n-doped semiconductor at low temperature may be written as

$$n = \sqrt{\frac{1}{2} N_c N_d} \exp [-(E_c - E_d)/(2k_B T)] \quad (\text{equation 1})$$

Describe how you can extract the magnitude of the energy level of the donor relative to the conduction band edge using a series of conductivity measurements.

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NB: In a decadic plot, where $\ln \sigma = 2.3 \log \sigma$, the slope of $\log \sigma$ vs. $1/T$ is given by $-(E_c - E_d)/(4.6k_B)$.

Q3b: Provide a sketch of the cross-section through an n-channel MOSFET device as typically used for high-speed switching or high-frequency amplification. Name all terminals. Indicate the sign and strength of doping levels in all relevant regions. Explain what the critical device dimensions are for use as an amplifier and why.

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Q3c: With the help of a suitable 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?

5 points

Solution:

In a type-I alignment, conduction and valence band offsets are anti-correlated, in a type-II alignment they are correlated (2 points for proper sketches). As a result, in type-I band alignment electrons and holes are both located in the same material, namely that with the smaller bandgap, while in type-II the electrons are located in one and the holes in the other material. In result, radiative recombination in type-II semiconductors are much less likely, so the optical output is reduced. Type-I alignment is thus preferred for optoelectronic devices.

Q3d: Name the two physical principles that the function of every LASER system relies on, and the corresponding components to be found in all LASER systems.

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Then a cavity with mirrors (one partially transparent or with a hole to couple out the light) acts as a resonator which provides optical feedback to amplify the radiation.

Q4 (a).Assume a solid with electron conc = $n \text{ m}^{-3}$

E-field is applied and electrons accelerate

$$a = -\frac{qE}{m^*}$$

 q = electronic charge E = E-field m^* = effective massRate of change of momentum with time for each electron

$$\frac{dp_e}{dt} = \frac{d(m^* v_d)}{dt} = m^* \frac{dv_d}{dt} = m^* a = -qE$$

Rate of change of momentum of all electrons

$$\left(\frac{dp}{dt}\right)_{\text{drift}} = -qEn$$

Assume electrons accelerate until scattered.

Assume that scattering event causes all momentum to be lost ($= m^* v_d$)Time constant τ is average time between scattering events.

Total change in momentum due to scattering events is

$$\left(\frac{dp}{dt}\right)_{\text{scatter}} = \left(\frac{\text{number of scattering events}}{\text{time}}\right) \times (\text{momentum change})$$

$$= -\frac{n}{\tau} \cdot m^* \langle v_d \rangle$$

 \uparrow avg. drift velocity.

4.2

At Equilibrium

$$\left(\frac{dP}{dt}\right)_{\text{drift}} + \left(\frac{dP}{dt}\right)_{\text{scatter}} = 0$$

$$-qEn - \frac{n}{\tau} m^* \langle v_d \rangle = 0$$

$$\text{So } \langle v_d \rangle = - \frac{q E \tau}{m^*}$$

Q4 (b)

(4.3)

$$\langle V_d \rangle = \frac{-q E \tau}{m^*}$$

$$V_d = -\mu E$$

$$\mu = \frac{q \tau}{m^*}$$

Material choice $\rightarrow m^*$ small.

material synthesis \rightarrow high purity crystal ^{do you need to discuss how to obtain high purity?}
make τ large. If high carrier densities are required, strategies to spatially separate ionised dopants and conduction region may need to be pursued.

Q4 (c)

e.g. for electrons

$$J_e^{\text{tot}}(x) = J_e^{\text{drift}} + J_e^{\text{diff}} = q\mu_e E_x n + qD_e \frac{dn}{dx}$$

4.4

$$D_e = \frac{k_B T \mu_e}{q}$$

$$\text{and } D_h = \frac{k_B T \mu_h}{q}$$

Q for holes.

$$J_h^{\text{tot}}(x) = J_h^{\text{drift}} + J_h^{\text{diff}} = q\mu E_p - qD_h \frac{dp}{dx}$$

J^{drift} is $\propto n, p$. \rightarrow minority carriers may be ignored if heavily doped material.

$J^{\text{diffusion}}$ is $\propto \frac{dn}{dx}, \frac{dp}{dx}$ \rightarrow minority carrier diffusion currents may be large.

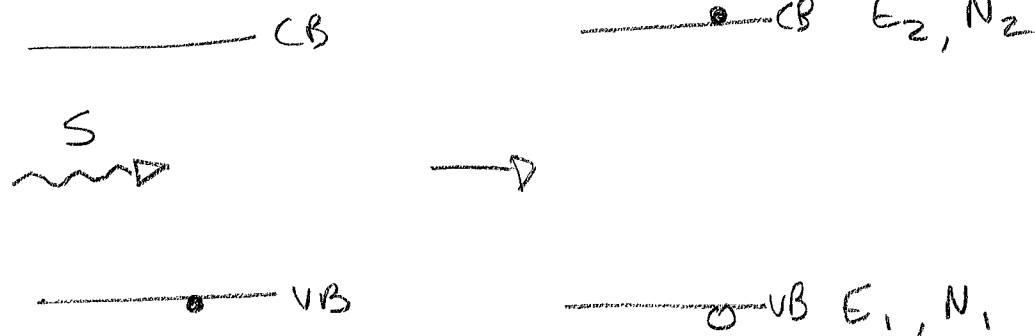
comments on majority carriers?

could have majority and minority carrier drift components depending on bias,

Q 5(a)

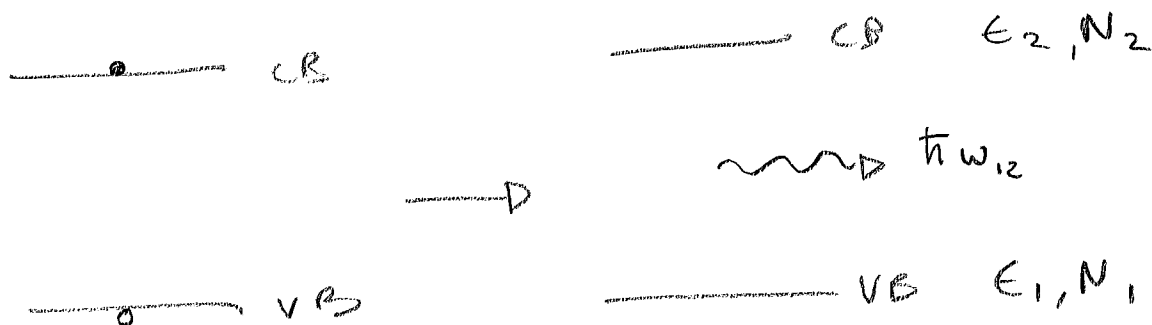
5.1

ABS



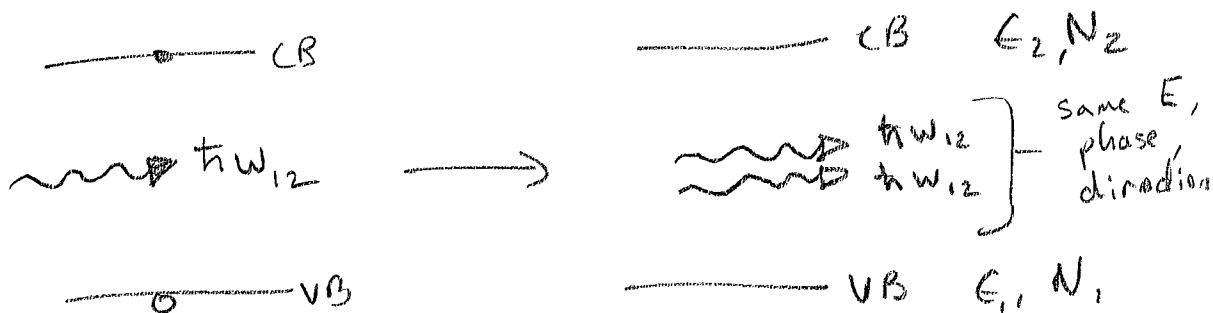
$$\frac{dN_2}{dt} = B_{12} \cdot S \cdot N_1$$

SPONTANEOUS



$$\frac{dN_2}{dt} = -A_{21} \cdot N_2$$

STIMULATED



$$\frac{dN_2}{dt} = -B_{21} \cdot S \cdot N_2$$

Q5(b)

S.2

As a current is applied so n and p increase in the intrinsic region.

As carrier densities increase so the absorption probability reduces and the stimulated emission rate increases.

When $N_1 = N_2$ we reach "inversion" and if there is no additional loss, as absorption and stimulated emission rates are equal, the material will appear to be transparent.

In real systems, carrier densities higher than those required for inversion are required to achieve transparency.

Q5(c)

5.3

$$E(n) = - \frac{\mu}{m_0} \cdot \frac{1}{\epsilon_r^2} \cdot \frac{R_H}{n^2}$$

$$r_n = \frac{m_0}{\mu} \cdot \epsilon_r \cdot n^2 \cdot a_H$$

$$\mu = \left(\frac{1}{m_e} + \frac{1}{m_h} \right)^{-1}$$

$$\mu = \left(\frac{1}{0.28 m_0} + \frac{1}{0.5 m_0} \right)^{-1} = 0.179 m_0$$

$$E_n = - \frac{0.179}{(7.9)^2} \cdot \frac{13.6}{n^2}$$

$$r_n = \frac{7.9}{0.179} \cdot 5.29 \times 10^{-11} \cdot n^2$$

n=1

$$E_1 = -39.1 \text{ meV}$$

$$r_1 = 2.3 \text{ nm}$$

n=2

$$E_2 = -9.8 \text{ meV}$$

$$r_2 = 9.3 \text{ nm}$$

At RT, thermal energy $k_B T \approx 25 \text{ meV}$. For $n=1$

\therefore as $E_1 > k_B T$, it is stable

for $n=2$ $E_2 < k_B T$ so it is not stable at RT.

Q5(d).

5.4

The Mott density is given by the inverse of the exciton density, and indicates the excitonic density at which the excitonic wave-functions overlap.

At this exciton density, excitonic effects may be lost, and the carriers may behave as an e-h plasma.

In wide band-gap materials (i.e. high binding energies), biexcitons may be observed.

At low temperatures Bose-Einstein condensates are possible.

$$N_{\text{Mott}} \approx \frac{1}{\frac{4}{3} \pi r_n^3}$$

GaN

$$r_1 = 13 \text{ nm}$$

$$N_{\text{Mott}} = \frac{1}{\frac{4}{3} \cdot \pi \cdot (13 \times 10^{-9})^3}$$

$$= 1.1 \times 10^{23} \text{ m}^{-3} = 1.1 \times 10^{17} \text{ cm}^{-3}$$

GaN

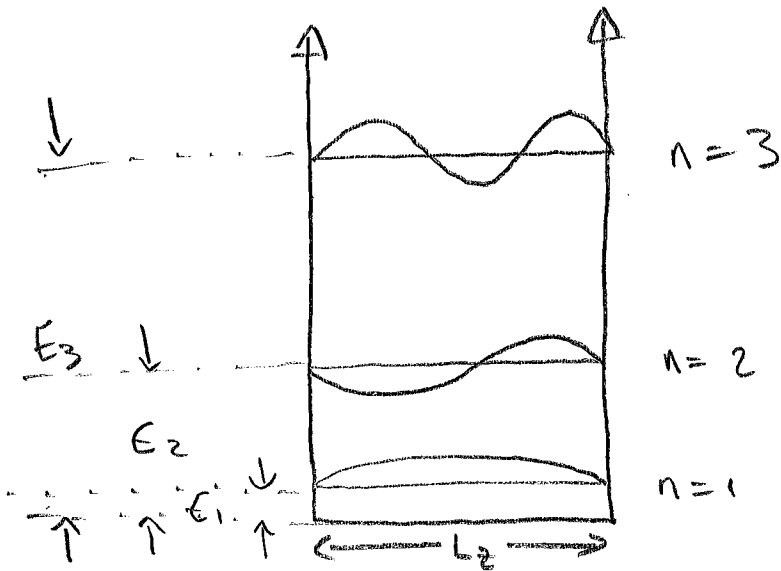
$$r_1 = 3.1 \text{ nm}$$

$$N_{\text{Mott}} = \frac{1}{\frac{4}{3} \cdot \pi \cdot (3.1 \times 10^{-9})^3}$$

$$= 8.8 \times 10^{24} \text{ m}^{-3} = 8.8 \times 10^{18} \text{ cm}^{-3}$$

Q6 (a)

6.1



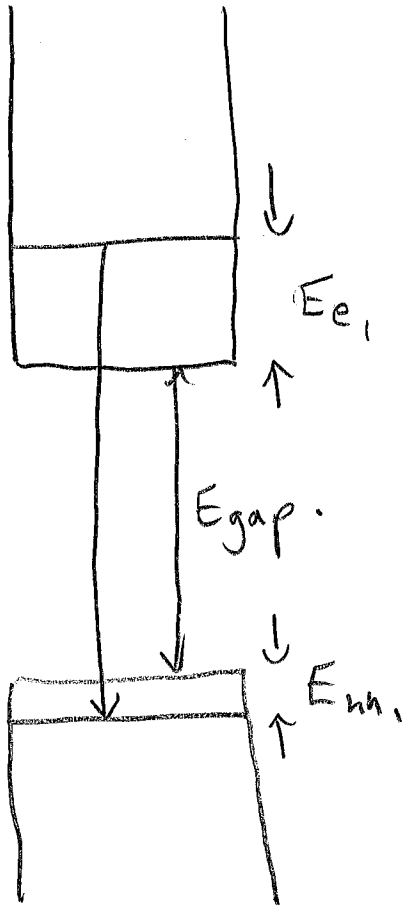
$$E_n = \frac{\hbar^2}{2m} \left(\frac{n\pi}{L_2} \right)^2$$

$$n = 1, 2, 3, \dots$$

$$\psi_n = A \sin \frac{n\pi x}{L_2}$$

Q6(a).

6.2



$$\text{Energy } e, hh_1 =$$

$$E_{gap} + E_{e1} + E_{hh1}$$

$$E_{e1} = \left(\frac{h^2}{2m} \right) \left(\frac{\pi}{L_z} \right)^2$$

$$= \frac{(1.05 \times 10^{-34})^2}{2 \times 0.063 \times 9.11 \times 10^{-31}} \cdot \left(\frac{3.142}{10 \times 10^{-9}} \right)^2$$

$$= 9.872 \times 10^{-21} \text{ J}$$

$$= 0.0617 \text{ eV}$$

$$E_{hh1} = \frac{(1.05 \times 10^{-34})^2}{2 \times 0.51 \times 9.11 \times 10^{-31}} \cdot \left(\frac{3.142}{10 \times 10^{-9}} \right)^2$$

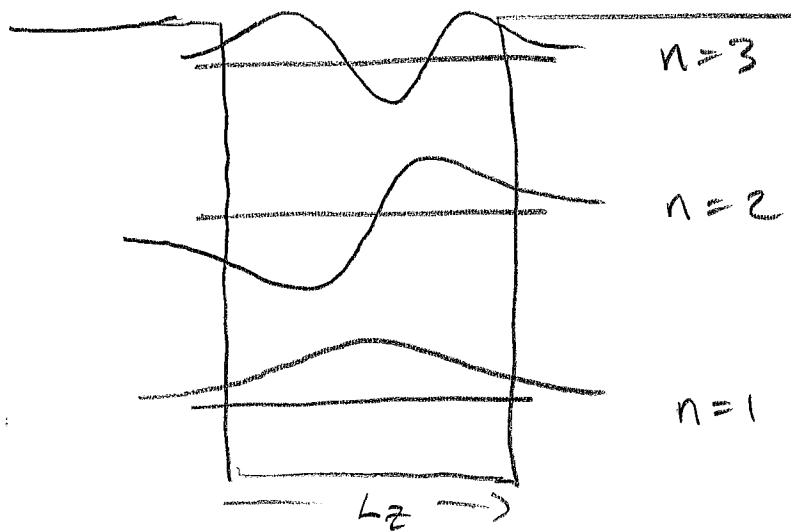
$$= 1.171 \times 10^{-21} \text{ J}$$

$$= 0.007 \text{ eV}$$

$$E(ehh_1) = 1.424 + 0.062 + 0.007 = 1.493 \text{ eV}$$

Q 6(b)

6.3

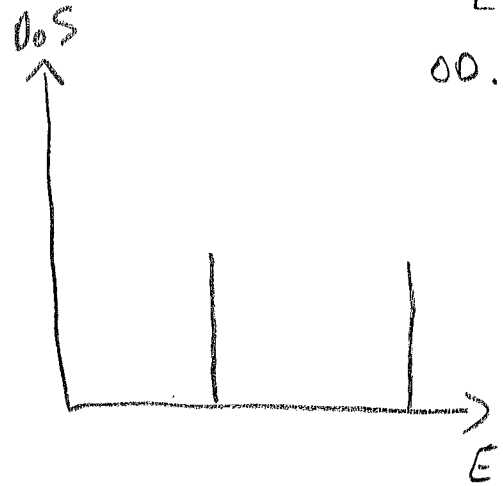
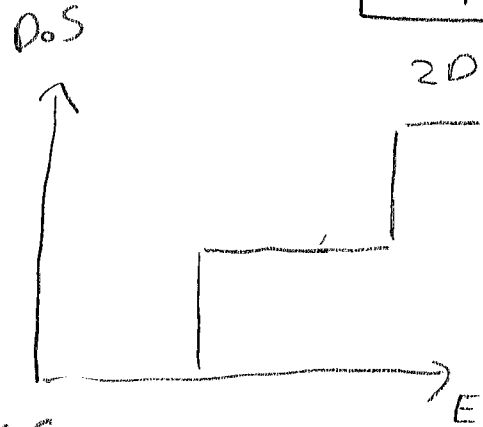
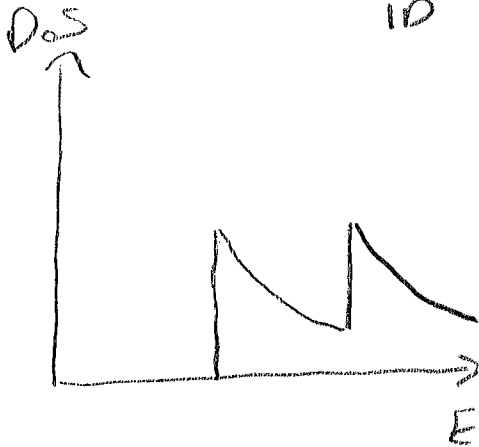
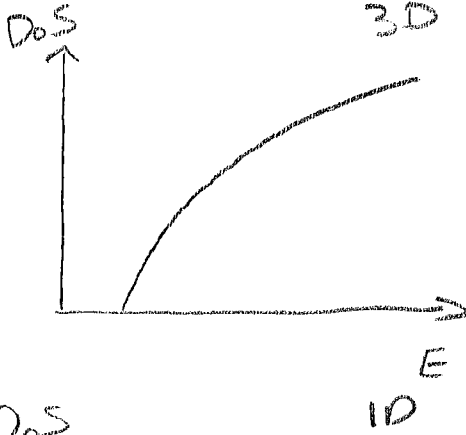


The effect of finite barriers on

- Confinement energies \rightarrow Reduced as compared to infinite barrier case. Reduction larger for higher order states.

- Wave-fuction \rightarrow Now penetrates the barrier, decaying exponentially.

Q 6 (c)



6.4

3D SYSTEM \rightarrow BULK SEMICONDUCTOR MATERIAL.

2D SYSTEM \rightarrow QUANTUM WELL - (A)

1D SYSTEM \rightarrow QUANTUM WIRE - (B)

0D SYSTEM \rightarrow QUANTUM DOT / BOX - (C).

(A) \rightarrow EPITAXY OF THIN LAYERS OF DIFFERING BAND GAP
 $\sim 5-10$ nm.

(B) \rightarrow EPITAXY OF THIN LAYERS ON PATTERNED SUBSTRATES

(C) \rightarrow USUALLY THROUGH STRANSKI-KRISTANOV GROWTH MODE.

Q6(d)

6.5

- ① Use strain to match m_e^* and m_h^* to maximise the joint density of states
- ② Use suitable QW widths and waveguide structures to maximise modal gain.
- ③ Utilise GRIN structures to enhance carrier capture in the QW.