BENHA UNIVERSITY
FACULTY OF ENGINEERING (SHOUBRA)
ELECTRONICS AND COMMUNICATIONS ENGINEERING

# CCE 201
# Solid State Electronic Devices

(2022 - 2023) term 231

## Lecture 3: Semiconductor Physics (part 3).

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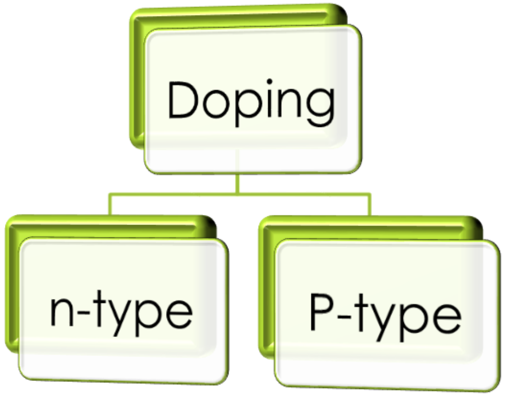
# Outlines

- Revision.
- Charge Neutrality.
- Summary.

# Revision:



- Q: Why can thermal generation not be used to affect meaningful current conduction?
  - A: Silicon crystal structure described previously **is not sufficiently conductive at room temperature**.
  - Additionally, a dependence on temperature is not desirable.
- How can this "problem" be fixed?
  - A: **doping** is the intentional introduction of impurities into an extremely pure (intrinsic) semiconductor for the purpose changing carrier concentrations.



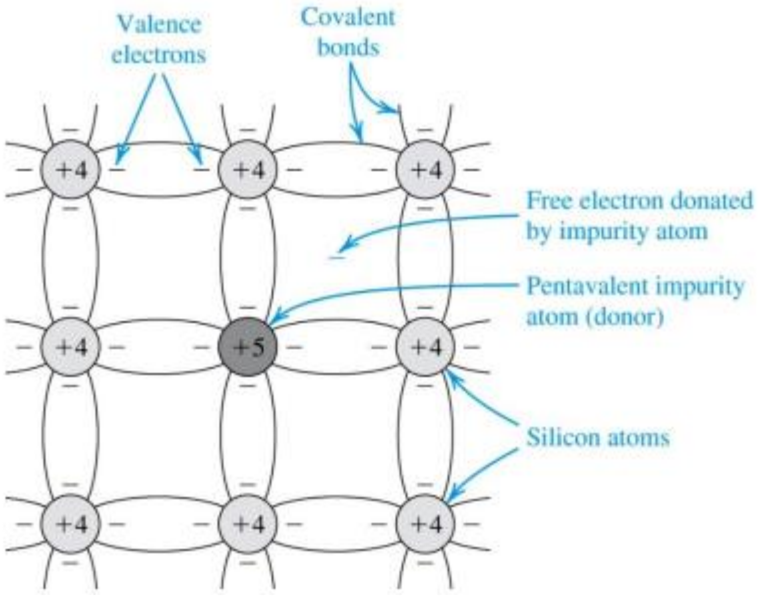
# Revision:

- **Doped Semiconductors** :

A semiconductor material that has been subjected to the doping process is called an extrinsic material

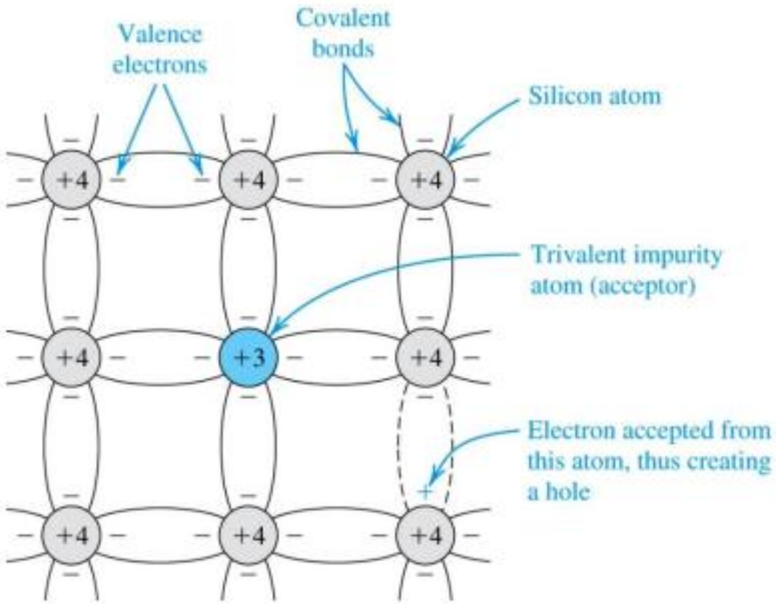
## n-type semiconductor

- Silicon is doped with element having a valence of 5.
- To increase the concentration of free electrons (n).
- electrons are the majority charge carriers.
- holes are the minority charge carrier.
- One example is phosphorus, which is a donor.




## p-type semiconductor

- Silicon is doped with element having a valence of 3.
- To increase the concentration of holes (p).
- holes are the majority charge carriers.
- electrons are the minority charge carrier.
- One example is boron, which is an acceptor.



# Revision:



$$F(E) = \frac{1}{1+e^{[(E-E_F)/kT]}}$$

$$n_i = N_C e^{-(E_C-E_{Fi})/kT}$$

$$n = n_i \exp\left(E_F - E_{Fi}/KT\right)$$

$$N_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}$$

$$p_i = N_v e^{-(E_{Fi}-E_V)/kT}$$

$$p = n_i \exp\left(E_{Fi} - E_F/KT\right)$$

$$N_v = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}$$

$$n_i = \sqrt{N_c N_v} e^{(-E_g/2kT)}$$

$$E_{Fi} = \frac{E_C+E_V}{2} + \frac{kT}{2}\ln\frac{N_V}{N_C}$$

$$E_{Fi} = \frac{E_C+E_V}{2} + \frac{3}{4}kT\ln\frac{m_h}{m_e}$$

$$E_{Fn} = E_{Fi} + kT\ln\frac{n}{n_i}$$

$$E_{Fp} = E_{Fi} - kT\ln\frac{p}{n_i}$$

# Outlines

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# Charge Neutrality Equation:



- So far, we have learnt how to calculate the carrier concentrations n and p if we know the Fermi energy $E_F$ relative to $E_C$ or $E_V$.
- However, how do we know where is $E_F$? In fact, we do not know. What is in **our control is the doping concentration.**
- So, we need to be able to calculate the carrier concentrations from the impurity concentrations, ND and NA.

## What is charge neutrality equation?

- It is simply a statement of the charge neutrality condition.
- A semiconductor in equilibrium is charge neutral everywhere inside the sample. If it were not neutral, then there will be electric fields that will give rise to electric currents against the assumption of equilibrium.

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

**Negative ions** **Positive ions**

# Charge Neutrality Equation:



## Solution of charge neutrality equation (n-type):

From $n_n + N_A = p_n + N_D$ and $n_n \times p_n = n_i^2$

By solving these two equations, we get n and p

$$n_n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

Once n is known, p is obtained by using the equation.

$$p_n = \frac{n_i^2}{n_n}$$

# Charge Neutrality Equation:



## (n-type) Special cases

$$n_n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$n_n = \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2} \qquad N_A = 0$$

$$n_n = N_D - N_A \qquad \frac{N_D - N_A}{2} \gg n_i \text{ So we can neglect ni w.r.t. } \frac{N_D - N_A}{2}$$

$$n_n = N_D \qquad N_A = 0,\ N_D \gg n_i$$

Once n is known, p is obtained by using the equation. $p_n = \frac{n_i^2}{n_n}$

# Charge Neutrality Equation:



## Solution of charge neutrality equation **(p-type):**

From $n_p + N_A = p_p + N_D$ and $n_p \times p_p = n_i^2$

By solving these two equations, we get p and n

$$\frac{n_i^2}{p} + N_A = p + N_D$$

$$p^2 + (N_D - N_A)p - n_i^2 = 0$$

$$p_p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

Once p is known, n is obtained by using the equation.

$$n_p = \frac{n_i^2}{p_p}$$

# Charge Neutrality Equation:



## (n-type) Special cases

$$p_p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

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$$p_p = N_A \qquad N_D = 0,\ N_A \gg n_i$$

Once n is known, p is obtained by using the equation. $n_p = \dfrac{n_i^2}{p_p}$

# Example 1:



Consider an n-type silicon for which the dopant concentration is $N_D = 10^{17}/\text{cm}^3$. Find the electron and hole concentrations at $T = 300\text{K}$.

**Solution**

The concentration of the majority electrons is $n_n \simeq N_D = 10^{17}\ /\text{cm}^3$

The concentration of the minority holes is $p_n \simeq \dfrac{{n_i}^2}{N_D}$

In Example 1, we found that at $T = 300$ K, $n_i = 1.5 \times 10^{10}/\text{cm}^3$. Thus,

$$p_n \simeq \frac{(1.5 \times 10^{10})^2}{10^{17}} = 2.25 \times 10^3/\text{cm}^3$$

Observe that $n_n \gg n_i$ and that $n_n$ is vastly higher than $p_n$.

# Example 2:



For a silicon crystal doped with boron, what must $N_A$ be if at $T = 300$ K the electron concentration drops below the intrinsic level by a factor of $10^6$?

**Solution**

At 300 K, $n_i = 1.5 \times 10^{10}/\text{cm}^3$

$p_p = N_A$

Want electron concentration

$$= n_p = \frac{1.5 \times 10^{10}}{10^6} = 1.5 \times 10^4/\text{cm}^3$$

$$\therefore N_A = p_p = \frac{ni^2}{n_p}$$

$$= \frac{(1.5 \times 10^{10})^2}{1.5 \times 10^4}$$

$$= 1.5 \times 10^{16}/\text{cm}^3$$

# Example 3:



A silicon sample is doped with $2x10^{15}$ $cm^{-3}$ P atoms. If the background acceptor impurity concentration is $1x10^{15}$ $cm^{-3}$ calculate the electron and hole concentrations in this sample. Assume complete ionization of all the impurities and the intrinsic carrier concentration in Si at room temperature to be $10^{10}$ $cm^{-3}$.

**Solution**

$$n = N_D - N_A = 2x10^{15} - 1x10^{15} = 1x10^{15}\ cm^{-3}.$$

$$p = n_i^2/n = (10^{10})^2 / 1x10^{15} = 10^{20}/10^{15} = 10^5\ cm^{-3}.$$

# Example 4:



An n-type Si sample has a donor concentration of $10^{16}$ $cm^{-3}$. Suppose we want to convert this sample into p-type with a hole concentration of $5x10^{15}$ $cm^{-3}$, what impurity and at what concentration would you use?

Solution: $p = N_A - N_D \Rightarrow N_A = p + N_D = 5x10^{15} + 1x10^{16} = 1.5x10^{16}$ $cm^{-3}$. We need to use an acceptor impurity such as B at a concentration of $1.5x10^{16}$ $cm^{-3}$.

# Summary:

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

# END OF LECTURE

# BEST WISHES