وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

Analog IC Design

Lecture 03
Review on Semiconductors Basics

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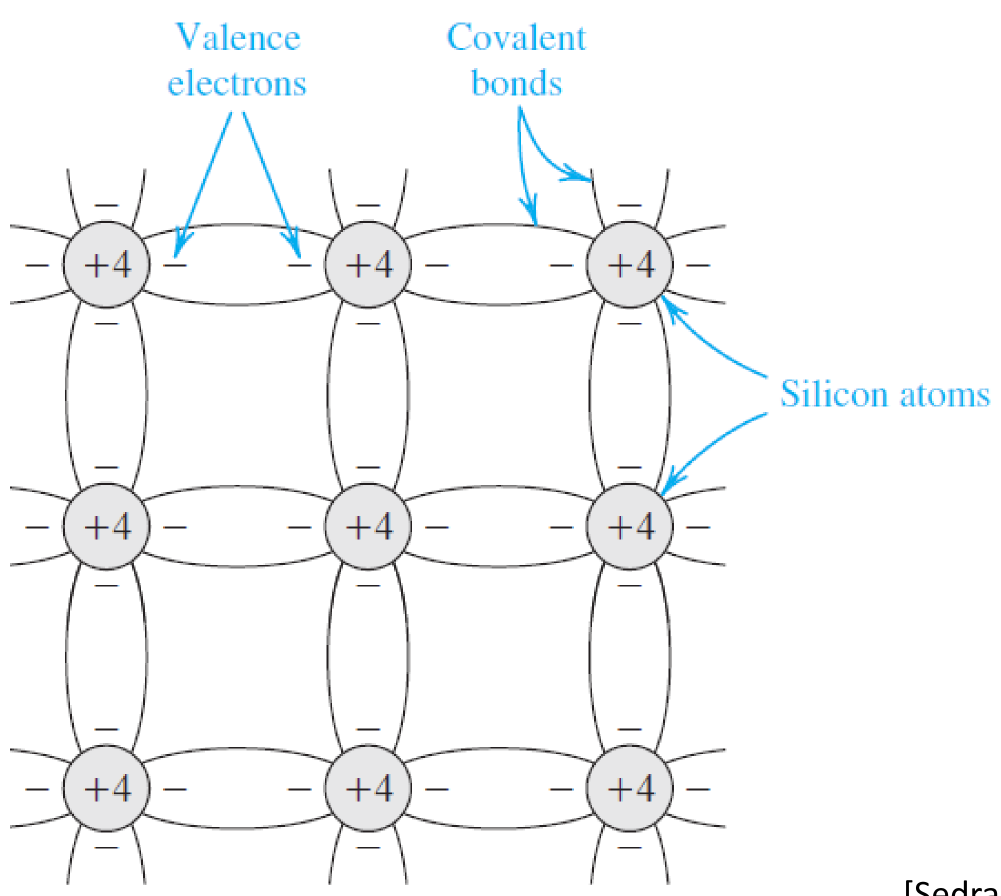
What are Semiconductors

- 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

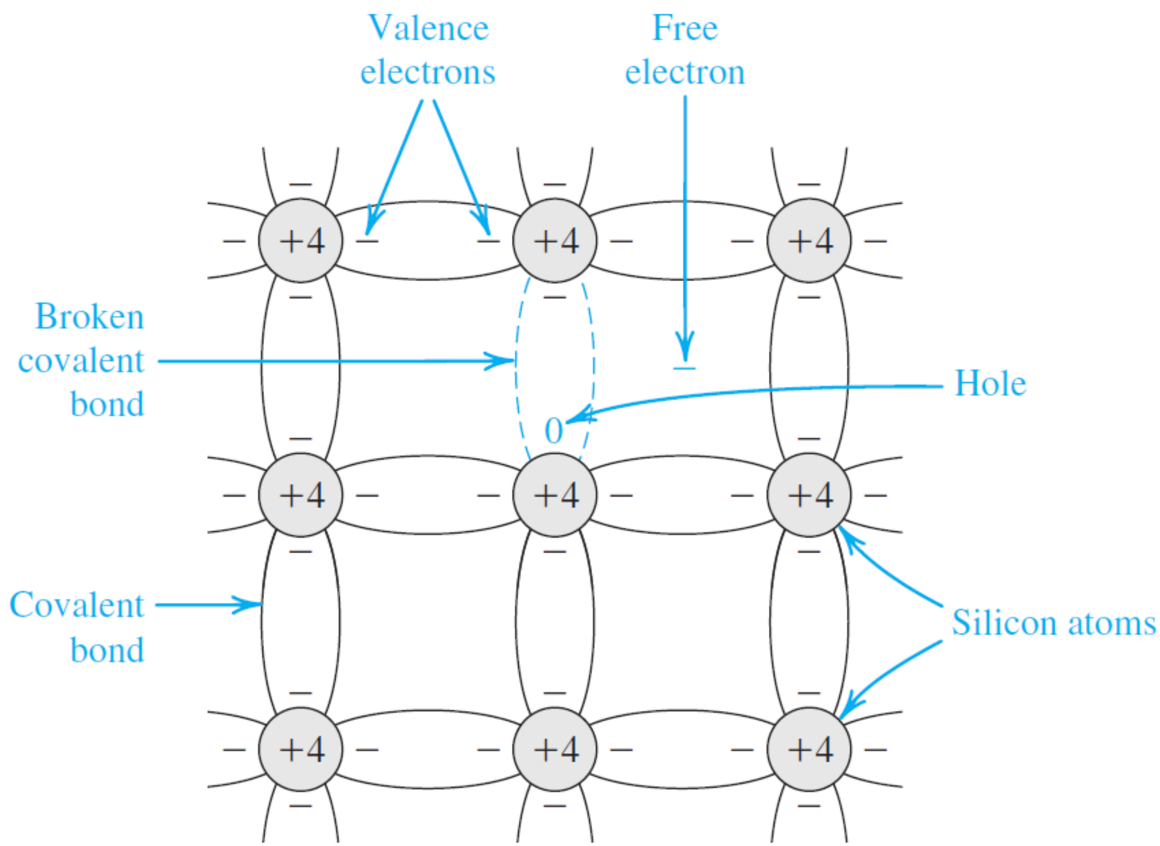
- Covalent bonds are formed by sharing of the valence electrons
- At 0 K, all bonds are intact and no free electrons are available



[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)

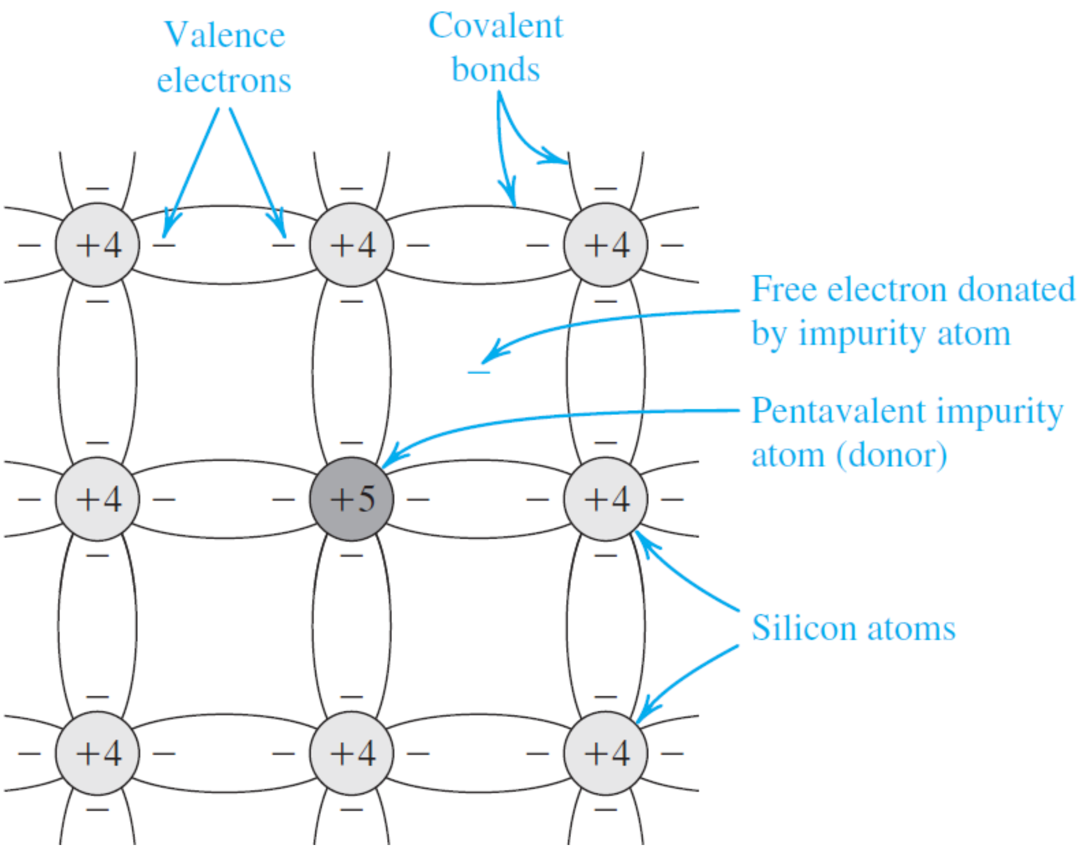
$$np = n_i^2$$

Doped Silicon

- Doping involves introducing impurity atoms into the silicon crystal
- To increase the concentration of free electrons (n) silicon is doped with an element with a valence of 5 (Ex: phosphorus)
  - Each dopant atom (donor) gives a free e^- and a fixed positive charge
  - 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 an element having a valence of 3 (Ex: boron)
  - Each dopant atom (acceptor) gives a h^+ and a fixed negative charge
  - Holes become the majority carriers ($p \gg n$)
  - The doped silicon is **p-type**

n-Type Silicon

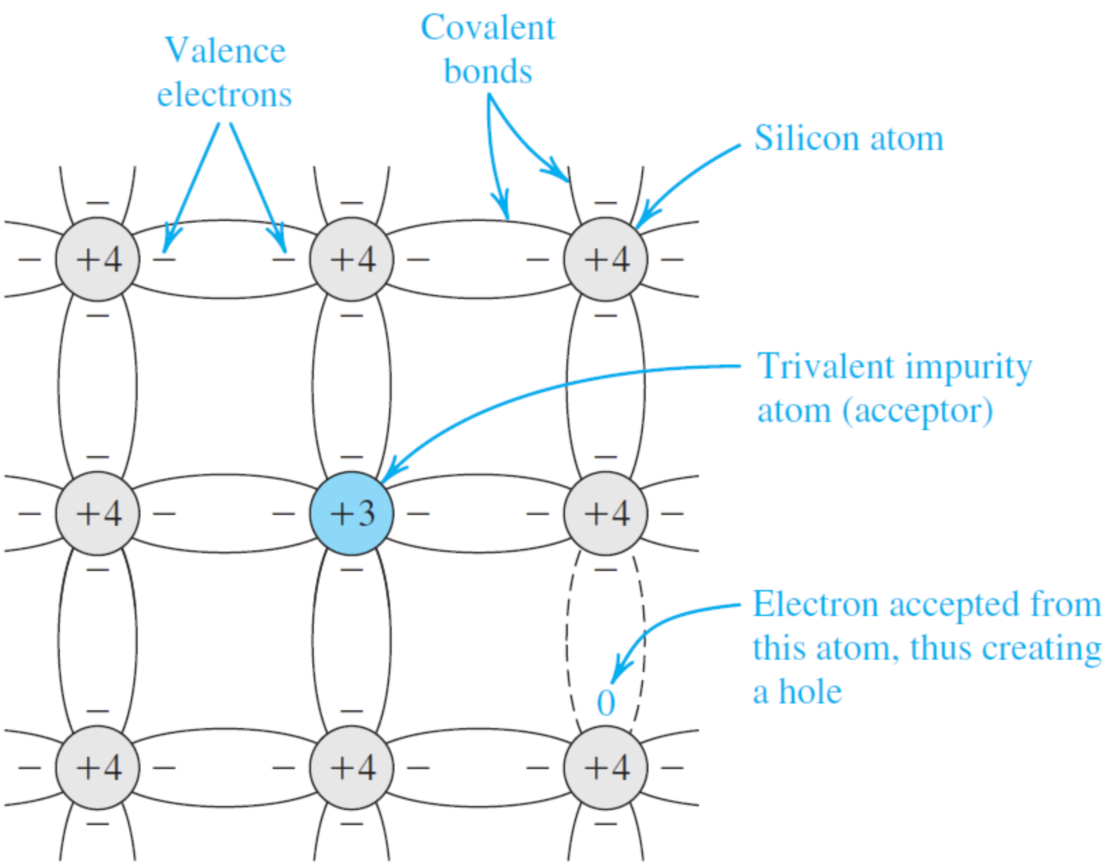
- ❑ Each dopant atom (donor) gives a free e^- and a fixed positive charge
- ❑ Electrons become the majority carriers ($n \gg p$)



[Sedra/Smith, 2015]

p-Type Silicon

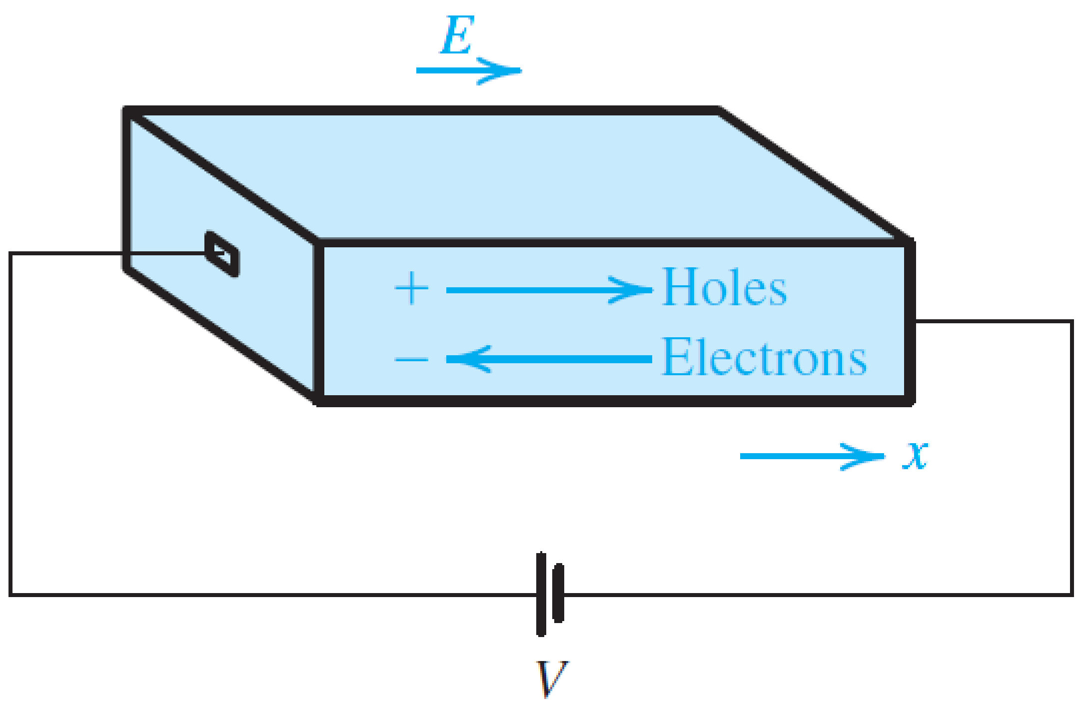
- Each dopant atom (acceptor) gives a h^+ and a fixed negative charge
- Holes become the majority carriers ($p \gg n$)



[Sedra/Smith, 2015]

Current Flow: (1) Drift Current

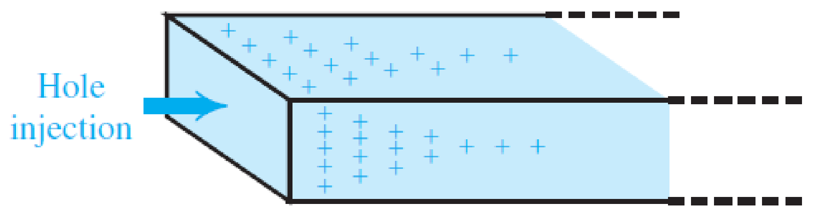
- Current flows due to electrical field (E)
  - Holes are accelerated in the direction of E
  - Free electrons are accelerated in the direction opposite to E



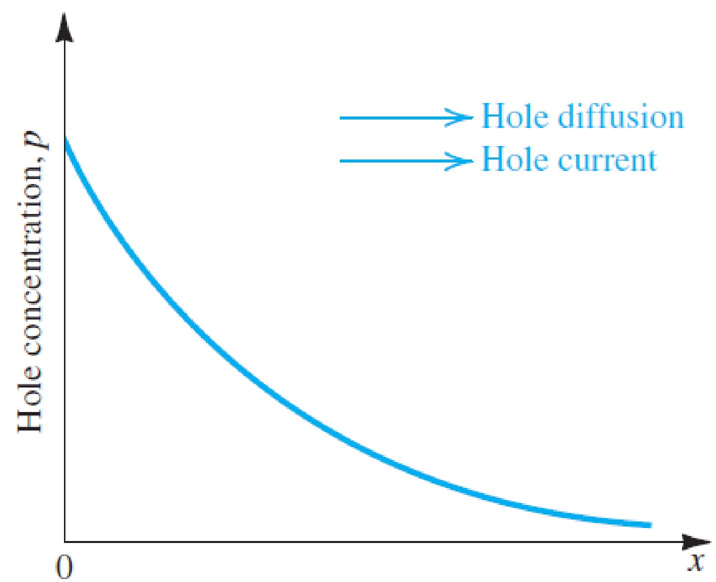
[Sedra/Smith, 2015]

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



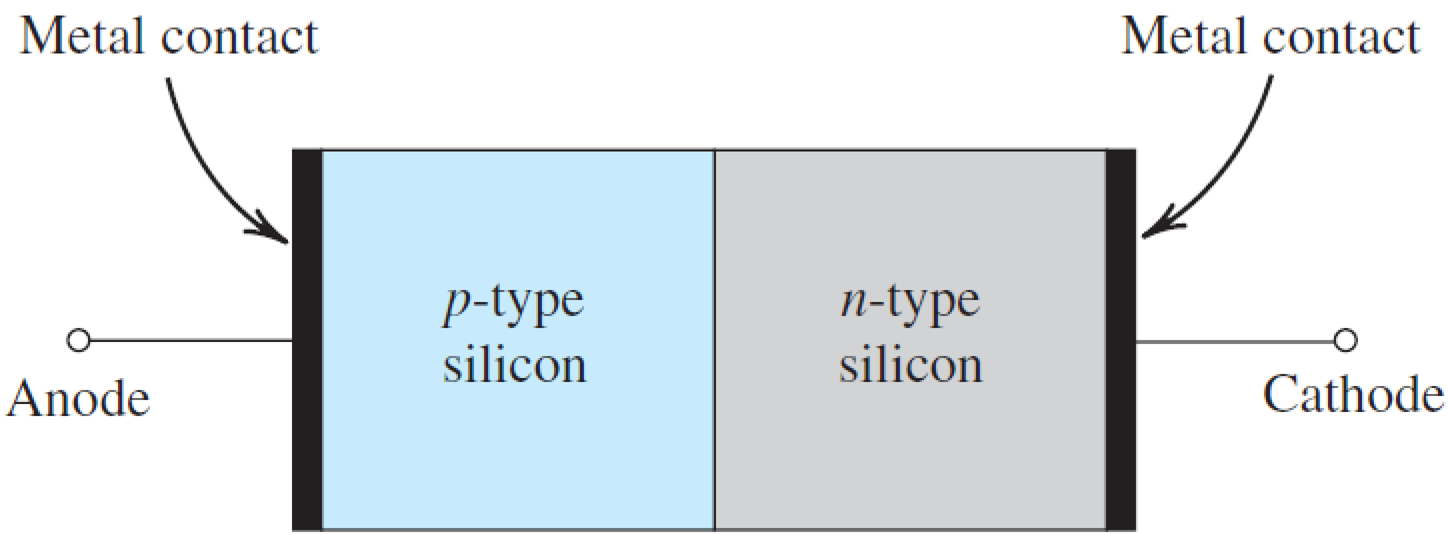
(a)

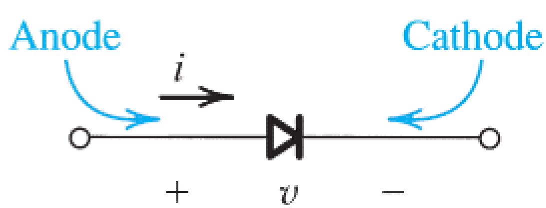


(b)

[Sedra/Smith, 2015]

The pn Junction (The Diode)

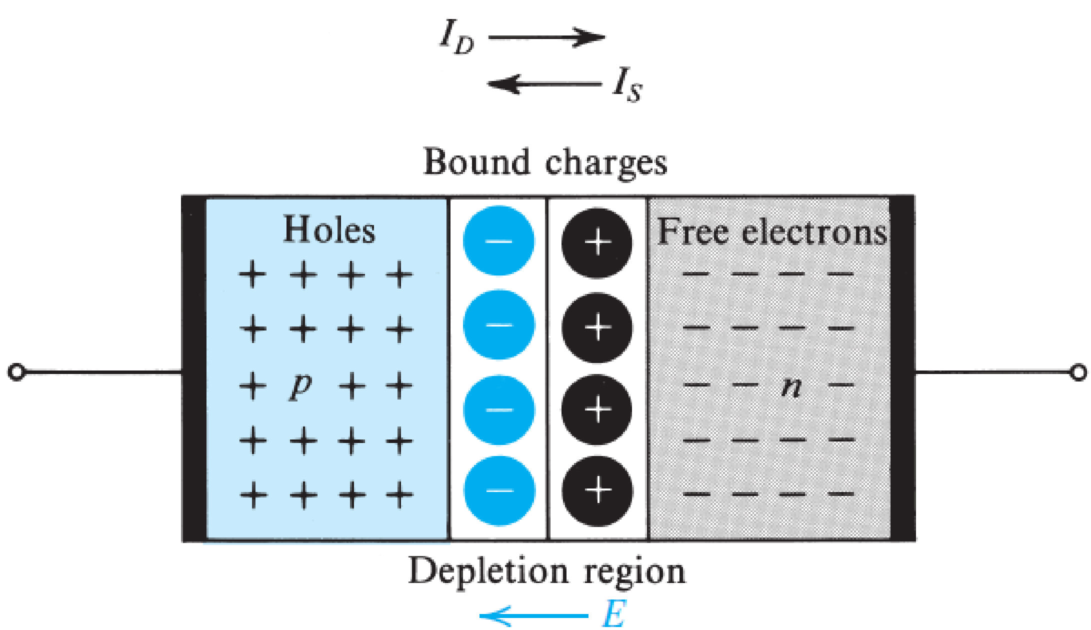




[Sedra/Smith, 2015]

pn Junction in Equilibrium (o.c.)

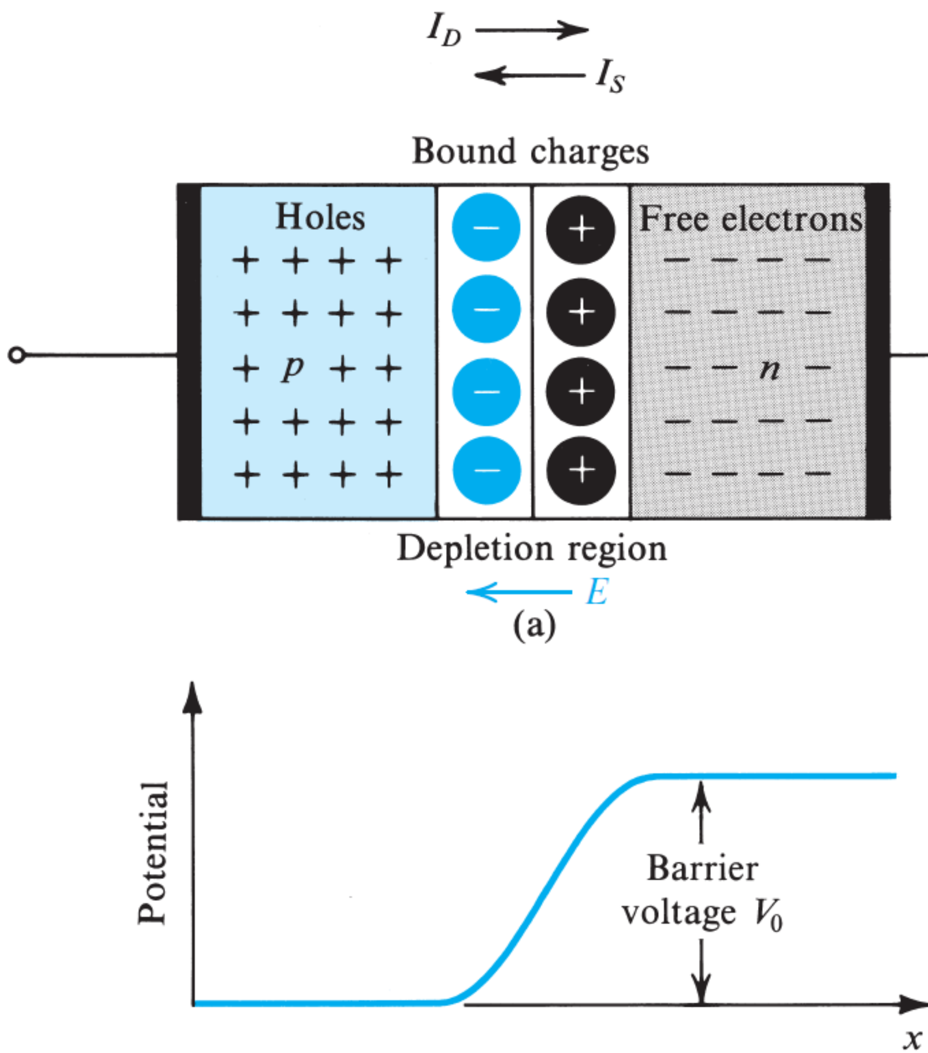
- Diffusion current (I_D) flows due to concentration gradient
  - A depletion region of uncovered fixed charges is formed
  - The uncovered charges create E → drift current (I_S)
- $I_D = I_S$ → net current ($I_D - I_S$) is zero
- Capacitance $(C) = \frac{\epsilon A}{d}$



[Sedra/Smith, 2015]

pn Junction in Equilibrium (o.c.)

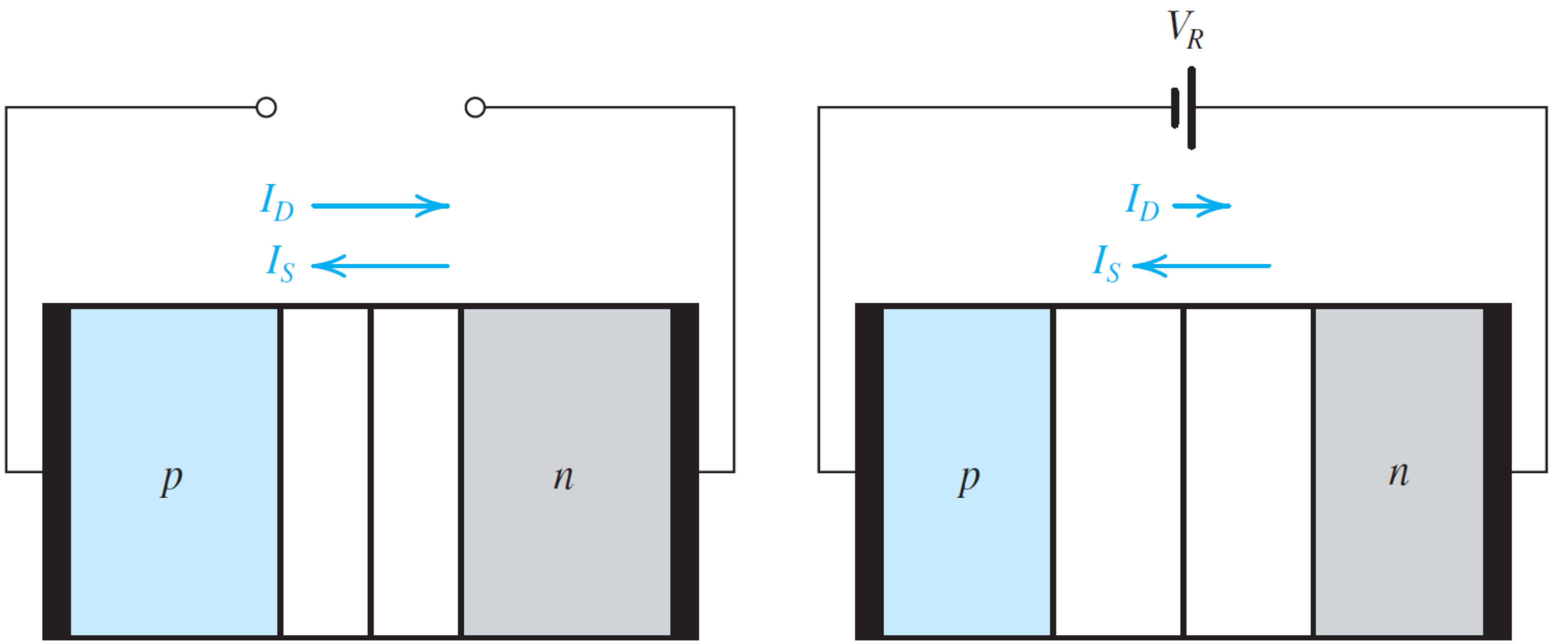
- The barrier voltage limits carrier diffusion



[Sedra/Smith, 2015]

pn Junction in Reverse (Rvr) Bias

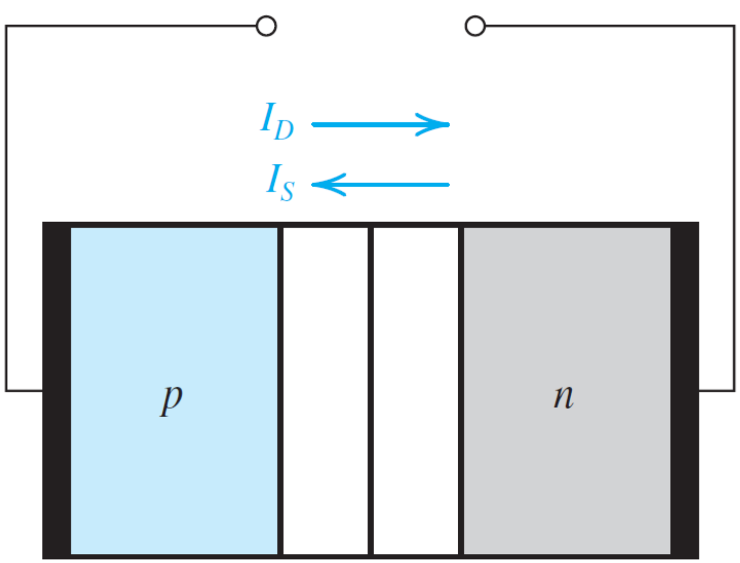
- The applied reverse voltage increases diffusion barrier
- The applied reverse voltage opposes diffusion current
- Net current is very small $\approx -I_S$
- Depletion width increases → capacitance decreases
  - Max capacitance at zero bias

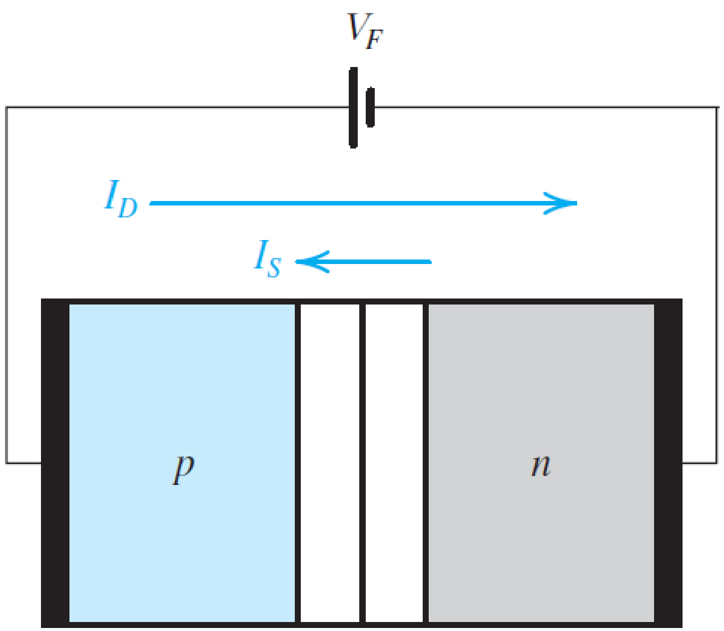


[Sedra/Smith, 2015]

pn Junction in Forward (Fwd) Bias

- The applied forward voltage decreases diffusion barrier
- The applied reverse voltage dramatically increases diffusion current
- Net current is very high $= I_D - I_S \approx I_D$

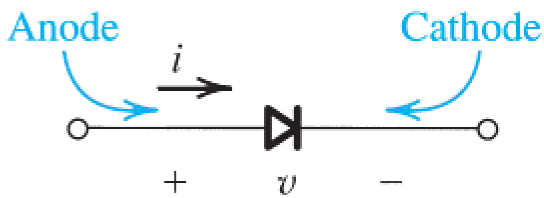


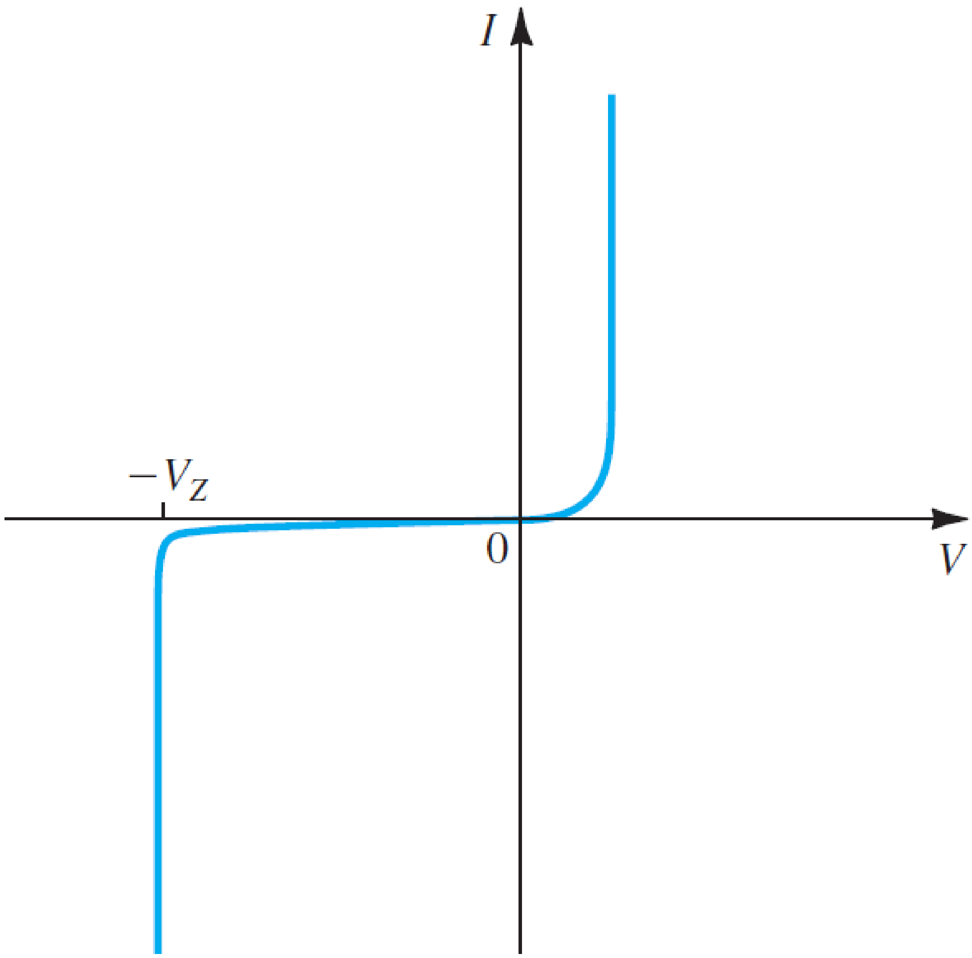


 [Sedra/Smith, 2015]

pn Junction IV Characteristics

- Forward: High diffusion current exponentially dependent on V_F
- Reverse: Very small drift current
- Breakdown: Very high reverse current at LARGE reverse bias voltage





[Sedra/Smith, 2015]

Thank you!