Analog IC Design

Lecture 03
Review on Semiconductors Basics

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Outline

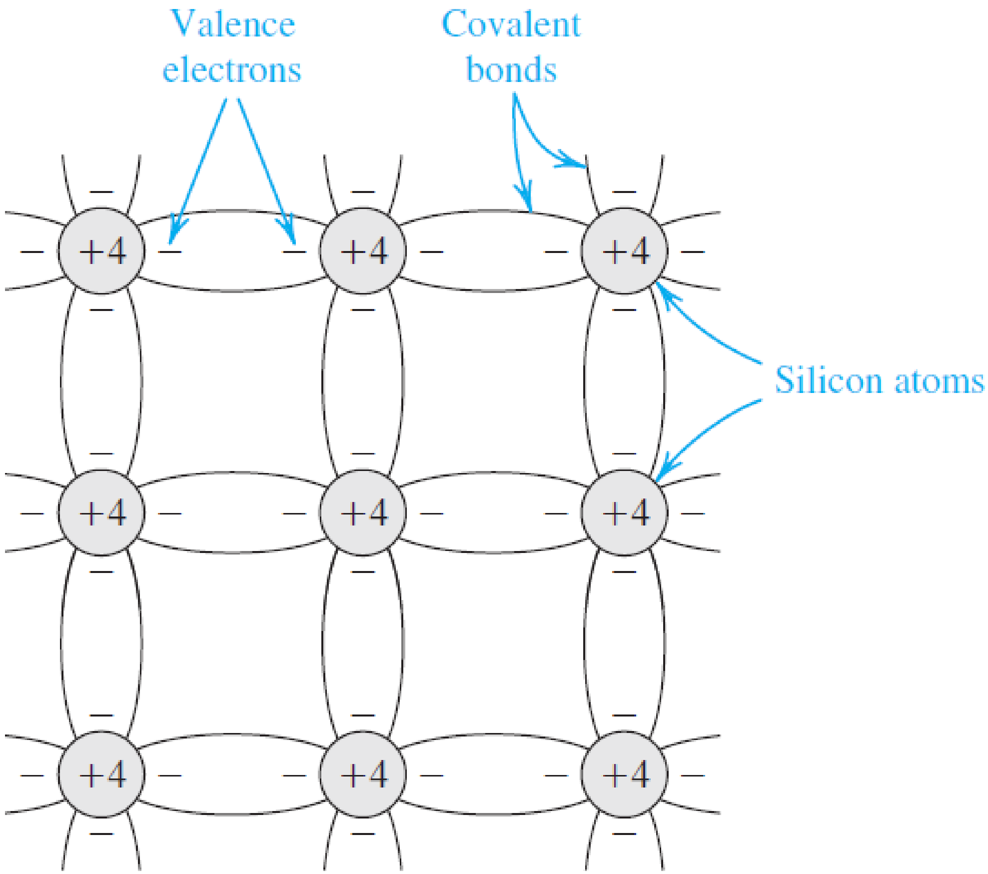
- What are semiconductors?
- Electrons and holes
- N-type and P-type silicon
- Drift and diffusion current
- The PN-junction

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
  - We have two types of carriers: electrons and holes
- Silicon (Si) is the semiconductor material used in the majority of today's electronic devices

Silicon Crystal

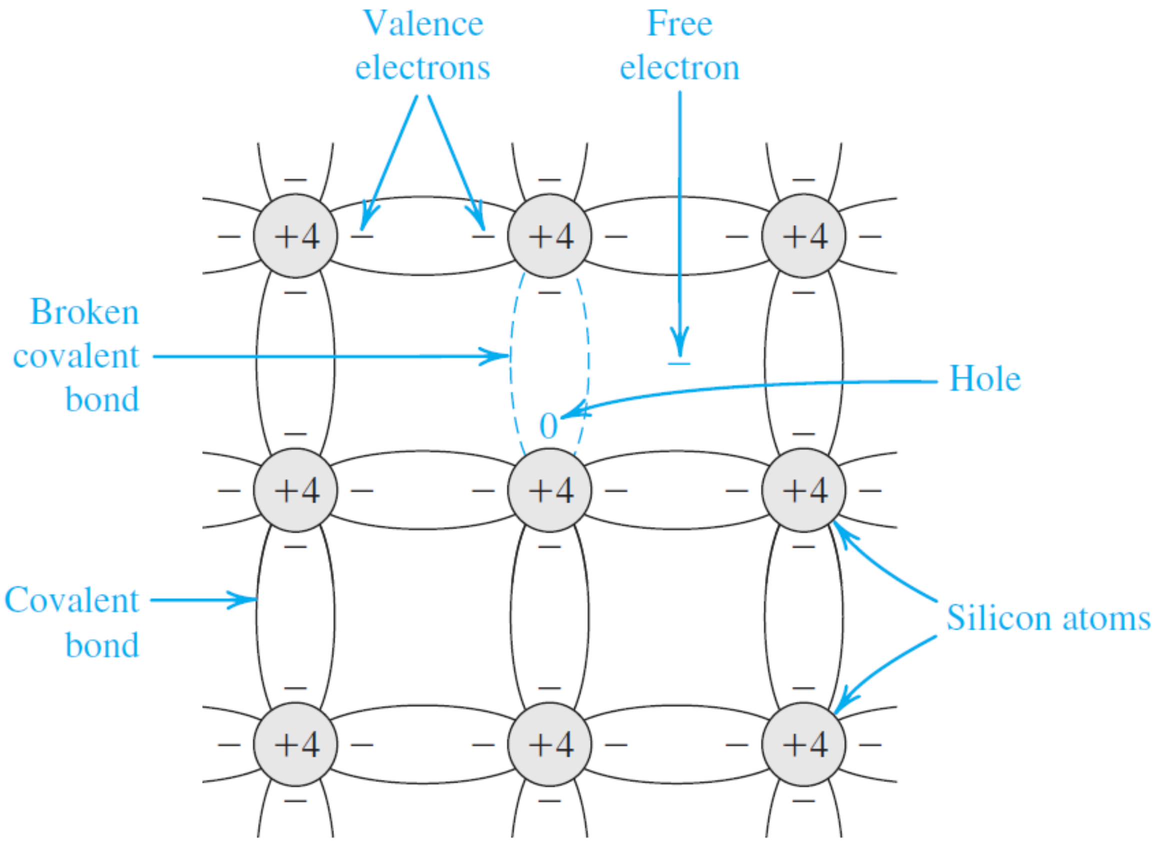
- Covalent bonds are formed by sharing of the valence electrons
- At 0 K, all bonds are intact and no free electrons are available



[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



[Sedra/Smith, 2015]

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)

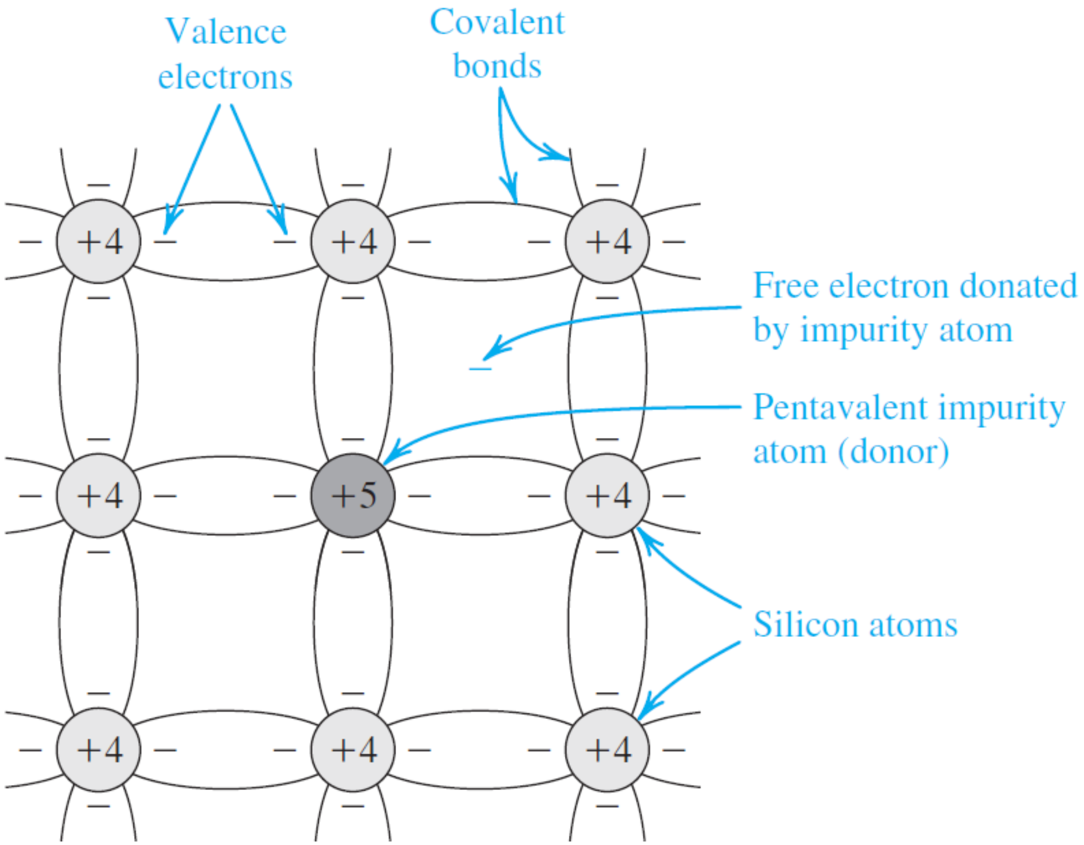
$$np = n_i^2$$

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 ($n \gg p$)
  - 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

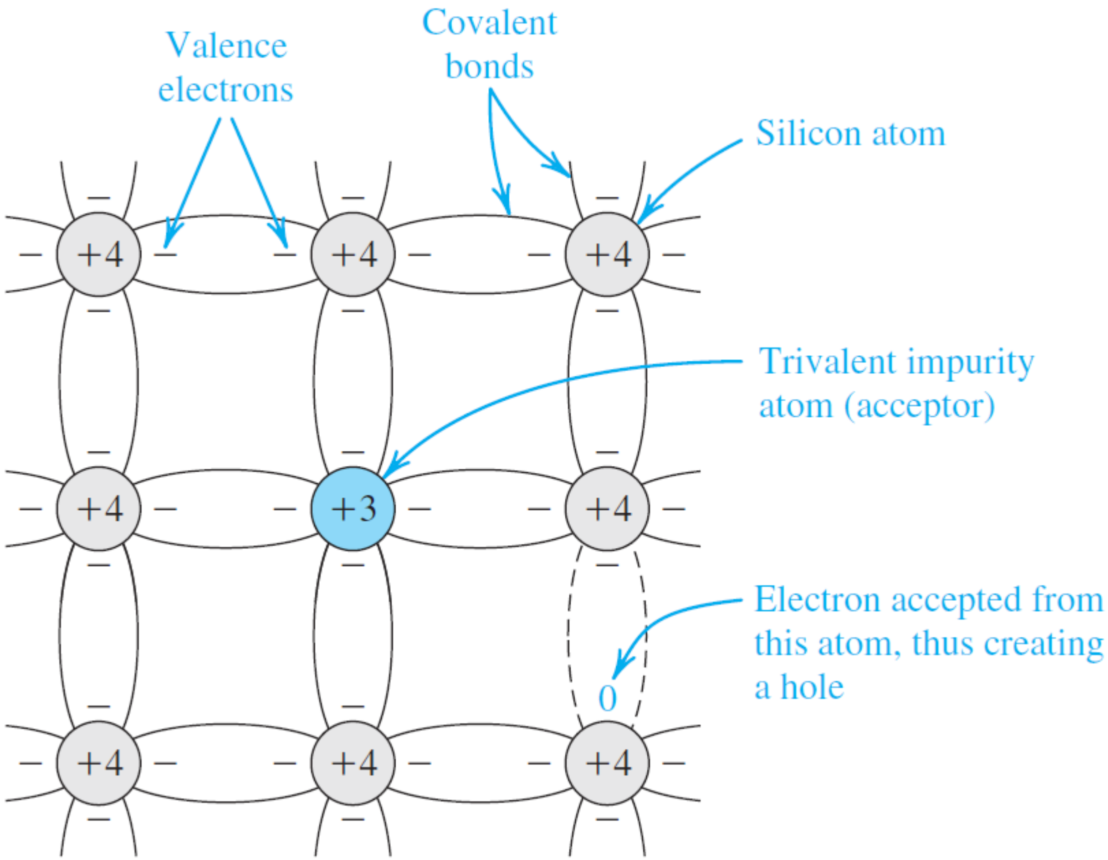
- Each dopant atom (donor) gives a free e^- and a fixed positive charge (+ve ion)
  - N_D: donor concentration
- Electrons become the majority carriers ($n \approx N_D \gg p$)



[Sedra/Smith, 2015]

P-Type Silicon

- Each dopant atom (acceptor) gives a h^{+} and a fixed negative charge (-ve ion)
  - N_A: acceptor concentration
- Holes become the majority carriers ($p \approx N_A \gg n$)



[Sedra/Smith, 2015]

Current Flow: (1) Drift Current

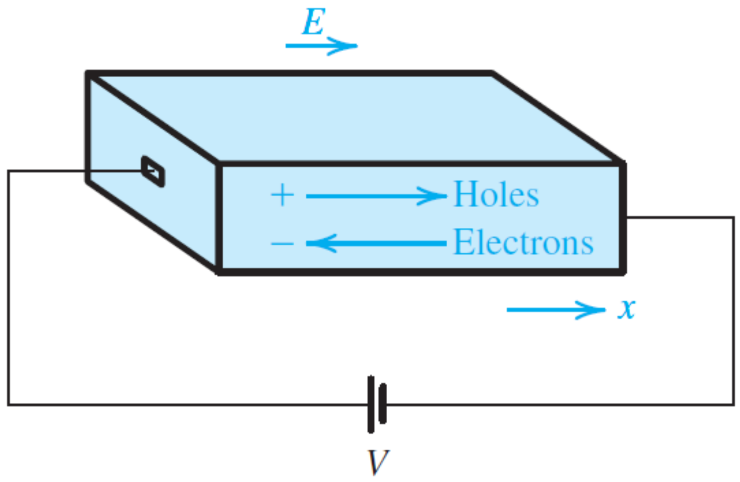
- Current flows due to electrical field (E)
  - Holes are accelerated in the direction of E

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

  - Free electrons are accelerated in the direction opposite to E

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

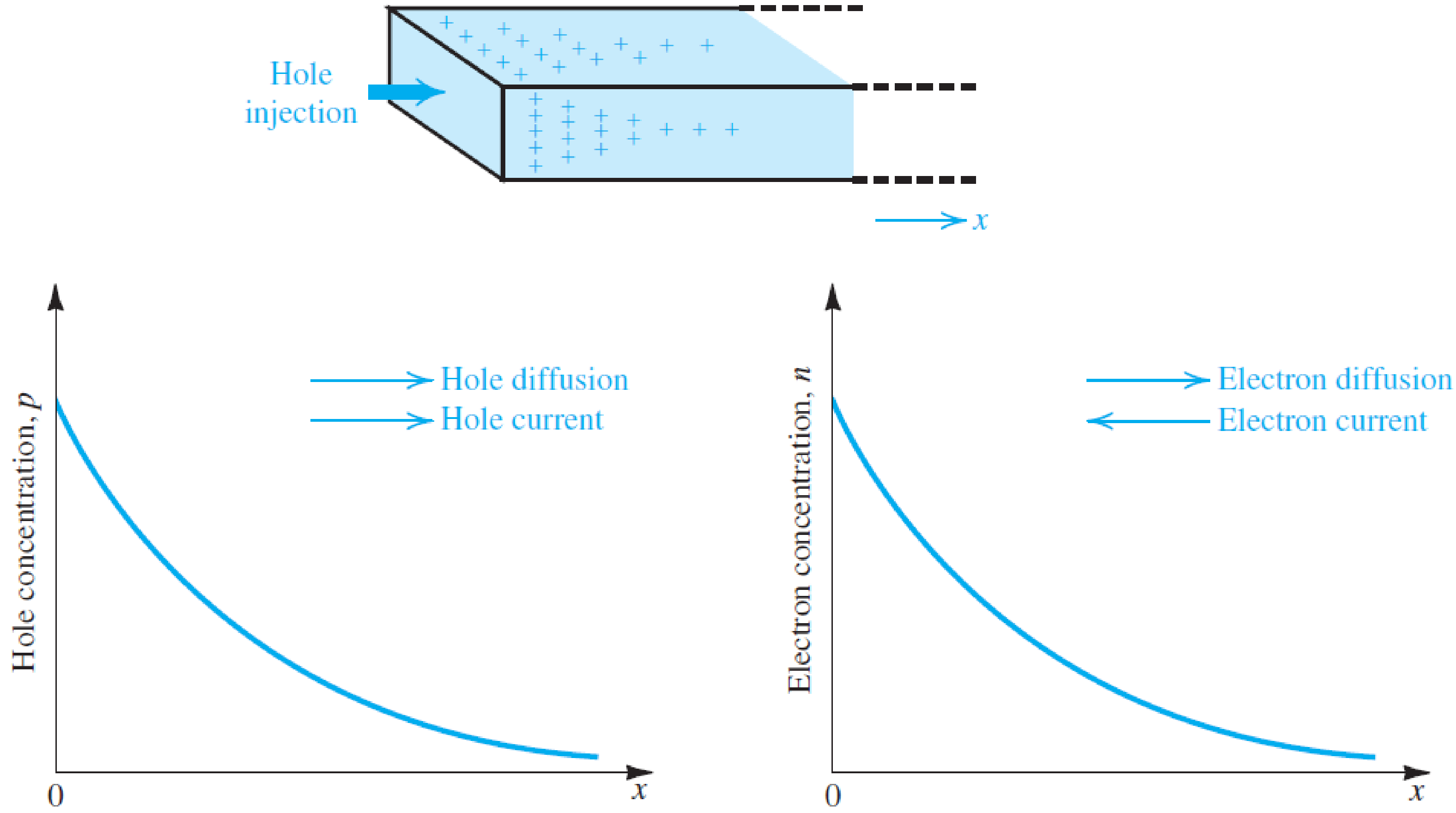
- μ is the mobility: $\mu_n = 2 - 4$ times μ_p
- Note that if there are no carriers, there will be no current, even if there is an electric field



[Sedra/Smith, 2015]

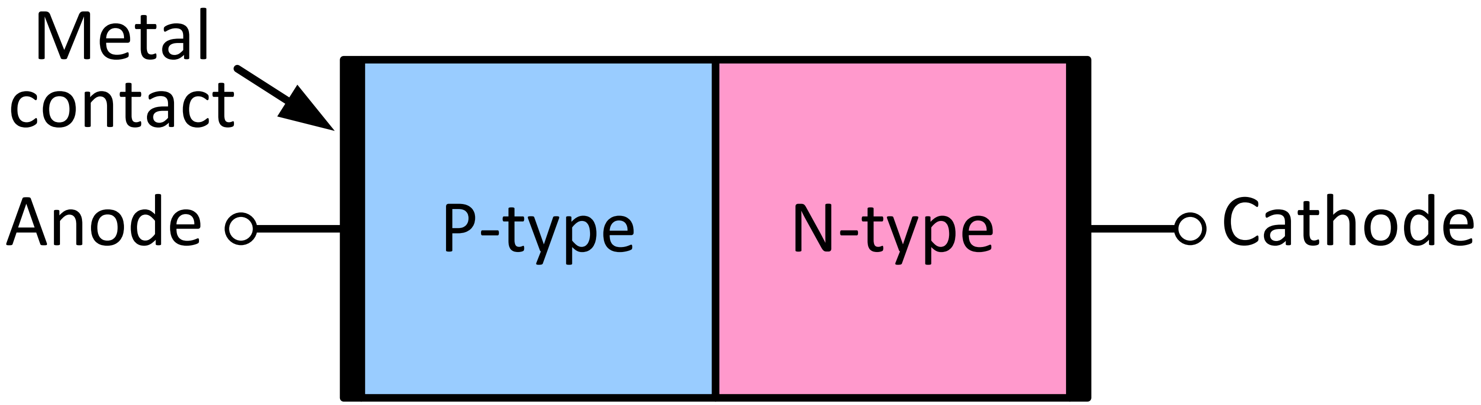
Current Flow: (2) Diffusion Current

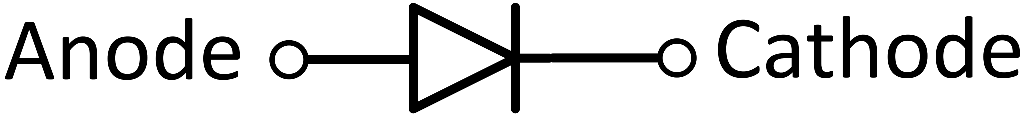
- Current flows due to carrier concentration gradient
  - Carriers diffuse from the region of high concentration to the region of low concentration



[Sedra/Smith, 2015]

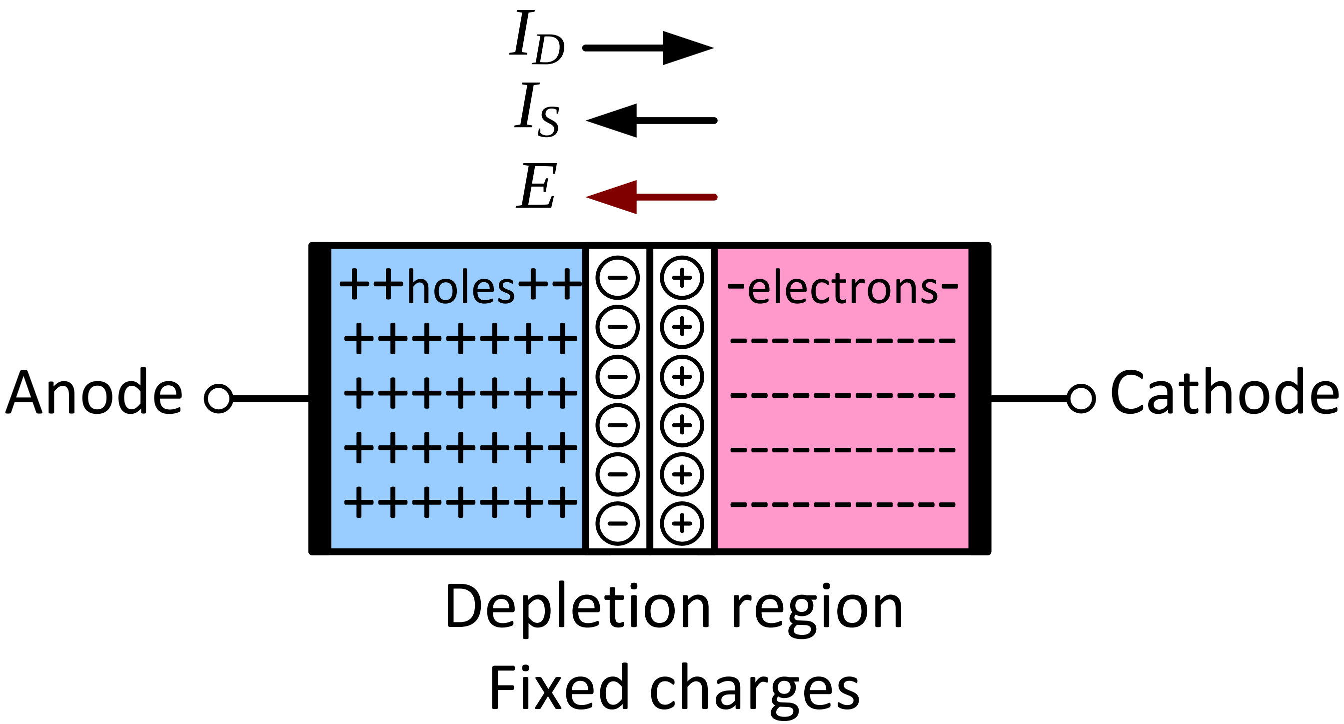
The PN Junction (The Diode)





PN Junction in Equilibrium (o.c.)

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

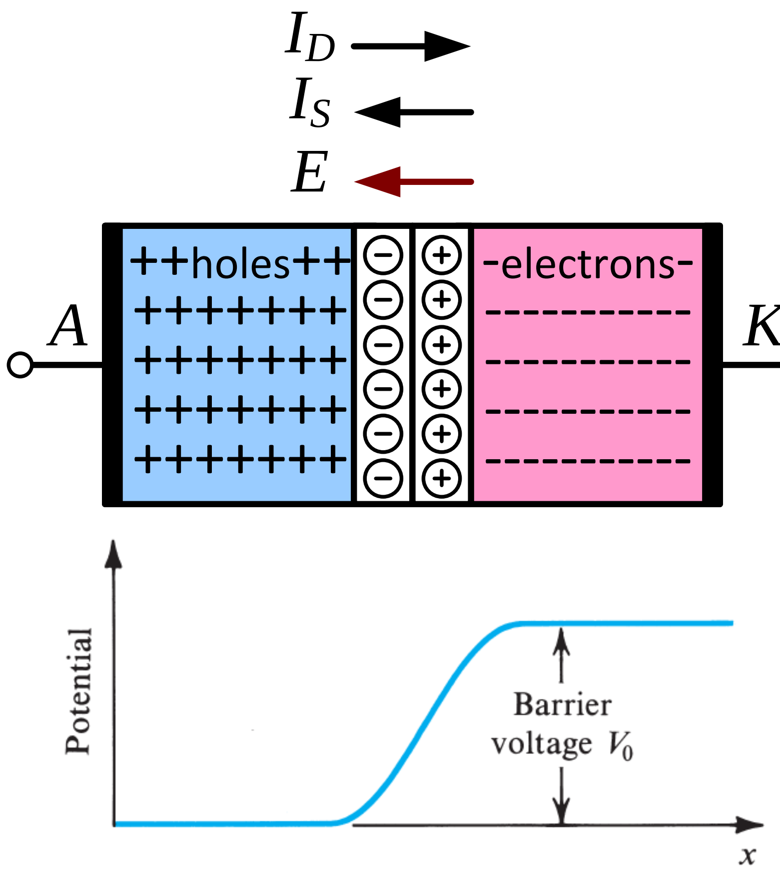


PN Junction in Equilibrium (o.c.)

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

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

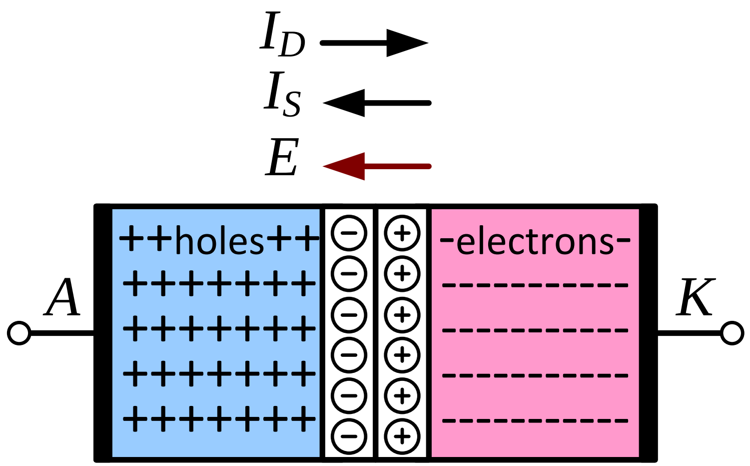
- The barrier voltage (V_0) limits carrier diffusion

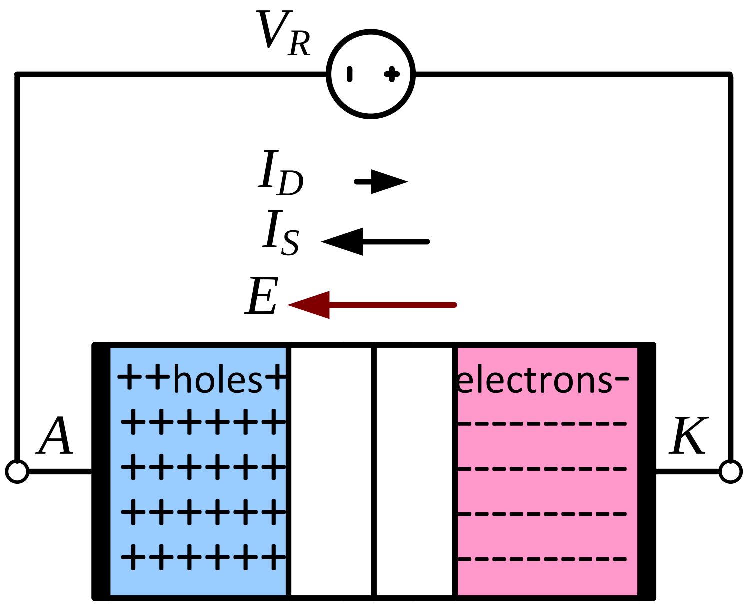


[Sedra/Smith, 2015]

PN Junction in Reverse (Rvr) Bias

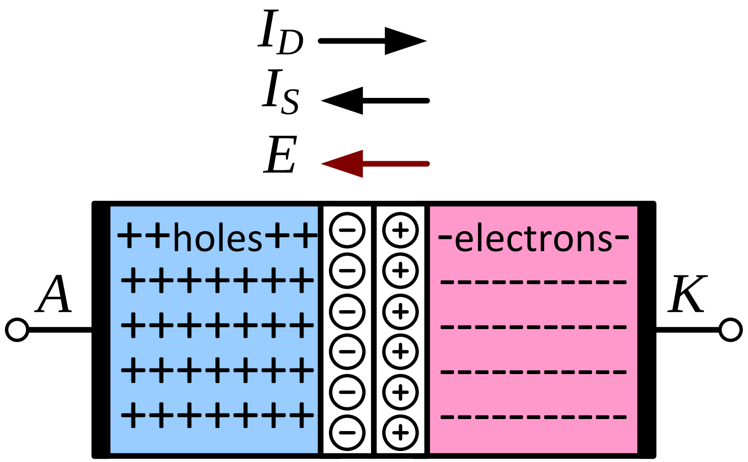
- The applied reverse voltage increases diffusion barrier
  - Opposes diffusion current
- Electric field increases
  - But drift current almost unchanged: no carriers to accelerate
- Net current is very small $\approx -I_S$
- Depletion width increases → capacitance decreases
  - Capacitance at zero bias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

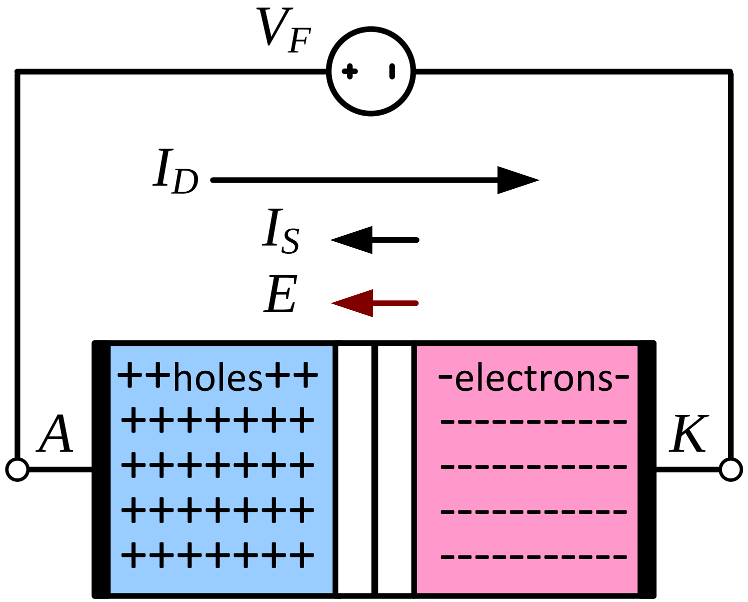




PN Junction in Forward (Fwd) Bias

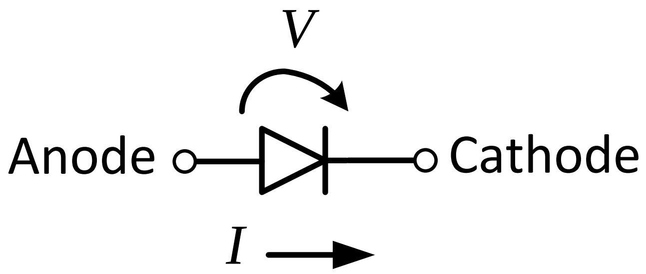
- The applied forward voltage decreases diffusion barrier
  - Dramatically increases diffusion current
- Net current is very high $= I_D - I_S \approx I_D = I_S e^{\frac{V_F}{V_T}}$
  - Forward current exponentially increases with voltage across diode (V_F)
- Depletion width decreases

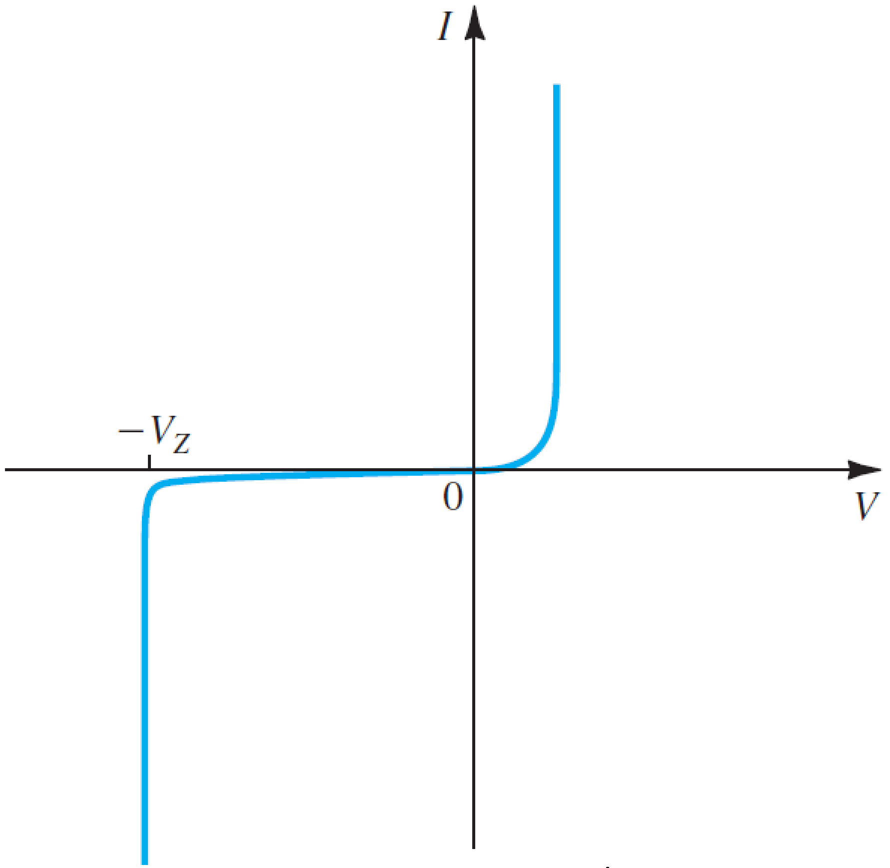




PN Junction IV Characteristics

- $I = I_S(e^{\frac{V}{V_T}} - 1)$
- 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





[Sedra/Smith, 2015]

Thank you!

References

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