Answermodel Device Physics exam

3-4-2023 8:30 10:30

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Question 3 (20 pts total)

a) With the help of a simple drawing discuss the differences between the density of states in ferromagnetic Cobalt from that of metallic Copper close to the Fermi level. (4 pts)

b. Using a parallel resistor model for a simple spin valve structure such as Co/Cu/Co derive the parallel and antiparallel state resistance of such a structure, when the thickness of both the Co layers are t_f and that of non-magnetic Cu t_{nm} The resistivity of the majority spins is $\rho_{f(M)}$ and the resistivity of the minority spins is $\rho_{f(m)}$ The resistivity of the non-magnetic metal is ρ_{nm}. (12 pts)

c.) Does the Giant magnetoresistance ratio depend on the spin dependent scattering in the bulk and/or at the interface? (4 pts)

Question 4 (30pts total)

a) Describe the working mechanism and draw the energy/band diagrams of a heterostructure optimized for the fabrication of inorganic LEDs. Sketch the JV characteristics of the device. Which type of heterostructure will give the best performance? How many layers will give the maximum performances, what is the function of this layers? (10 pts)

b) Describe the working mechanism and draw the energy/band diagrams of an inorganic solar cell. Draw the JV characteristics in dark and under illumination and write down how the efficiency of a solar cell can be calculated. Which type of illumination should be used to measure solar cells? In case of organic semiconductors, what are the main differences with what you wrote above? (10 pts)

c) Is the band-gap of the semiconductor an important parameter for the functioning of a solar cell? In what way? Which will be the difference between the JV characteristics of a device made with a semiconductor of 3.2 eV band gap and of 1.2 eV band-gap. (10 pts).

Exam Device Physics 3-4-2023 8:30-10:30

Write the answer to each of 4 questions on a separate sheet. Please put your name and study number on each. Total 100 points

Question 1 (30 pts total)

A semiconductor has a bandgap E_g, and an effective density of states for electrons N_C and for holes N_V. The temperature is T. A pn junction is formed by doping the semiconductor with a donor density N_D and an acceptor density N_A. The semiconductor is in the extrinsic regime.

a) Give an expression for the position of the Fermi energies in the (bulk) p and n doped regions. (6 pts)

b) Draw and explain the band structure of a pn junction in equilibrium. Describe why depletion regions are formed. Give the expression for the widths of the depletion regions in the p and n regions. (6 pts)

c) Describe how/if the band diagram changes for equilibrium, forward and reverse directions. Make drawings. (6pts)

d) Give the expression for the I/V characteristics of a pn junction. Describe in a few lines why the I/V characteristic has this form. Explain which properties of the semiconductor influence the I/V characteristic. (6 pts)

e) Describe the role of electron-hole recombination in a pn junction. In what regions of the pn junction can it occur, and why? Is there a difference in recombination when the pn junction is in equilibrium, or in forward or reverse bias? (6 pts)

Question 2 (20 pts total)

Consider a metal-insulator-semiconductor (MIS) junction. The semiconductor is n-doped.

a) Give the band diagram for the following regimes: 1) flatband condition, 2) depletion regime, 3) inversion regime, 4) accumulation regime. Describe for these regimes where the mobile carriers are, and what type they are (electrons/holes). (6 pts)

b) Derive the expression for the density of states in 2 dimensions. (6pts)

c) Describe how you can make a 2 dimensional electron gas using a MIS junction. What are the requirements (for example: for the properties of the semiconductor, the insulating barrier, temperature and gate voltage) to realize such a system? (8 pts)

(A)

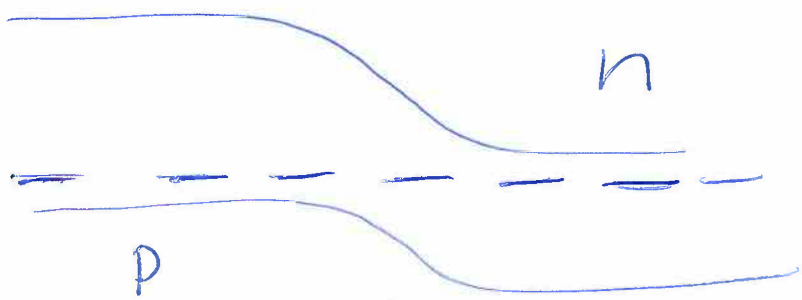
1 a) $n = N_c \exp\left(\frac{E_F - E_C}{kT}\right)$ $n = N_D$

$N_D = N_c \exp\left(\frac{E_F - E_c}{kT}\right)$ $E_F = E_c + kT \ln\left(\frac{N_D}{N_c}\right)$

$p = N_v \exp\left(\frac{E_v - E_F}{kT}\right)$ $p = N_A$

$N_A = N_v \exp\left(\frac{E_v - E_F}{kT}\right)$ $E_F = E_v - kT \ln\left(\frac{N_A}{N_v}\right)$

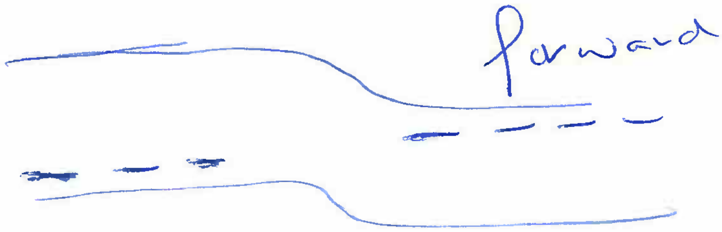
b)

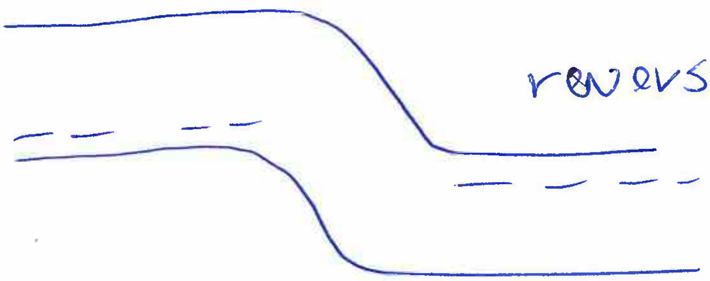


depletion region to overcome band shifts and V_{bi}

See lecture notes

c)





d) $I = I_0\left(\exp\left(eV/kT\right) - 1\right)$

doping, bandgap, temperature, recombination

(B)

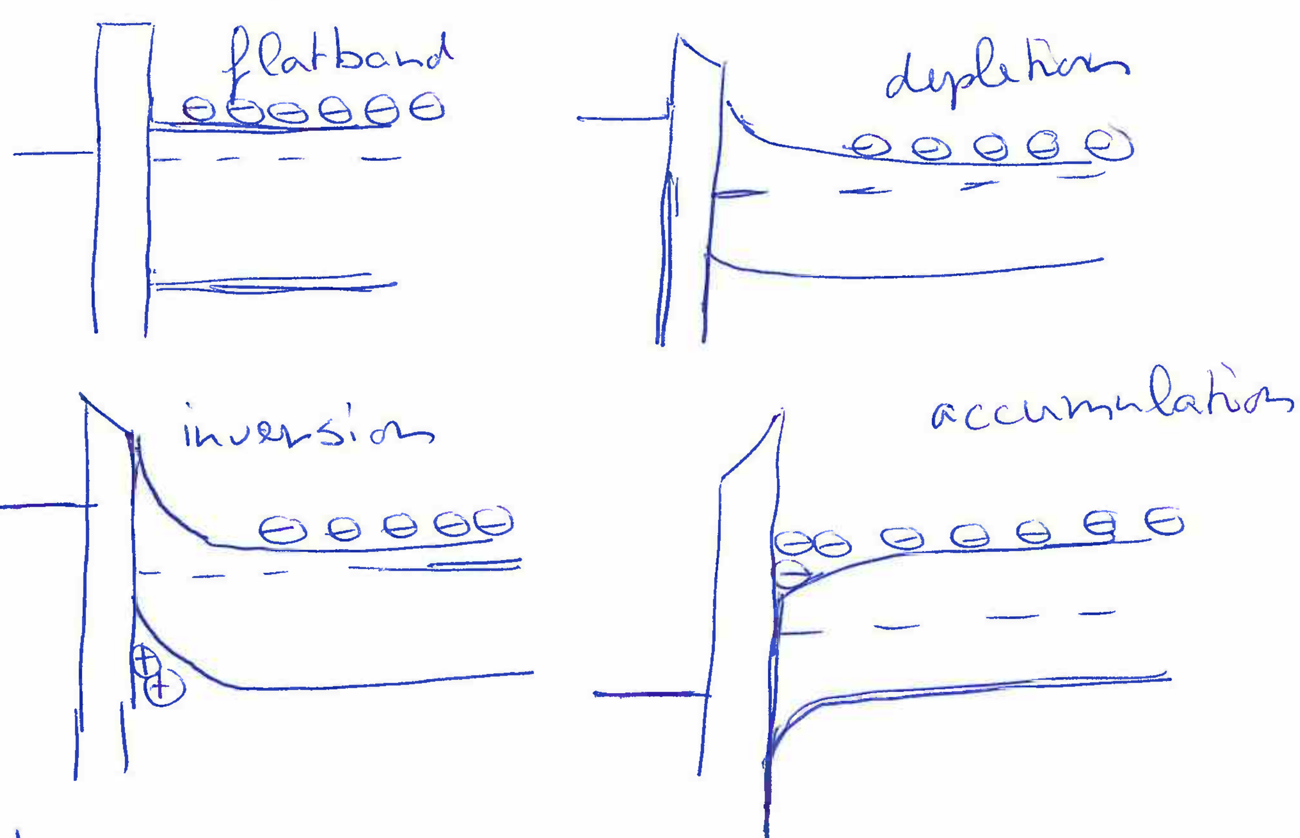
e) in equilibrium: recombination = generation

forward: recombination in depletion region also due to minority carrier injection.

reverse: generation in depletion region dominates

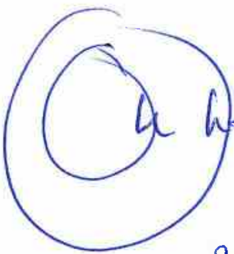
2)

a)



b)

$\Delta k = \frac{2\pi}{L}$ area $= (\Delta k)^2 = \left(\frac{4\pi}{L}\right)^2$



k $k+dk$

$\text{total} = 2 \cdot \frac{2\pi k \, dk}{\left(\frac{4\pi}{L}\right)^2}$

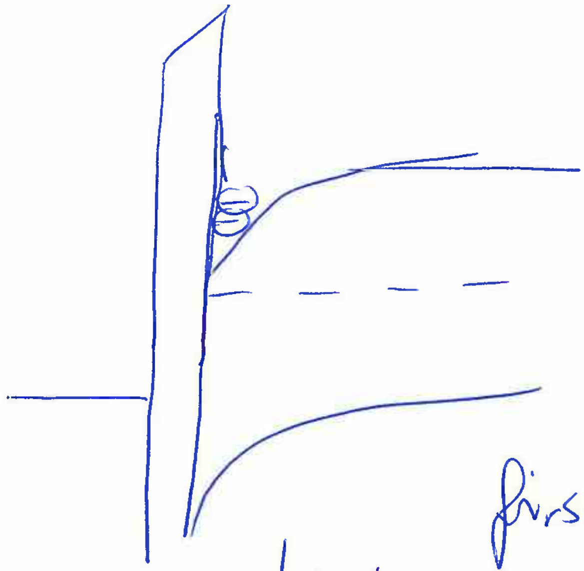
↑ spin

$E = \frac{\hbar^2 k^2}{2m^*}$ $dE = \frac{\hbar^2}{m^*} k \, dk$

$\text{total} = \frac{2}{\left(\frac{2\pi}{L}\right)^2} \cdot 2\pi \frac{\hbar^2}{m^*} dE$ $\text{DOS} = \frac{\hbar^2}{m^* \pi}$

(C)

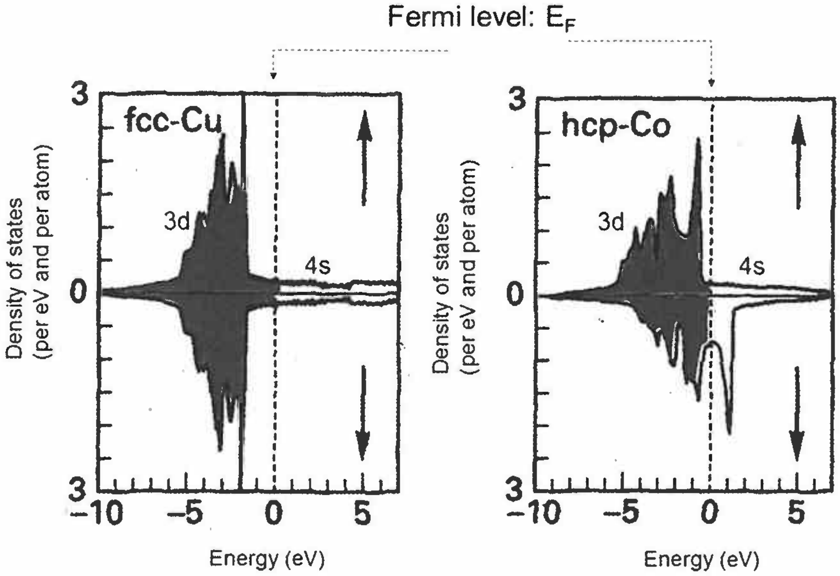
c)



create inversion
charge density such
that E_F is inbetween
first and second quantized state
& temperature < $E_2 - E_1$

Question Spintronics Banerjee 2023

Q1 a: With the help of a simple drawing discuss the differences between the density of states in ferromagnetic Cobalt from that of metallic Copper close to the Fermi level. (5 pts)



The differences lies when we consider magnetization and spin polarization. Magnetization is defined as $M = N^{maj} - N^{min}$ Integrated over <u>all</u> the electrons at <u>all</u> energies (this must be mentioned). By this definition Magnetization of Cu=0 and that of Co is not equal to 0. By the same analogy spin polarization defined as $P(E_F) = \frac{N^{maj}(E_F) - N^{min}(E_F)}{N^{maj}(E_F) + N^{min}(E_F)}$ in Co is finite but that in Cu is zero.

b. Using a parallel resistor model for a simple spin valve structure such as Co/Cu/Co derive the parallel and antiparallel state resistance of such a structure, when the thickness of both the Co layers are t_f and that of non-magnetic Cu t_nm and corresponding resistivities being ρ_f(M,m) and ρ_nm. (12 pts)

$$R\_P=\frac{2(\rho_M t_F+\rho_{mt_F}+\rho_{st_S})}{(2\rho_{Mt_F}+\rho_{st_S})(2\rho_{mt_F}+\rho_{Ft_S})} \qquad R\_AP=\frac{2(\rho_{Mt_F}+\rho_{st_S}+\rho_{mt_F})}{(\rho_{Mt_F}+\rho_{st_S}+\rho_{mt_F})(\rho_{mt_F}+\rho_{st_S}+\rho_{Mt_F})}$$

These need to be solved in detail, not just writing the above term, use the parallel resistor model (was a homework assignment) and to be expressed in terms of the required parameters as asked in the question.

c. Does the Giant magnetoresistance ratio depend on the spin dependent scattering in the bulk or of the interface? (3 pts)

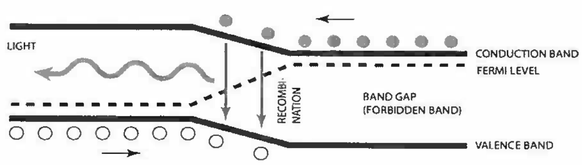
It depends on both. Bulk spin dependent scattering is related to the spin scattering asymmetry of majority and minority spins (spin diffusion lengths being different for both spin types) whereas several experiments have showed interfaces when interchanged for the same layer stack also yields differences in GMR.

E

Questions Maria

a) Describe the working mechanism and draw the energy/band diagrams of an heterostructure optimised for the fabrication of inorganic LEDs. Sketch the JV characteristics of the device. Which type of heterostructure will give the best performance? How many layers will give the maximum performances, which is the function of this layers? (10 points)

A Light emitting diode (LED) is essentially a pn junction diode. When carriers are injected across a forward-biased junction, it emits incoherent light. Most of the inorganic semiconductor LEDs are using a highly doped n and a p-junction.
When a Voltage V is applied across the junction, the built-in potential is reduced. This allows the electrons from the n side to get injected into the p-side (and vice versa). Since electrons are the minority carriers in the p-side, this process is called minority carrier injection. These electrons injected into the p-side recombine with the holes (in the depletion region). This recombination results in spontaneous emission of photons (light).

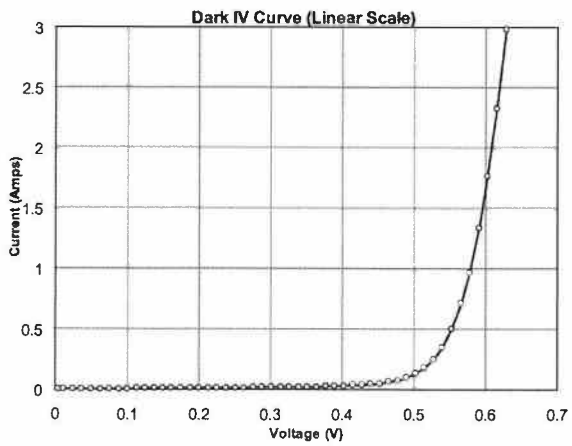


The equation governing this device is the Shockley equation which has the general form:

$$J \quad J_p \quad J_n \quad J_s(e^{qV/kT} \quad 1)$$

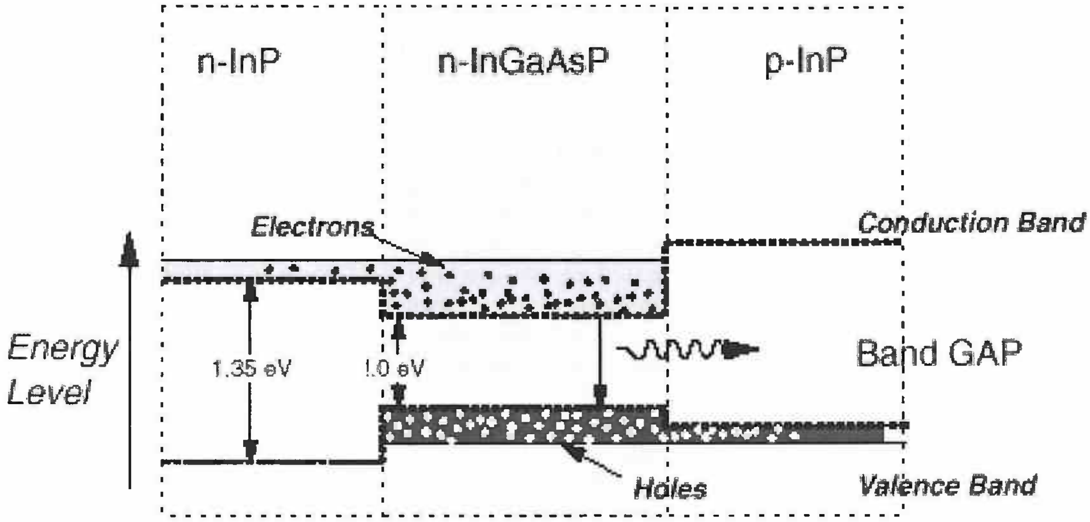
$$\frac{qD_p p_{n0}}{L_p} \quad \frac{qD_n n_{p0}}{L_n} \quad (e^{qV/kT} \quad 1)$$

And the following IV characteristics.



The highest efficiency will be obtained by direct band-gap semiconductors.
Optimised devices use typeI heterostructure with the aim to quantum confine in a high QY material the injected charges.

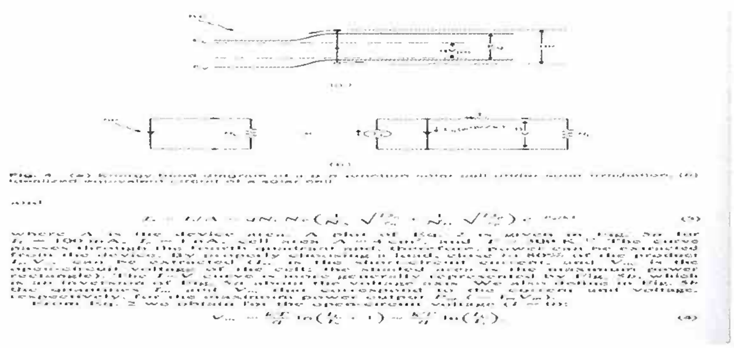
- One of the most efficient device structures is the double heterostructure. See in Figure below. This is a structure where the type I heterostructure configuration is utilized.
Best efficiencies are obtained with 3 layers+ electrodes or 5 layers + electrodes. Cathode, Hole blocking layer, electron transport layer, recombination layer, hole transport layer, electron blocking layer, Anode.



Bandgap boundaries are denoted by dotted lines

b) Describe the working mechanism and draw the energy/band diagrams of an inorganic solar cell. Draw the JV characteristics in dark and under illumination and write down how the efficiency of a solar cell can be calculated. Which type of illumination should be used to measure solar cells? In case of organic semiconductors, which one are the main differences with what you wrote above? (10 points)

The energy band diagram of a p-n junction solar cell is:



There are two causes of charge carrier motion and separation in a solar cell:

- drift of carriers, driven by the electric field, with electrons being pushed one way and holes the other way

- diffusion of carriers from zones of higher carrier concentration to zones of lower carrier concentration (following a gradient of chemical potential).

These two "forces" may work one against the other at any given point in the cell. For instance, an electron moving through the junction from the p region to the n region (as in the diagram above) is being pushed by the electric field against the concentration gradient. The same goes for a hole moving in the opposite direction.

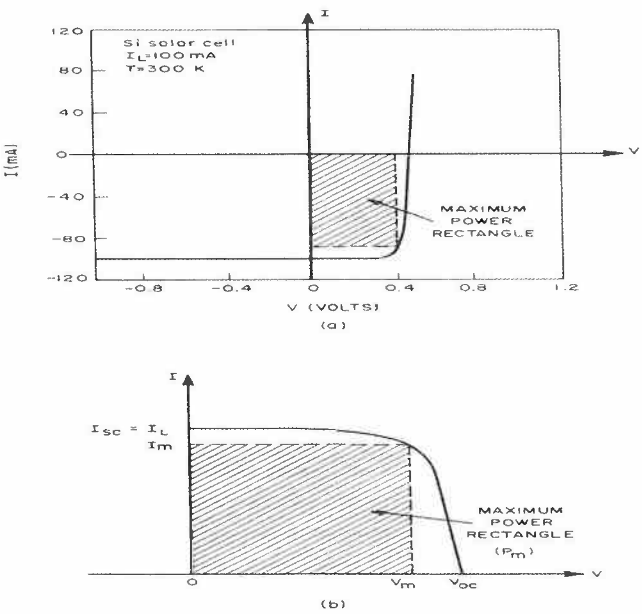
It is easiest to understand how a current is generated when considering electron-hole pairs that are created in the depletion zone, which is where there is a strong electric field. The electron is pushed by this field toward the n side and the hole toward the p side. (This is opposite to the direction of current in a forward-biased diode, such as a LED in operation.) When the pair is created outside the depletion region, where the electric field is smaller, diffusion also acts to move the carriers, but the junction still plays a role by sweeping any electrons that reach it from the p side to the n side, and by sweeping any holes that reach it from the n side to the p side, thereby creating a concentration gradient outside the depletion region.

A solar cell is always a type II heterostructure

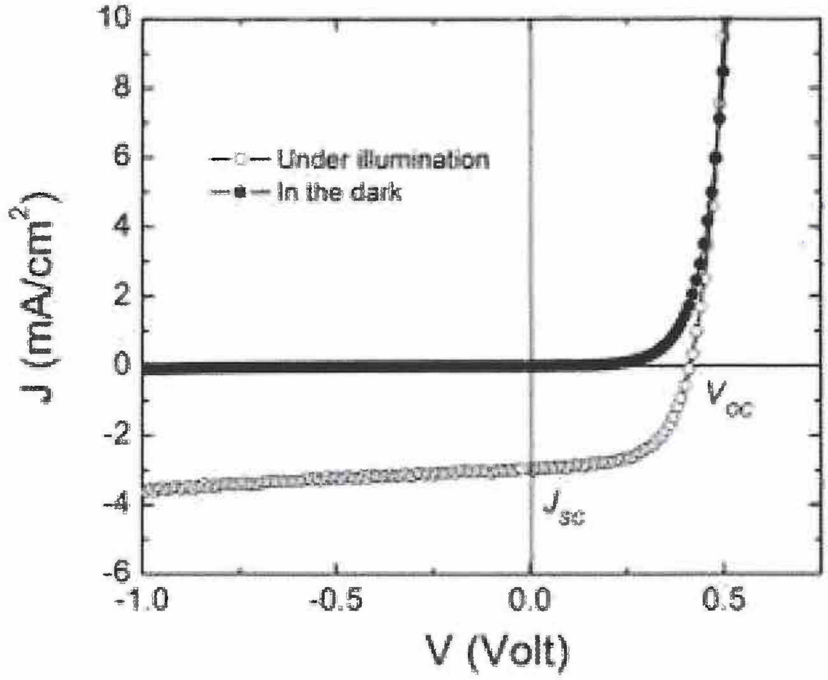
The general equation governing this device is:

$$I \quad I_s(e^{qV/kT} \quad 1) \quad I_L$$

Which result under illumination in the following JV characteristics.



The JV characteristics in the dark and under illumination are as follows:



The efficiency is calculated using the following equation:

$$\frac{I_m V_m}{P_{in}} \quad \frac{FF\ I_L V_{oc}}{P_{in}}$$

Where Im and Vm are the maximum voltage and current and Pin is the power of the light incident normalized for the area of the cell. IL is the short circuit current, Voc is the open circuit voltage and FF is the fill factor.
The standard for characterizing a solar cell is called AM1.5 and correspond to the situation in which the sun makes an angle of 48.2° respect to the Zenith. It is an average of the irradiation on the planet along the whole year.

c) Is the band-gap of the semiconductor an important parameter for the functioning of a solar cell? In which way? Which will be the difference between the JV characteristics of a device made with a semiconductor of 3.2 eV band gap and of 1.2 eV band-gap. (10 points).

The band-gap of the active semiconductor is fundamental in determining the maximum efficiency achievable. As the light source is our sun, therefore a light source where UV light is not very strong and visible and NIR light is rather intense the maximum efficiency will be for semiconductors of band-gap around 1.2 eV. Therefore the 3.2 eV solar cell will give a large Voc (around 3V), with a small current (few photons are present in the solar spectrum at that energy). The 1.2 eV band gap will give a small voltage (about 0.7V) with a large current.

Below is an example on how the JV characteristics will progress with increasing band gap. The band gaps are different than in the question.