18 February 2020

وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

24 جمادى الثانية 1441

Analog IC Design

Lecture 03
Review on Semiconductors Basics

Dr. Hesham A. Omran

Integrated Circuits Lab (ICL)
Electronics and Communications Eng. Dept.
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Outline

- What are semiconductors?
- Electrons and holes
- N-type and P-type silicon
- Drift and diffusion current
- The PN-junction

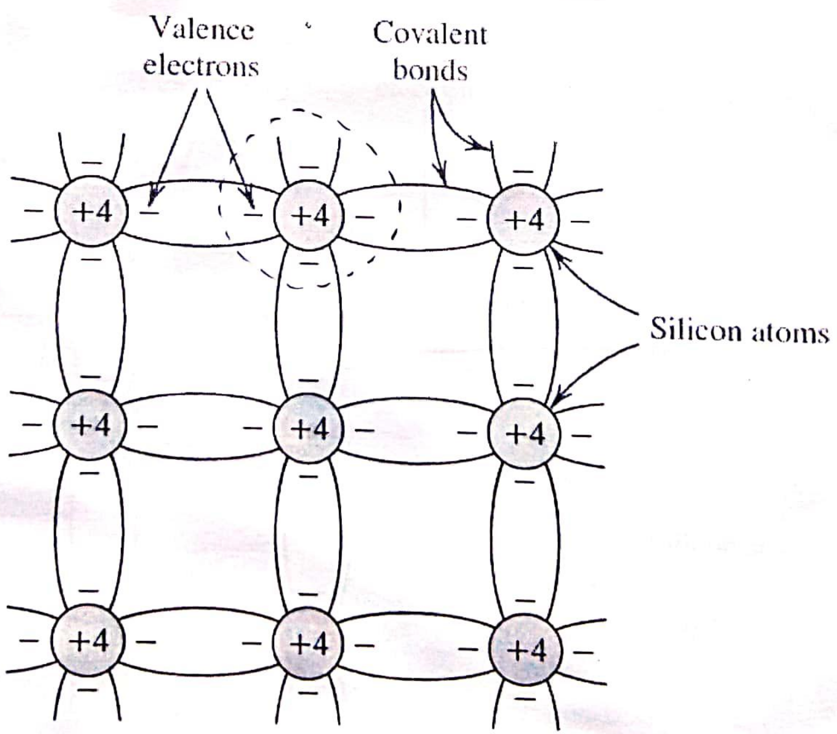
What are Semiconductors

- Conductors → Ex: copper
- Insulators → Ex: glass
- Semiconductors are materials whose conductivity lies between that of conductors and insulators
- **What is so special about semiconductors?**
  - ★ The electrical conductivity can be dramatically changed by introducing extrinsic dopant atoms → by orders of magnitude.
  - We have two types of carriers: electrons and holes
- Silicon (Si) is the semiconductor material used in the majority of today's electronic devices

"Era of Solid State Electronics"

Silicon Crystal

- Covalent bonds are formed by sharing of the valence electrons
- At 0 K, all bonds are intact and no free electrons are available



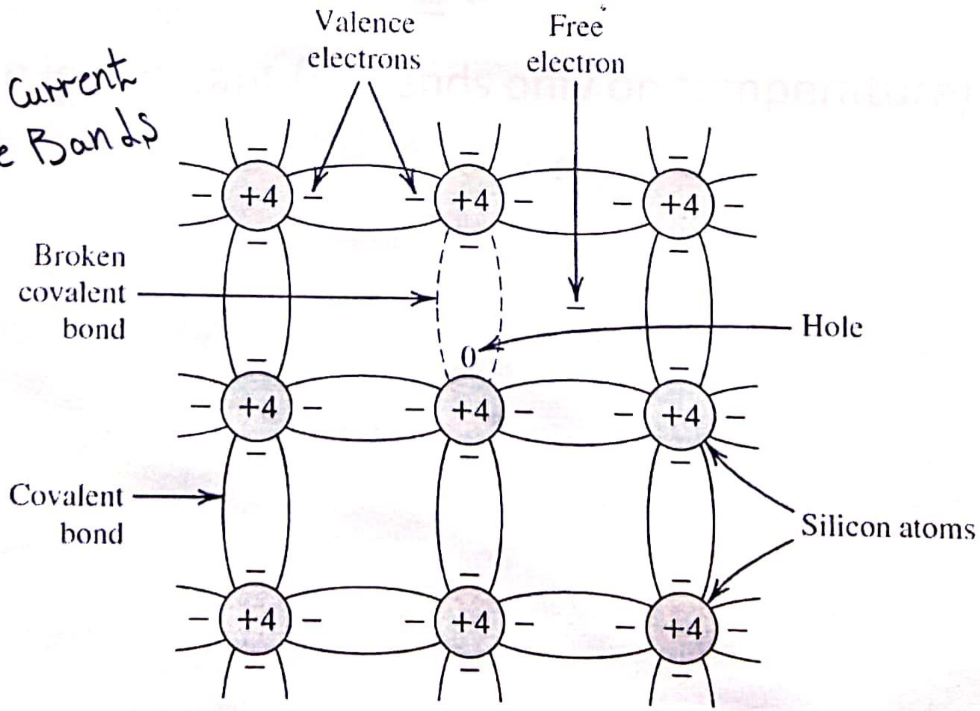
[Sedra/Smith, 2015]

Electrons and Holes

- ❑ At room temperature, some of the covalent bonds are broken by thermal generation
- ❑ Each broken bond gives rise to a free electron (e^-) and a hole (h^+)
  - Both e^- and h^+ become available for current conduction

in Conduction Bands

Conducts Current in Valence Bands



[Sedra/Smith, 2015]

Pure

Intrinsic Silicon

- Carrier concentration is the number of charge carriers per unit volume (cm^3)
- At thermal equilibrium, the recombination rate is equal to the generation rate
- The concentration of free electrons (n) is equal to the concentration of holes (p)

$$n = p = n_i$$

- The product of n and p is constant (depends only on temperature) → "Math Action Law"

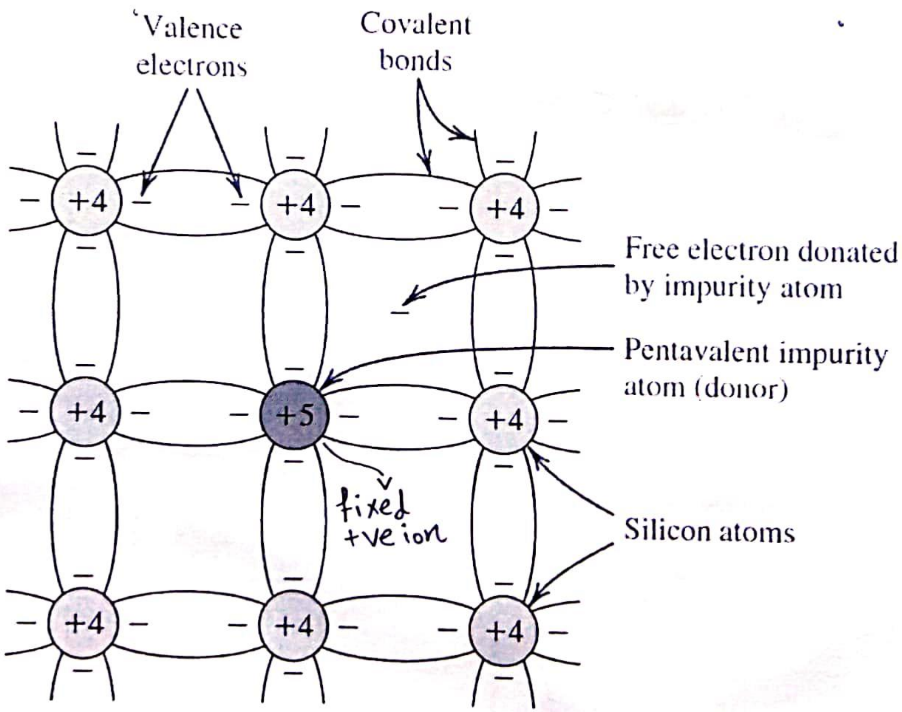
$$np = n_i^2$$

Doped (Extrinsic) Silicon

- Doping involves introducing impurity atoms into the silicon crystal
- To increase the concentration of free electrons (n) silicon is doped with a pentavalent (valence = 5) impurity (Ex: Phosphorus)
  - Each dopant atom (donor) gives a free e^- and a fixed positive charge (+ve ion)
  - Electrons become the majority carriers ($n \gg p$) $\uparrow n \cdot p \downarrow = n_i^2$
  - The doped silicon is **n-type**
- To increase the concentration of holes (p) silicon is doped with a trivalent (valence = 3) impurity (Ex: Boron)
  - Each dopant atom (acceptor) gives a h^+ and a fixed negative charge (-ve ion)
  - Holes become the majority carriers ($p \gg n$)
  - The doped silicon is **p-type**

N-Type Silicon

- Each dopant atom (donor) gives a free e^- and a fixed positive charge (+ve ion)
  - N_D: donor concentration
- Electrons become the majority carriers ($n \approx N_D \gg p$)



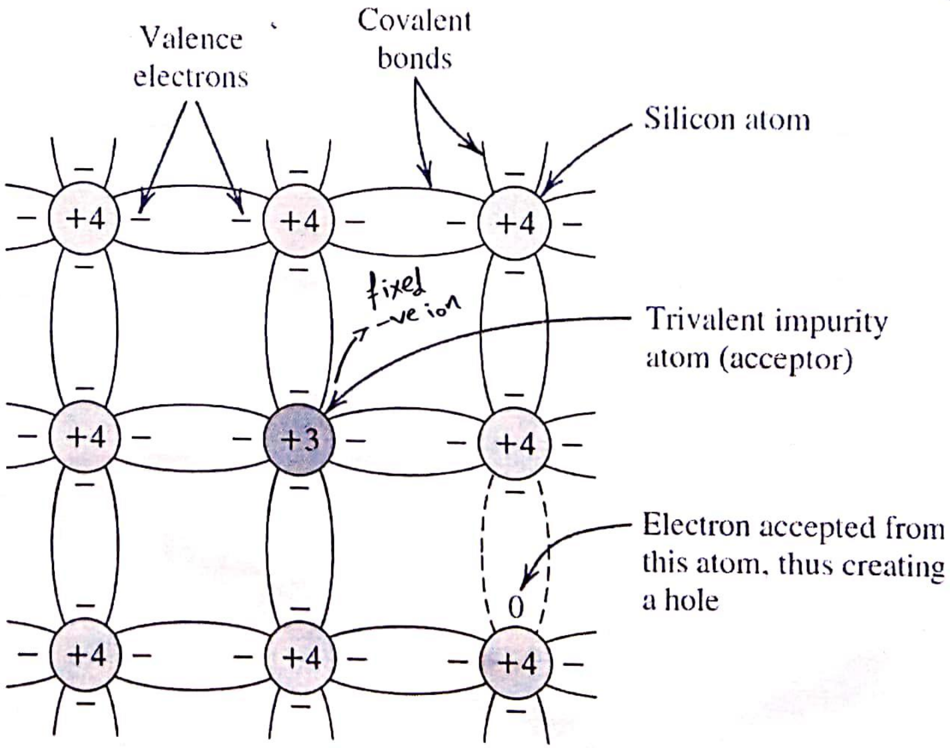
[Sedra/Smith, 2015]

P-Type Silicon

- Each dopant atom (acceptor) gives a h^+ and a fixed negative charge (-ve ion)
  - N_A: acceptor concentration

Cannot Contribute in Current Conduction.

- Holes become the majority carriers ($p \approx N_A \gg n$)



[Sedra/Smith, 2015]

Current Flow: (1) Drift Current

- Current flows due to electrical field (E)
  - Holes are accelerated in the direction of E

Mobility

$$h^+ \text{ drift velocity} = v_{p-drift} = \mu_p E$$

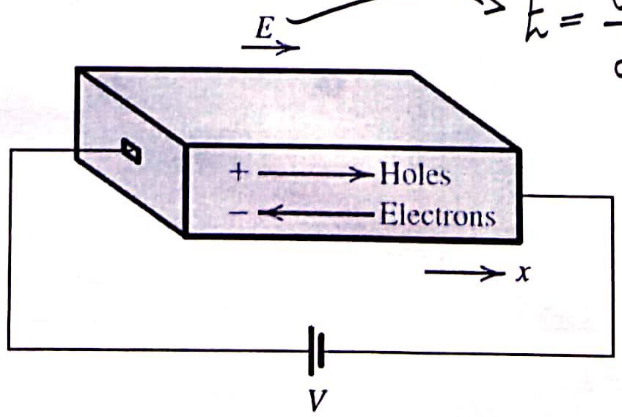
  - Free electrons are accelerated in the direction opposite to E

$$e^- \text{ drift velocity} = v_{n-drift} = -\mu_n E$$

opposite direction

- μ is the mobility: $\mu_n = 2 - 4$ times μ_p → You should check your technology
- Note that if there are no carriers, there will be no current, even if there is an electric field

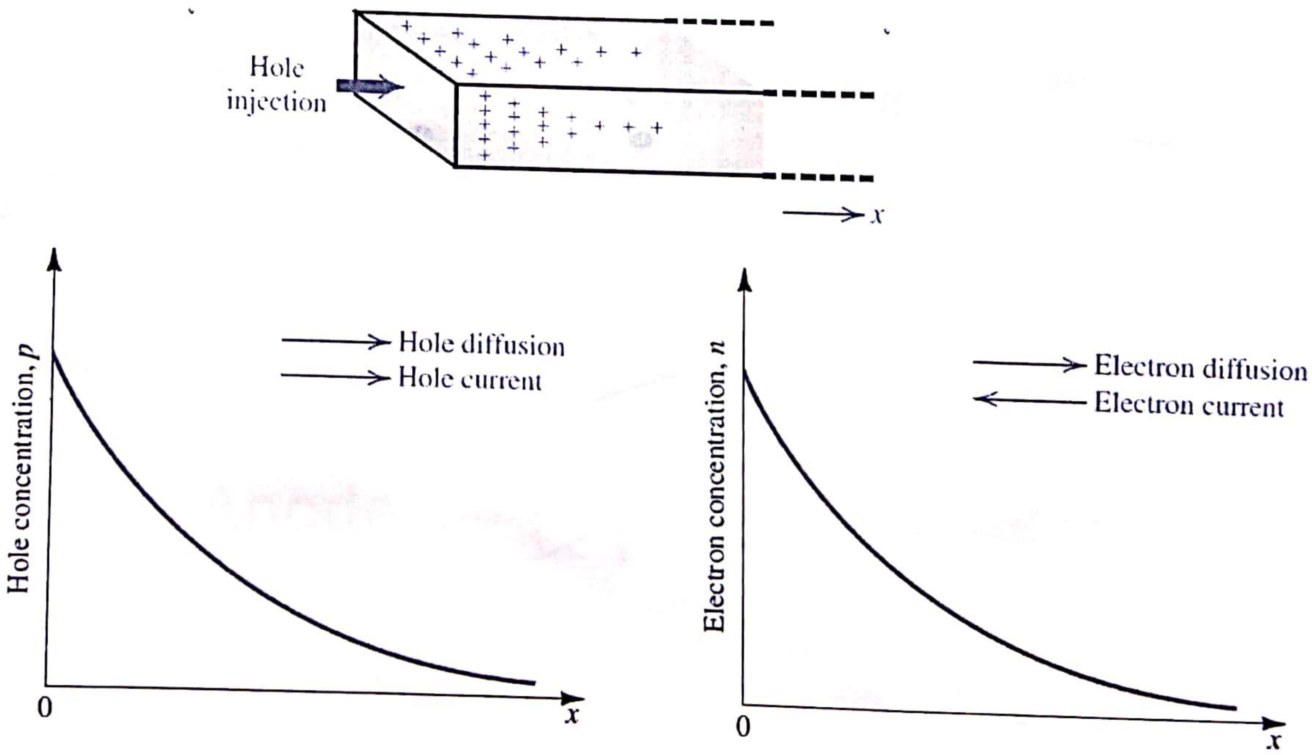
$E = \frac{V}{d}$



[Sedra/Smith, 2015]

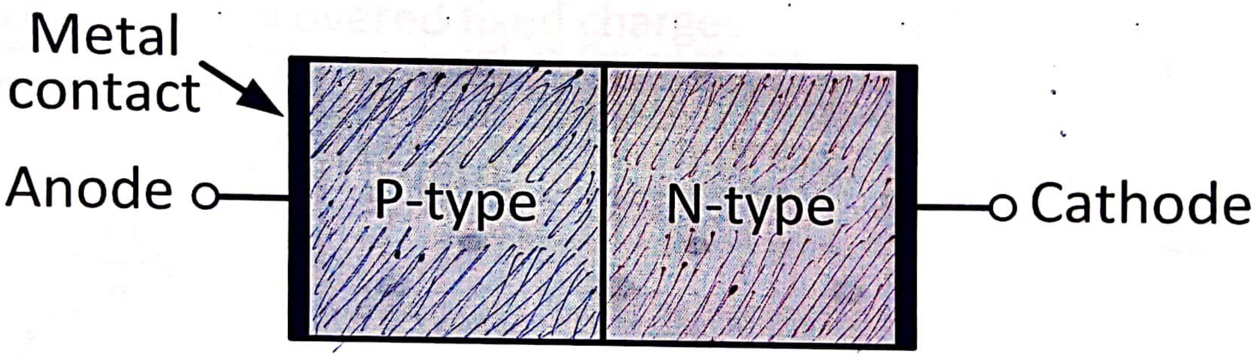
Current Flow: (2) Diffusion Current

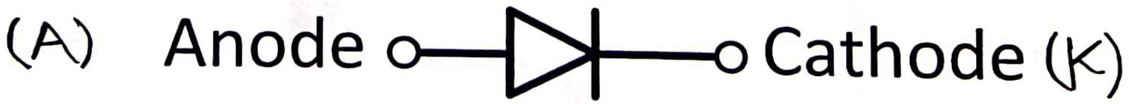
- Current flows due to carrier concentration gradient
  - Carriers diffuse from the region of high concentration to the region of low concentration



[Sedra/Smith, 2015]

The PN Junction (The Diode)



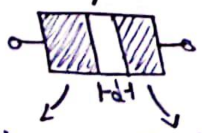


PN Junction in Equilibrium (o.c.)

- Diffusion current (I_D) flows due to concentration gradient
  - A depletion region of uncovered fixed charges is formed
    → they were covered with carriers (e or h)
  - The uncovered charges create E → drift current (I_S)
- $I_D = I_S$ → net current ($I_D - I_S$) is zero
- Capacitance (C) $= \frac{\epsilon A}{d}$

→ They were covered by their carriers, but they turn into uncovered after the carriers leave then these charges contribute to form an electric field.

insulator



two conductors

d: width of the depletion region

A: Cross-sectional Area for the PN Junction

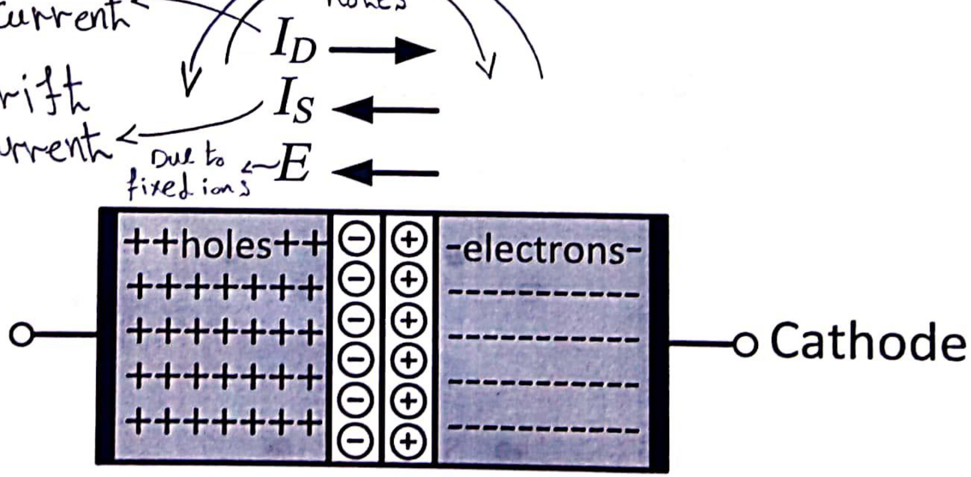
electrons

holes

Diffusion current

Drift current

Due to fixed ions



Depletion region
Fixed charges

PN Junction in Equilibrium (o.c.)

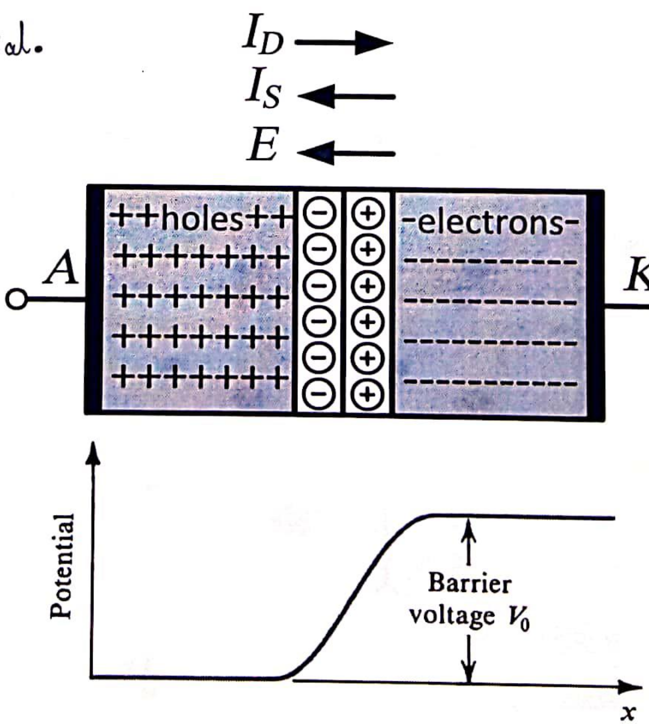
- Built-in electric field and barrier voltage due to depletion region

$$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) \approx 2.3V_T \log\left(\frac{N_A N_D}{n_i^2}\right) \approx 0.6 - 0.9V$$ (on Voltage)

Doesn't widly varry as the logarithmic function is a weak function.

- The barrier voltage (V_0) limits carrier diffusion

• Electric field is the gradient of the Potential.
• Potential is the integration of electric field.



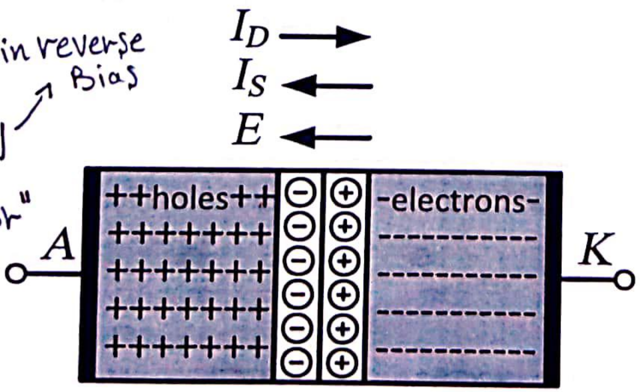
[Sedra/Smith, 2015]

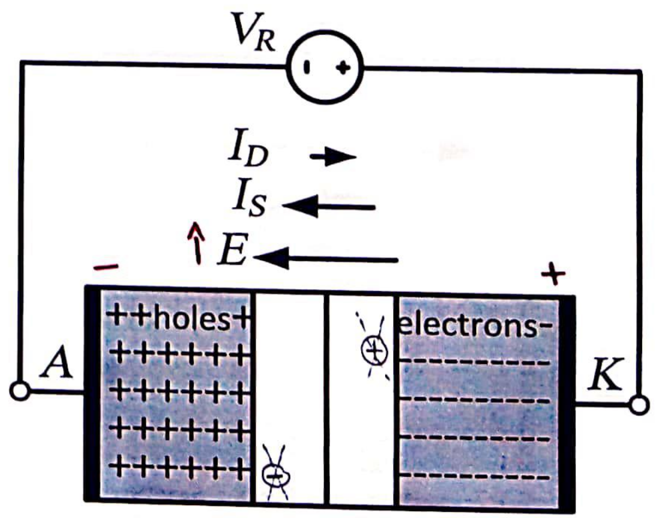
PN Junction in Reverse (Rvr) Bias

- The applied reverse voltage increases diffusion barrier
  - Opposes diffusion current
- Electric field increases
  - But drift current almost unchanged: no carriers to accelerate
- Net current is very small $\approx -I_S$
- Depletion width increases → capacitance decreases
  $\rightarrow d\uparrow$ $\rightarrow C\downarrow$
  - Capacitance at zero bias is larger

$\downarrow C = \dfrac{\epsilon A}{d\uparrow}$

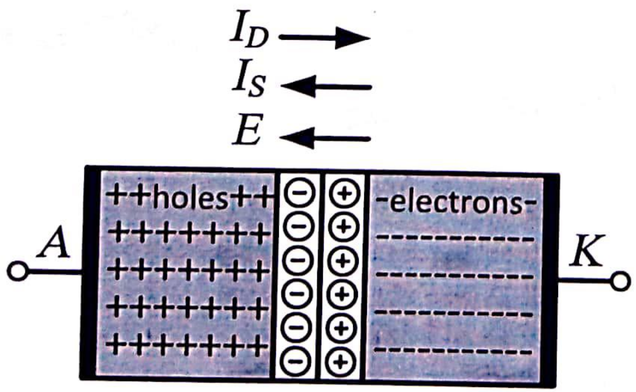
★ We can use the PN Junction as a "Varactor" (Variable Capacitor) in reverse Bias

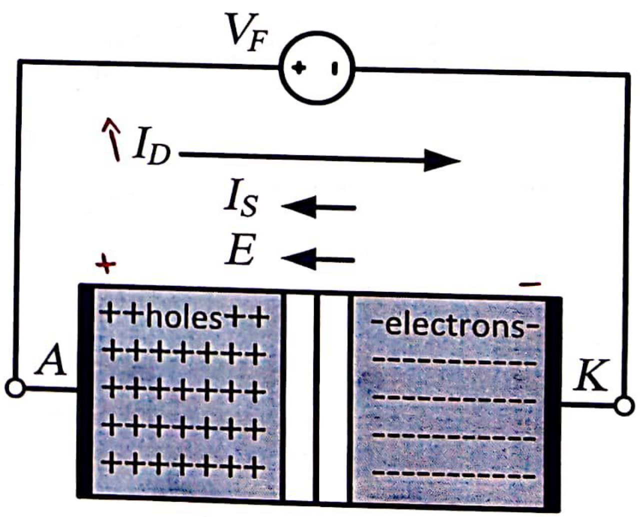




PN Junction in Forward (Fwd) Bias

- The applied forward voltage <u>decreases diffusion barrier.</u>
  - Dramatically increases diffusion current
- Net current is very high $= I_D - I_S \approx I_D = I_S e^{\frac{V_F}{V_T}}$
  - Forward current exponentially increases with voltage across diode (V_F)
- Depletion width decreases

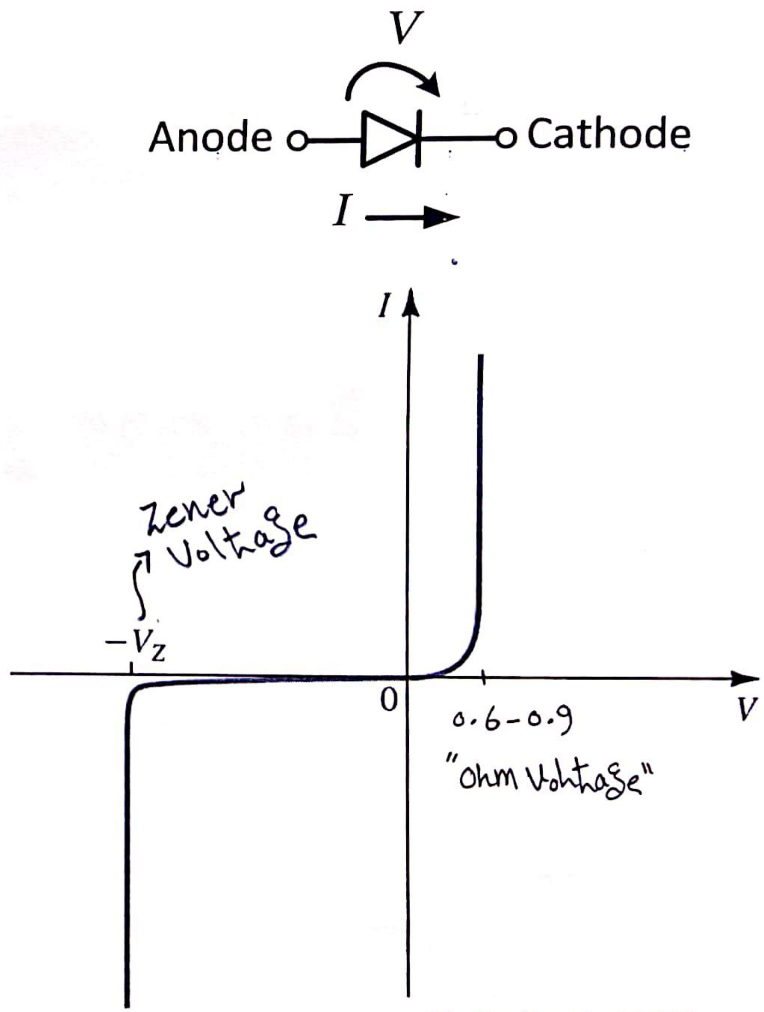




PN Junction IV Characteristics

- $I = I_S\left(e^{\frac{V}{V_T}} - 1\right)$
- Forward: High diffusion current exponentially dependent on $V = V_F$
- Reverse: Very small drift current almost independent of $V = -V_R$
- Breakdown: Very high reverse current at LARGE reverse bias voltage

★Some diodes are designed intentionally to work in Breakdown region: "Zener Diodes" which are used in "Voltage Regulators".



[Sedra/Smith, 2015]

Thank you!

Dr. Hesham Omran's Lectures

Fady Sabry Negm's Notes

References

- A. Sedra and K. Smith, "Microelectronic Circuits," Oxford University Press, 7th ed., 2015.
- B. Razavi, "Fundamentals of Microelectronics," Wiley, 2nd ed., 2014.

وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

Allah almighty said in the Qur'an :
“and you ˹O humanity˺ have been given but little knowledge.”

لو أن الناس كلما استصعبوا أمرًا تركوه ما قام للناس دنيا ولا دين

The Muslim Caliph Umar ibn Abdulaziz, May Allah have mercy on him, **Said:**
“If every time people found something difficult, they abandoned it, then neither worldly affairs nor religion would have ever been established for people.”

- All Credits for these lectures go to **Dr. Hesham Omran**, Associate Professor at Ain Shams University and CTO at Master Micro, May Allah bless Dr. Hesham for these Lectures.

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- These Notes were made by: **Fady Sabry Negm** and any success or guidance is from Allah, and any mistake or lapse is from me and Satan.