D. J. SANGHVI COLLEGE OF ENGINEERING
DEPARTMENT OF ELECTRONICS ENGINEERING
ELECTRONIC DEVICES SEM III
WEEK 1 TEST

N.B. : **[Total Marks: 100]**

1) Answer questions on the question paper **itself**.
2) Write your **SAP ID** on the top of the first page.
3) This test is based on **semiconductor fundamentals** topic.

1. **Important Definitions:** Please write a brief definition of each of the following terms. Please write your answers in the space provided below. **[30]**

Conduction Band: The lowest unfilled energy band in a semiconductor.(Contains no electrons at $0K$.)

Valence Band: The highest filled energy band in a semiconductor. (Is completely full at $0K$.)

Band Gap: The energy gap between the top of the valence band and the bottom of the conduction band.

Intrinsic Semiconductor: An undoped semiconductor whose properties are native to the semiconductor itself and not determined by dopants.

Extrinsic Semiconductor: A semiconductor whose properties are the result of the presence of impurities (dopants) in the semiconductor.

Majority Carriers: The carrier type (i.e. electrons or holes) that is more abundant in a semiconductor.

Minority Carriers: The carrier type that is less abundant in a semiconductor.

Fermi Level: The energy level at which 50% of available states are occupied by electrons. (There does not actually have to be a state at this level, as is often the case in semiconductors).

n^+ **Material**: A semicondutor with heavy n-type doping, often at the $10^{18}cm^{-3}$ level or higher.

p^+ **Material**: A semicondutor with heavy p-type doping, often at the $10^{18}cm^{-3}$ level or higher.

[TURN OVER

Degenerate Material: A semiconductor with a very high doping level, such that the Fermi level is near or within the valence or conduction band edge, making it behave more like a metal.

Minority Carrier Lifetime: The average time that a minority carrier can exist in a semiconductor before it recombines with a majority carrier.

Photo-generation: The process by which carriers are generated in which a photon is absorbed by a semiconductor and excites an electron from the valence band into the conduction band.

Equilibrium: Describes a state of a thermodynamic system in which there is no net flow of energy or matter. This represents a minimum energy and maximum entropy of the system. A semiconductor cannot be at equilibrium if there is an applied electric field or current flow.

Law of Mass Action: It tells us that at equilibrium, the product of the electron concentration and the hole concentration are equal to the square of the intrinsic carrier concentration.

2. Indicate which of the following statements are true: Tick on the correct options: **[02]**

The conduction band is the highest filled energy band in a semiconductor or an insulator. It is completely full at $0K$.

The Fermi level inside a semiconductor is also the chemical potential of the electrons in the material.

Equilibrium occurs in a system when its properties do not change with time. This could occur in the presence of an applied electric field or other driving force.

Fermi level is the energy level at which 50% of available states are occupied by electrons.

At equilibrium, the product of n_0 and p_0 is a constant.

Explanation:

The conduction band is the lowest unfilled energy band in a semiconductor or an insulator. It contains no electrons at $0K$.

The first part of statement 3 is correct: Equilibrium occurs in a system when its properties do not change with time. However, equilibrium conditions cannot be met in the presence of a driving force, such as an applied electric field.

3. Which of the following statements are true. Tick on the correct options: **[02]**

In order to make intrinsic semiconductors, dopant impurity levels must be kept very low.

Group-III elements can be used as n-type dopants in silicon.

Group-III elements can be used as p-type dopants in silicon.

Group-V elements can be used as p-type dopants in silicon.

Group II, IV, and VI elements can all be suitable dopants for GaAs.

4. How many Joules in an electron volt ? **[01]**

1

9.22×10^{-31}

1.38×10^{-23}

6.63×10^{-34}

$\checkmark 1.6 \times 10^{-19}$

5. Which of the following is true about the conduction(valence band) ? **[01]**

It is mostly full(empty) of electrons

It is mostly empty(full) of electrons

Both are exactly half full of electrons

Both are mostly empty of electrons

Both are mostly full of electrons

6. Which of the following is true about an intrinsic semiconductor ? **[01]**

Electron concentration n equals hole concentration p

The concentration of electrons is n_i

The concentration of holes is n_i

The concentration of electrons and holes increases with increasing temperature

All of the above

7. Where is a donor level located on an energy band diagram ? **[01]**

Far above E_C

A little below E_C

About midway between E_C and E_V

A little above E_V

Way above E_V

8. Which of the following is true in equilibrium ? **[01]**

$n = n_i = 1/p$

$n = n_i$

✓ $p_i = n_i$

✓ $np = n_i^2$

$p = p_i$

9. What is the mathematical statement of space-charge neutrality ? **[01]**

$n + N_A^- = p + N_D^+$

10. Velocity, mobility, and electric field are related by $v = \mu E$. What are the units of mobility ? **[01]**

cm/s

cm^2/s

$cm^2.V/s$

✓ $cm^2/(V.s)$

$cm^2.V.s$

11. As the doping of a semiconductor increases, the mobility generally: **[01]**

Stays the same

Increases

Decreases

First increases, then decreases

First decreases, then increases

12. The Einstein relation relates what two quantities ? **[01]**

The diffusion coefficient and the minority carrier lifetime

The diffusion length and the minority carrier lifetime

The hole and electron mobilities

The mobility and the diffusion coefficient

The hole and electron diffusion coefficient

13. Which of the following is the minority carrier diffusion length ? **[01]**

$L_n = \sqrt{\mu_n/\tau_n}$

$L_n = \sqrt{D_n/\tau_n}$

$L_n = \sqrt{\mu_n \tau_n}$

✓ $L_n = \sqrt{D_n \tau_n}$

$L_n = D_n \tau_n$

14. Which of the following describes the parameter τ_n in a p-type semiconductor **[01]**

It is the average time it takes for an electron to diffuse across the region.

It is the average time between scattering events.

It is the average time before a minority carrier electron recombine with a hole.

It is the average time for an electron to drift across the region.

None of the above

15. a) For intrinsic Silicon, what is the intrinsic carrier concentration (in carriers per cm^3) at room temperature? **[02]**

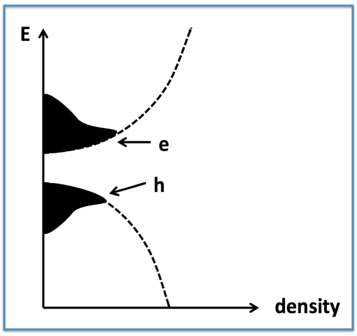
n_i in (cm^3) :

$n_i = 10^{10}/cm^3$ **at room temperature**.

b) How many orders of magnitude lower is the intrinsic carrier concentration in silicon compared to the concentration of atoms in the crystal ? (For example, the number 10 is two orders of magnitude smaller than the number 1000)

The density of Si atoms is $5 \times 10^{22}/cm^3$**. This roughly 12 orders of magnitude lower than the intrinsic carrier concentration.**

16. Identify the following diagrams: Tick the correct option.
Diagram 1: What does the shaded region represent? **[02]**



Density of States for an intrinsic semiconductor

Density of States for an n-type semiconductor

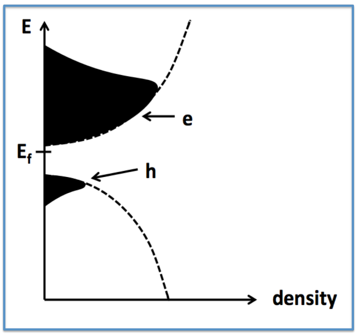
Density of States for an p-type semiconductor

Carrier Distribution in an intrinsic semiconductor

Carrier Distribution in an n-type semiconductor

Carrier Distribution in an p-type semiconductor

17. Identify the following diagrams: Tick the correct option.
Diagram 2: What does the shaded region represent? **[02]**



Density of States for an intrinsic semiconductor

Density of States for an n-type semiconductor

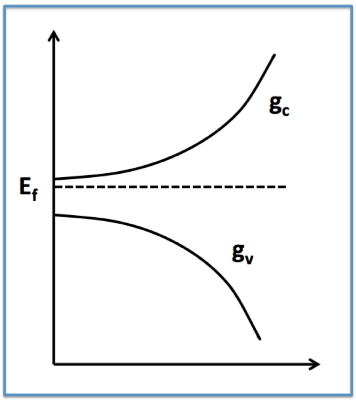
Density of States for an p-type semiconductor

Carrier Distribution in an intrinsic semiconductor

Carrier Distribution in an n-type semiconductor

Carrier Distribution in an p-type semiconductor

18. Identify the following diagrams: Tick the correct option. **[02]**



Density of States for an intrinsic semiconductor

Density of States for an n-type semiconductor

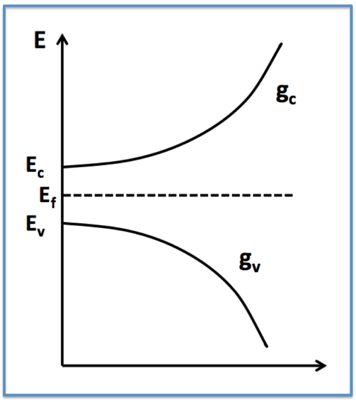
Density of States for an p-type semiconductor

Carrier Distribution in an intrinsic semiconductor

Carrier Distribution in an n-type semiconductor

Carrier Distribution in an p-type semiconductor

19. Identify the following diagrams: Tick the correct option. **[02]**



Density of States for an intrinsic semiconductor

Density of States for an n-type semiconductor

Density of States for an p-type semiconductor

Carrier Distribution in an intrinsic semiconductor

Carrier Distribution in an n-type semiconductor

Carrier Distribution in an p-type semiconductor

20. Assume that a piece of silicon at room temperature is doped with 10^{16} cm^{-3} phosphorus atoms. What is the hole concentration in the material ? **[02]**

p (in cm^3) : $10^4/cm^3$

Explanation: We can assume that all of the donor atoms are ionized;

$N_D = n = 10^{16}/cm^3$

$np = n_i^2$

In silicon at room temperature: $n_i = 10^{10}/cm^3$

$10^{16}p = (10^{10})^2$

$p = 10^4/cm^3$

21. Problem on Fermi−Dirac Function: **[03]**

Let's assume that we have an impurity level that is located $0.05eV$ below the Fermi level in silicon. What is the probability that this state is occupied at $300K$? Given: $KT = 0.026eV$

P(occupation) : 0.87

Explanation: The Fermi function tells us the probability that a state is occupied:

$f(E) = 1/\{1 + exp(E - E_F)/kT\}$

$(E - E_F) = -0.05eV$

$kT = 0.026eV$

$f(E) = 0.87$

22. A semiconductor is doped with acceptor impurities with density $N_A = 10^{19}\ cm^{-3}$. The impurity level is at $E_g/5$ above E_v, $E_g = 20kT$, E_i is $10KT$ above E_v and $E_f = 5kT$ above E_v (note that T, the temperature, is not necessarily room temperature). The effective masses for electrons and holes are same. **[10]**

What fraction of acceptors are ionized ?

Explanation:

P(Acceptor Ionized)=$f(E) = 1/\{1 + exp[-(E_F - E_A)/kT]\}$

Draw band digram and locate E_F and E_A with respect to E_V and E_C, thus we get

$E_F - E_A = 5kT - 4kT$

P(Acceptor Ionized)=$f(E) = 1/\{1 + exp(-1)\}$

P(Acceptor Ionized)=0.73

What is n_i ?

Explanation:

Since 73% of acceptors are ionized, we can write

$p = 0.73N_A = 0.73 \times 10^{19}/cm^3$

$p = n_i\, exp\left[(E_i - E_F)/kT\right]$

$E_i - E_F = 5kT$

$0.73 \times 10^{19} = n_i\, exp(5)$

$n_i = 4.92 \times 10^{16}/cm^3$

What are the values of n and p ?

Explanation:

$p = 0.73 N_A = 0.73 \times 10^{19}/cm^3$ (from previous problem)

$pn = n_i^2$

$n_i = 4.92 \times 10^{16}/cm^3$ (from previous problem)

$n = 2.4 \times 10^{13}/cm^3$

23. Problem on Drift Transport

Assume that you have a piece of silicon doped with $10^{16}/cm^3$ of phosphorus atoms. Assume that you apply an electric field of $5kV/cm$ across the silicon. At this doping level, $\mu_n = 1248 cm^2/Vs$ and $\mu_p = 437 cm^2/Vs$ in silicon at room temperature. **[06]**

What is the velocity of the electrons in the silicon under these conditions

v_d (in cm/s) : $6.24 \times 10^6 cm/s$

Explanation:

$v_d = \mu E$

$v_d = (1248 cm^2/Vs)(5000V/cm) = 6.24 \times 10^6 cm/s$

What current density does this correspond to ?

J (in A/cm^2) : 9984 A/cm^2

Explanation:

Since $n >> p$

$J = qn\mu_n E$

Plugging all the values from the problem, we get:

$J = 9984\ A/cm^2$

What is the conductivity of the silicon under the conditions described above ?

σ (in S/cm) : 1.9968

Explanation:

$\sigma = J/E = 9984/5000$

$\sigma = 1.9968 S/cm$

24. Problem on Einstein Relation **[02]**

At room temperature, electrons in GaAs have a mobility of about $7000 cm^2/Vs$ at a doping level of $10^{16}/cm^3$. Calculate the diffusion coefficient of electrons in GaAs at this doping concentration at room temperature.

D_n (in cm^2/s) : 182 cm^2/s

Explanation:

Einstein relation is: $D_n/\mu_n = kT/q$

$kT/q = 0.026V$

$D_n = 182\ cm^2/s$

25. Find the Fermi potential for a p-type Si semiconductor having dopant concentration $N_A = 10^{16}/cm^3$. Given: $n_i = 10^{10}$, $kT/q = 26mV$: **[02]**

ϕ_{F_p} in (Volts): 0.36 V

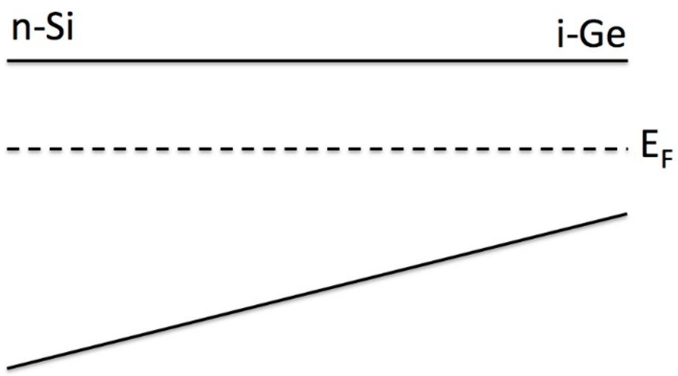
Explanation:

$$\phi_{F_p} = \frac{kT}{q} ln\left(\frac{N_A}{n_i}\right)$$

$$\phi_{F_p} = 26 \times 10^{-3} ln\left(\frac{10^{16}}{10^{10}}\right)$$

$$\phi_{F_p} = 0.36 \text{ Volts}$$

26. Consider the band diagram shown below, and then answer the following questions: **[10]**



Is the semiconductor at equilibrium ?

Yes

No

Explanation:

The fermi level is flat; therefore the semiconductor is at equilibrium.

What is the direction of electron diffusion ?

The electrons diffuse from left to right

The electrons diffuse from right to left

There is no net electron diffusion current

Explanation:

There is no concentration gradient of electrons; therefore there is no electron diffusion.

What is the direction of electron drift?

The electrons drift from left to right

The electrons drift from right to left

There is no net electron drift current

Explanation:

Because there is no electron diffusion current, there is no electron drift current opposing it.

What is the direction of hole diffusion ?

The holes diffuse from left to right

The holes diffuse from right to left

There is no net hole diffusion current

Explanation:

The concentration of holes is higher on the right hand side than on the left hand side. Therefore, the holes diffuse from right to left.

What is the direction of hole drift?

The holes drift from left to right

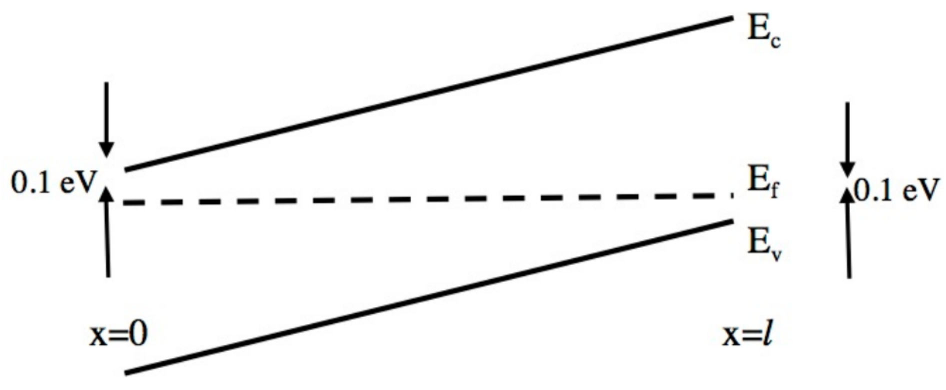
The holes drift from right to left

There is no net hole drift current

Explanation:

Holes drift up the band. Therefore, the holes diffuse from left to right.

27. Consider a piece of Si with a band structure as shown below. At each end of the sample, the energy difference between the Fermi level and the band edge is $0.1eV$. Take $E_g = 1.1eV$ and neglect the mobility and mass difference between electrons and holes. **[10]**



Indicate which of the following statements with regards to the band structure shown are true:

A dopant concentration gradient could cause the bands to behave in the manner shown.

An externally applied electric field could cause the bands to behave in the manner shown.

This material does not have an internal electric field.

A hole would have a lower energy on the right side of the diagram than on the left.

Explanation:

Because the bands are slanted, there is an internal electric field where the higher energies are on the right. However, this band structure cannot be a result of an externally applied electric field, because the fermi level is flat, which implies that the material is under equilibrium conditions.

What is the direction of electron diffusion ?

The electrons diffuse from left to right

The electrons diffuse from right to left

There is no net electron diffusion current

What is the direction of electron drift?

The electrons drift from left to right

The electrons drift from right to left

There is no net electron drift current

What is the direction of hole diffusion ?

The holes diffuse from left to right

The holes diffuse from right to left

There is no net hole diffusion current

What is the direction of hole drift?

The holes drift from left to right

The holes drift from right to left

There is no net hole drift current

Explanation:

Carrier diffusion occurs along the concentration gradient. Since there is a higher concentration of electrons on the left because there are more available electron states, electrons will diffuse from left to right. Similarly, there are a greater number of available hole states on the right, so holes will diffuse from right to left.

There is also an internal electric field which points to the right. Since electrons have a negative charge, they will travel in the opposite direction of the field, moving from right to left. Holes have a positive charge, so they will move from left to right in the direction of electric field.

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