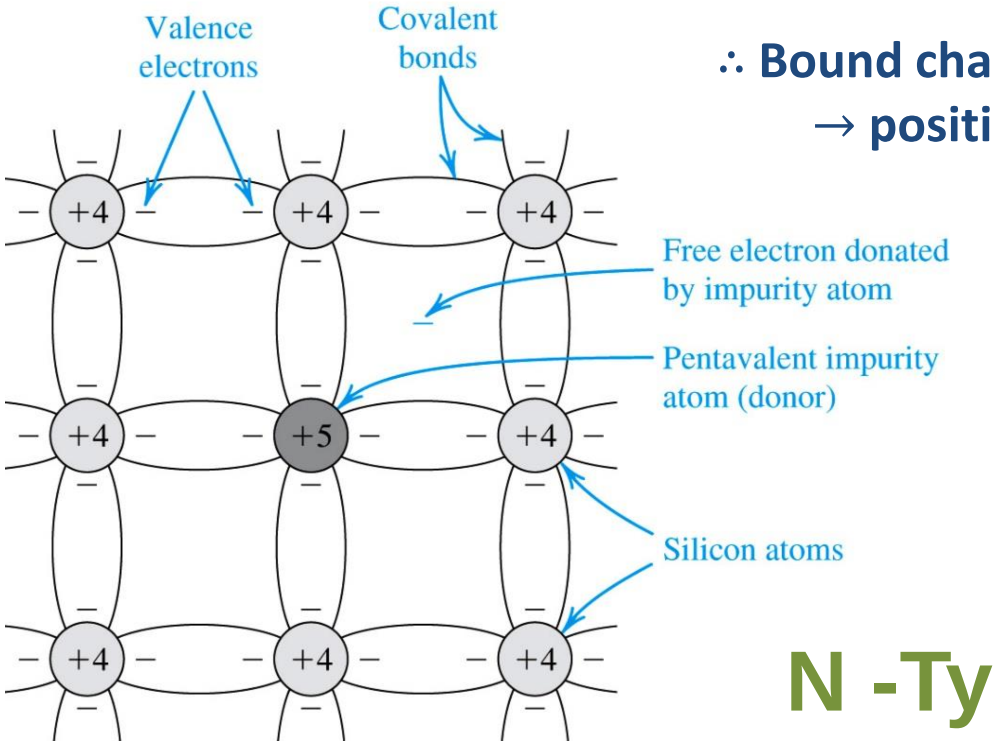
Last Lecture → Semiconductor Types

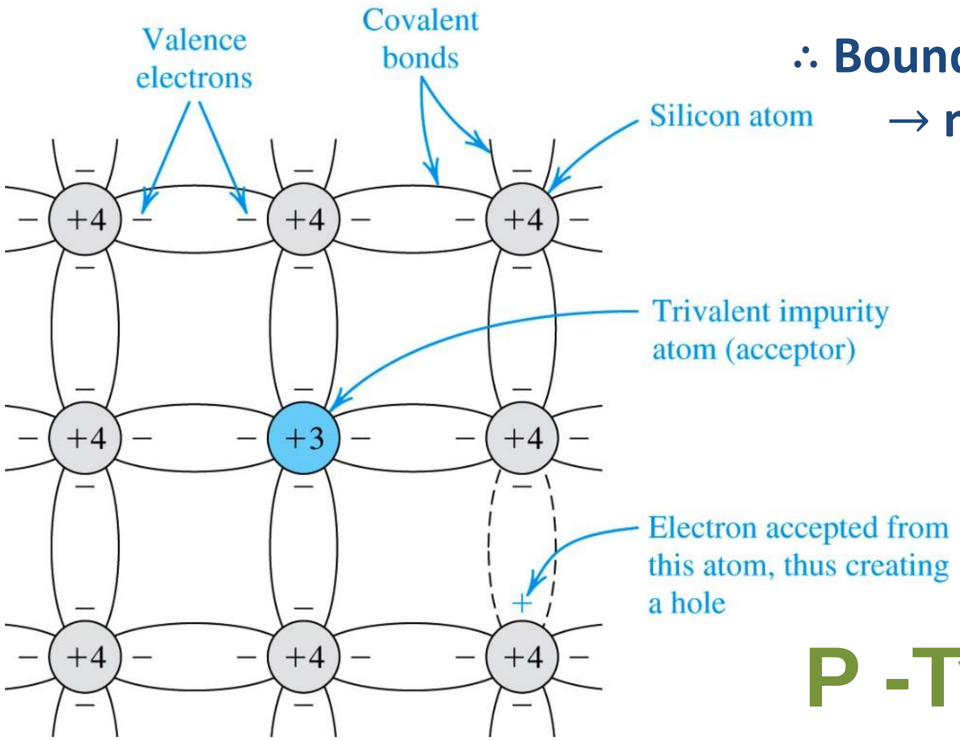
- Antimony (Sb) – 5 Valence Electrons
- n-type: electrons >> holes
  - Majority carriers – electrons
  - Minority carriers - holes



∴ Bound charge
→ positive

N -Type

- Boron (B) – 3 Valence Electrons
- p-type: holes >> electrons
  - Majority carriers – holes
  - Minority carriers - electrons

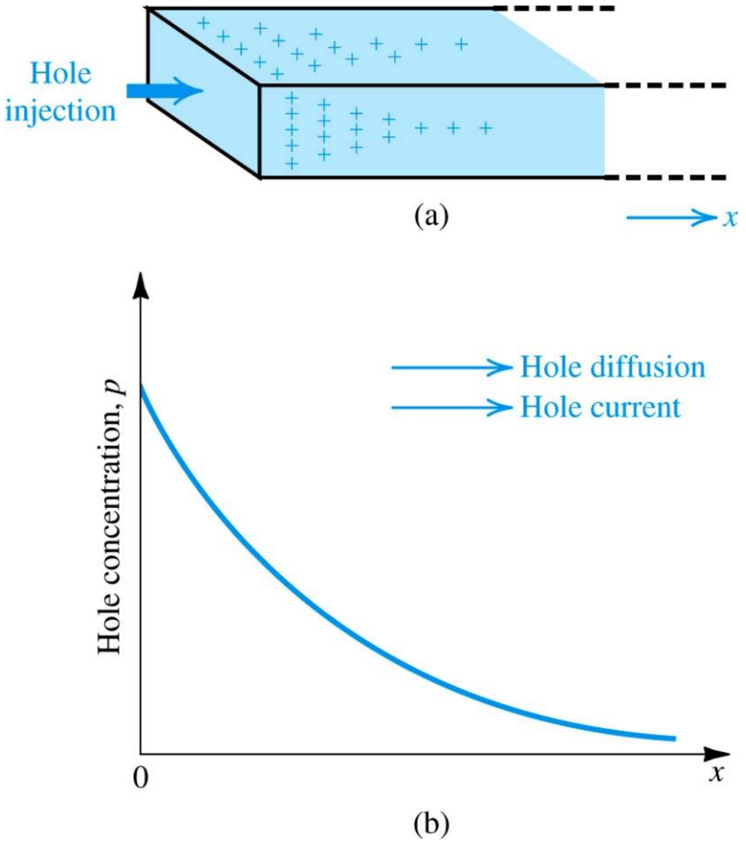


∴ Bound charge
→ negative

P -Type

Last Lecture → Current Flow in Semiconductors

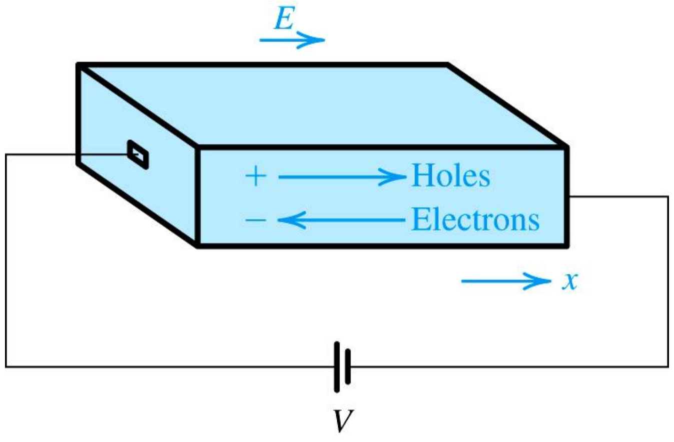
… there are two distinctly different mechanisms for the movement of charge carriers and hence for current flow in semiconductors: *drift* and *diffusion*



Drift Current

When and electrical field E is established in a semiconductor crystal…

- *Holes are accelerated in the direction of E!*
- *Free electrons are accelerated in the direction opposite of E!*



Diffusion Current

When the density of charge carrier in a piece of semiconductor is not uniform…

- *Charge carriers will diffuse from the region of high concentration to the region of low concentration!*

Problem 3.6

A young designer, aiming to develop intuition concerning conducting paths within an integrated circuit, examines the end-to-end resistance of a connecting bar 10µm long, 3µm wide, and 1µm thick, made of various materials. The designer considers:

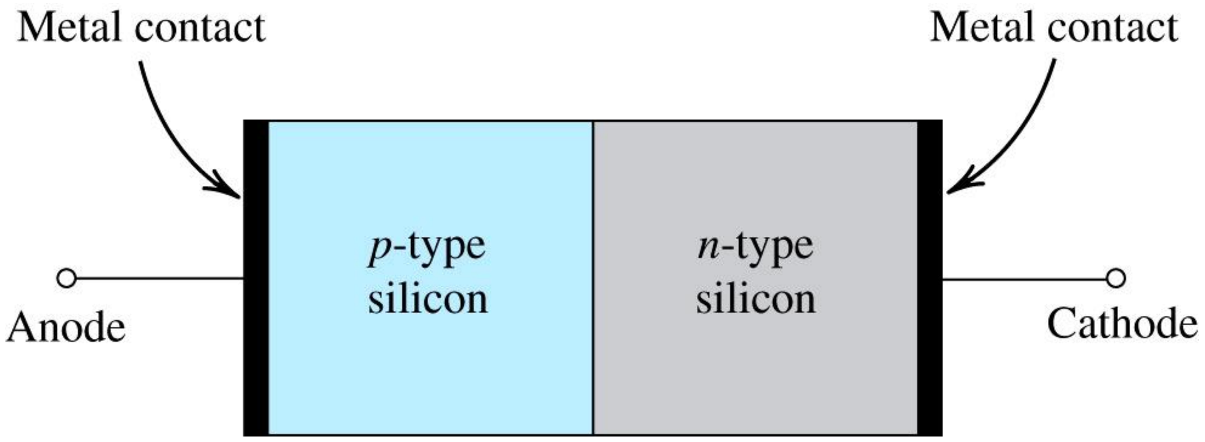
- **a) intrinsic silicon**
- **b) n-doped silicon with $N_D=10^{16}/cm^3$**
- **c) n-doped silicon with $N_D=10^{18}/cm^3$**
- **d) p-doped silicon with $N_A=10^{16}/cm^3$**
- **e) Aluminum with resistivity of 2.8 µΩ·cm.**

Find the resistance in each case. For intrinsic silicon use the data in Table 3.1. For doped silicon, assume $\mu_n=2.5\cdot\mu_p=1200cm^2/V\cdot s$. (Recall that $R=\rho L/A$)

- **Silicon $n_i = 1.5 \times 10^{10}$ /cm³**
- **$q = 1.6 \times 10^{-19}$ C**

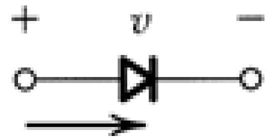
	n (1/cm³)	p (1/cm³)	ρ Ω·cm	R Ω
a)	1.5×10^{10}	1.5×10^{10}	227×10^{3}	7.57M
b)	10^{16}	2.25×10^{4}	0.463	15
c)	10^{18}	2.25×10^{2}	4.63m	0.15
d)	2.25×10^{4}	10^{16}	0.768	25.6
e)	-	-	2.8µ	93.3µ

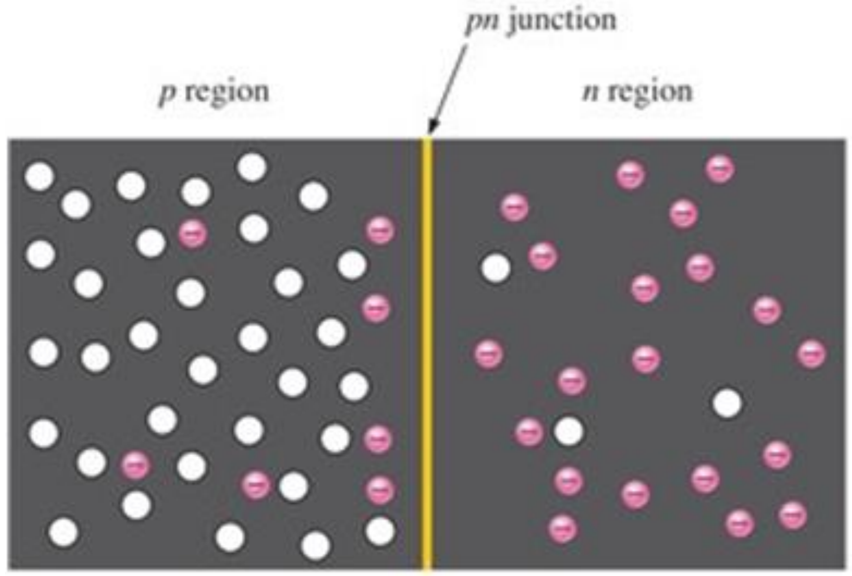
The PN Junction



- *p*-type semiconductor
- *n*-type semiconductor
- metal contact for connection

Symbol



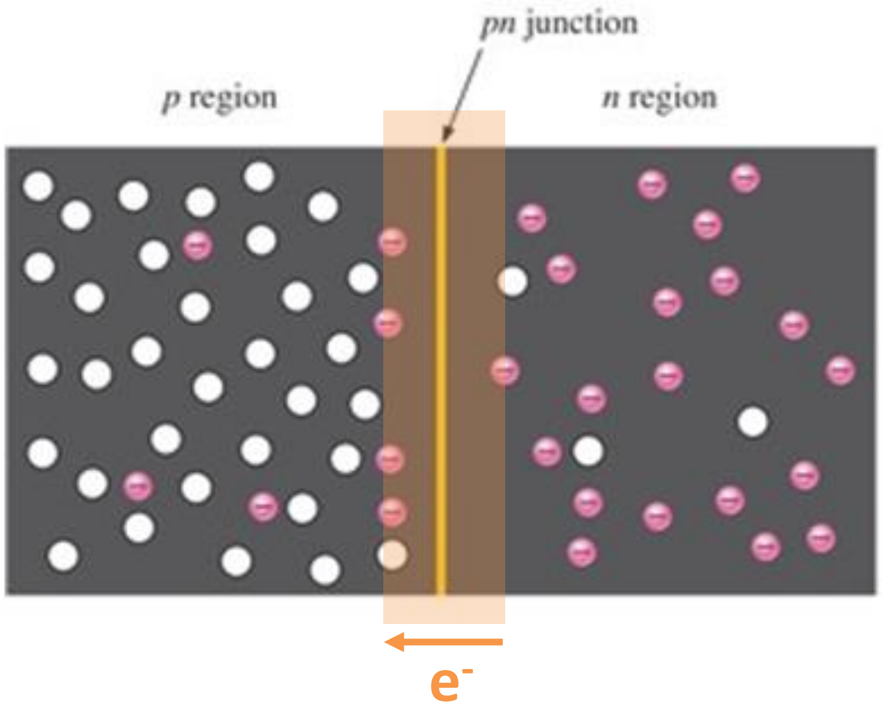


higher holes concentration

higher e^- concentration

The PN Junction

- **Initially**

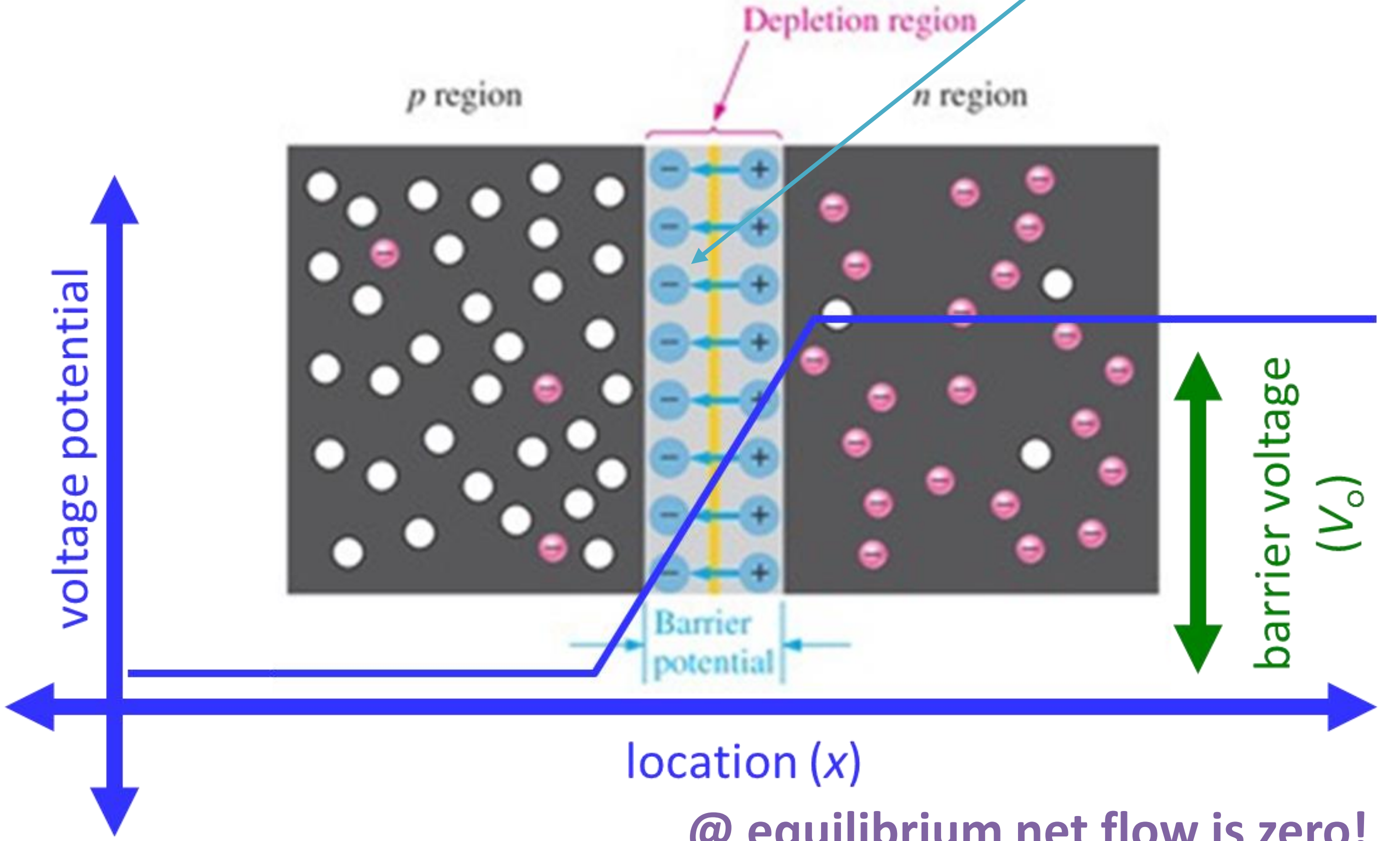


I_{diff}

diffusion current

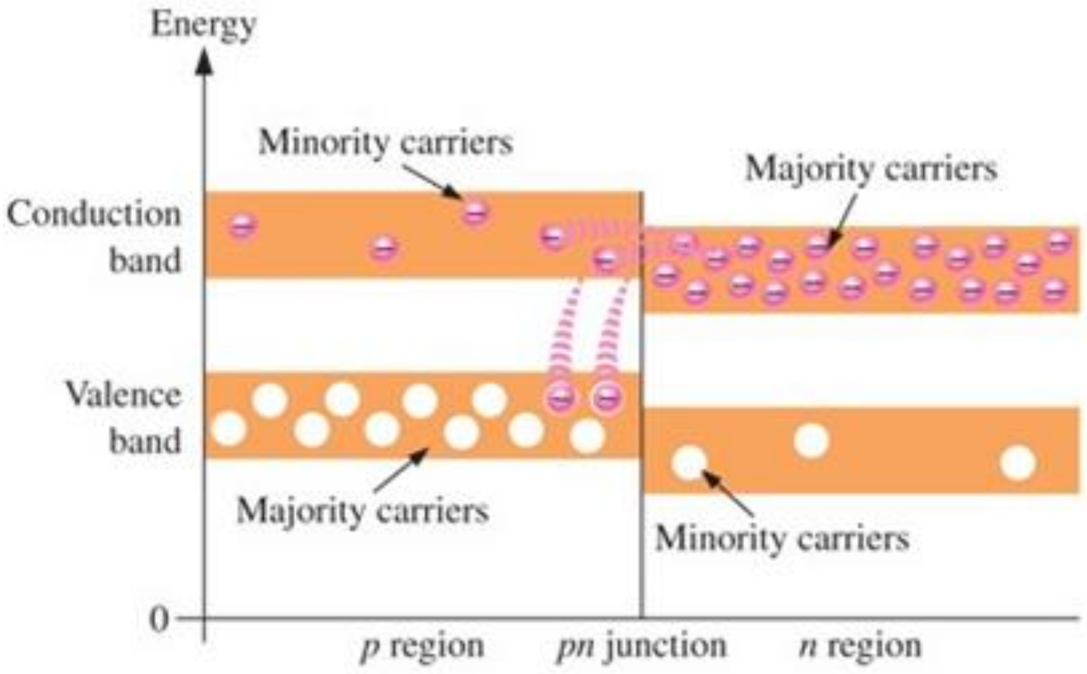
- **@ Equilibrium**

uncovered bound charges!

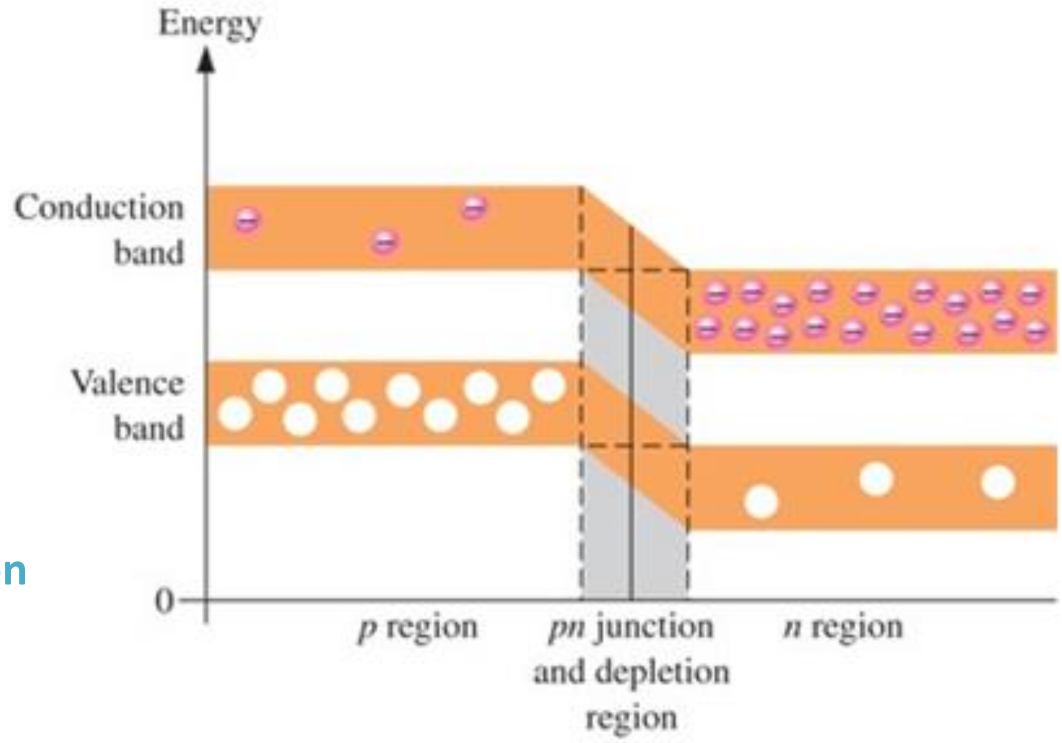


@ equilibrium net flow is zero!

The Equilibrium PN Junction



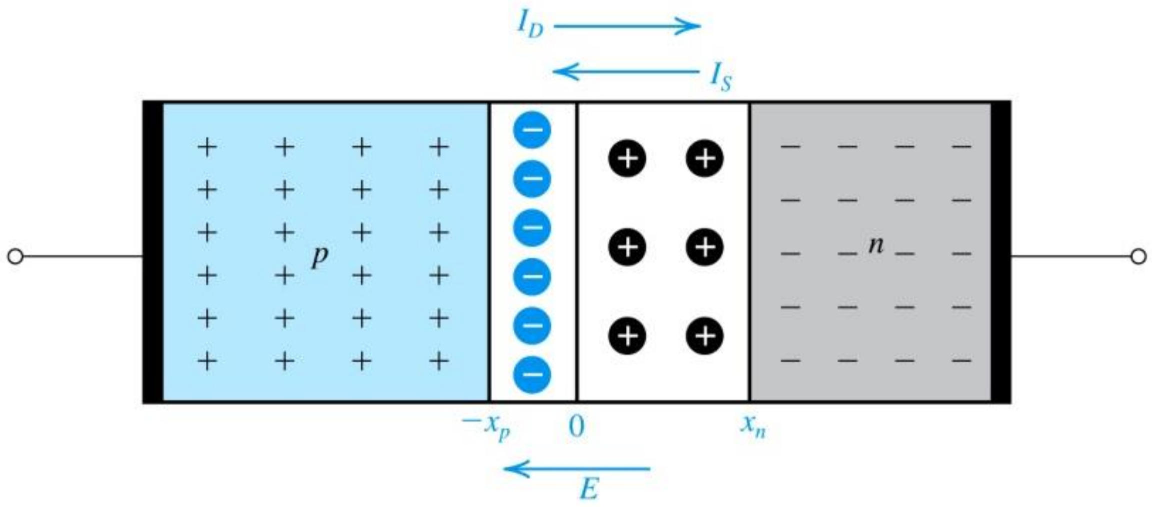
Diffusion



- Energy levels are aligned.
- Free electrons can easily diffuse across the junction.

- The energy level of the n region decreases.
- The depletion region acts like an “energy hill”.

The Equilibrium PN Junction → $N_A > N_D$



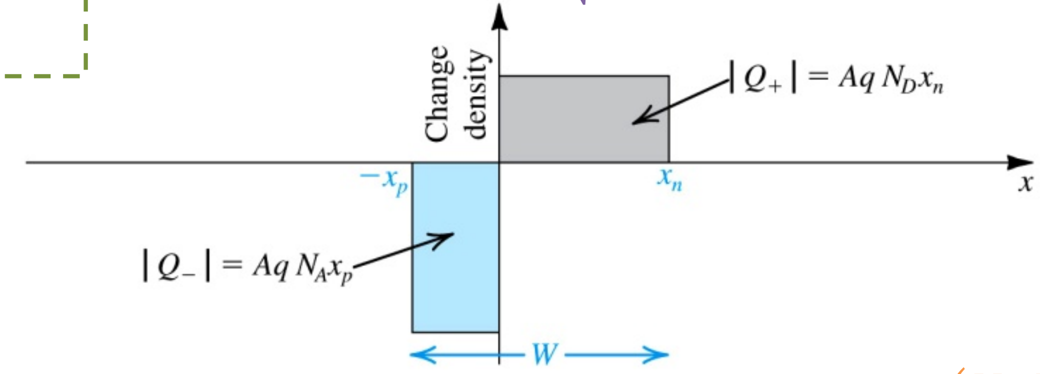
- **The depletion region will extend further in to region with "less" doping.**
- **However, the "number" of uncovered charges is the same.**

∴ charge is equal, but width is different

$$\frac{x_n}{x_p} = \frac{N_A}{N_D}$$

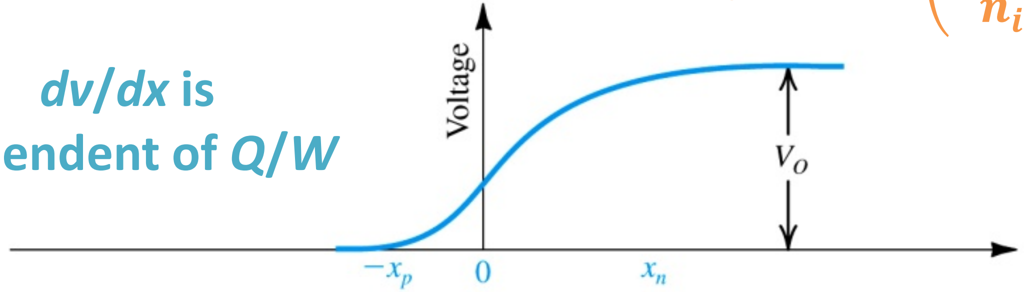
$$W = x_n + x_p$$

$$= \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_A} + \frac{1}{N_D}\right][V_0 + V_R]}$$

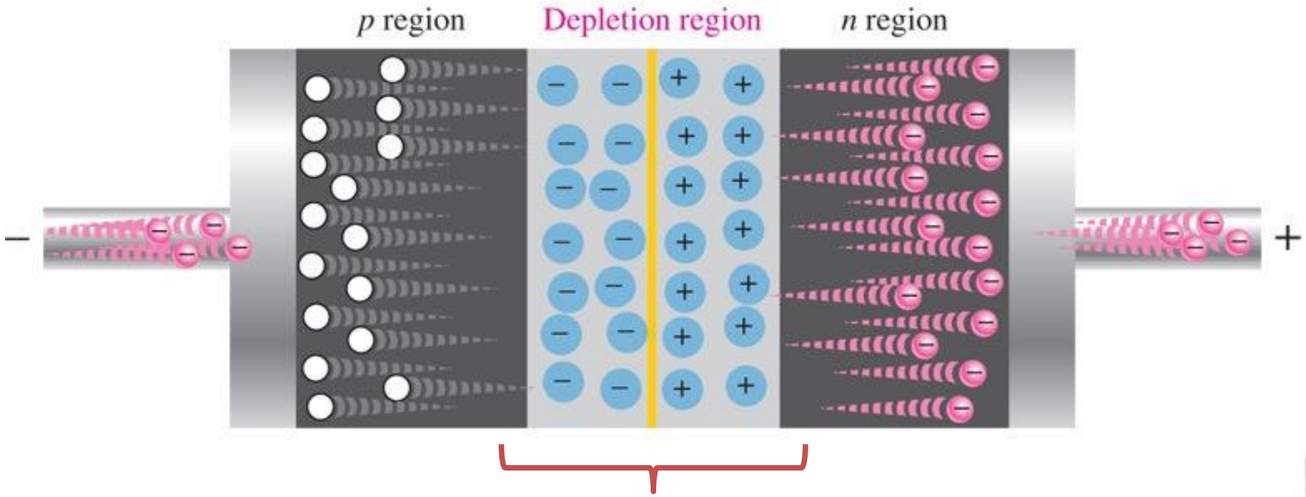


$$V_0 = V_T \ln\left(\frac{N_A N_D}{{n_i}^2}\right)$$

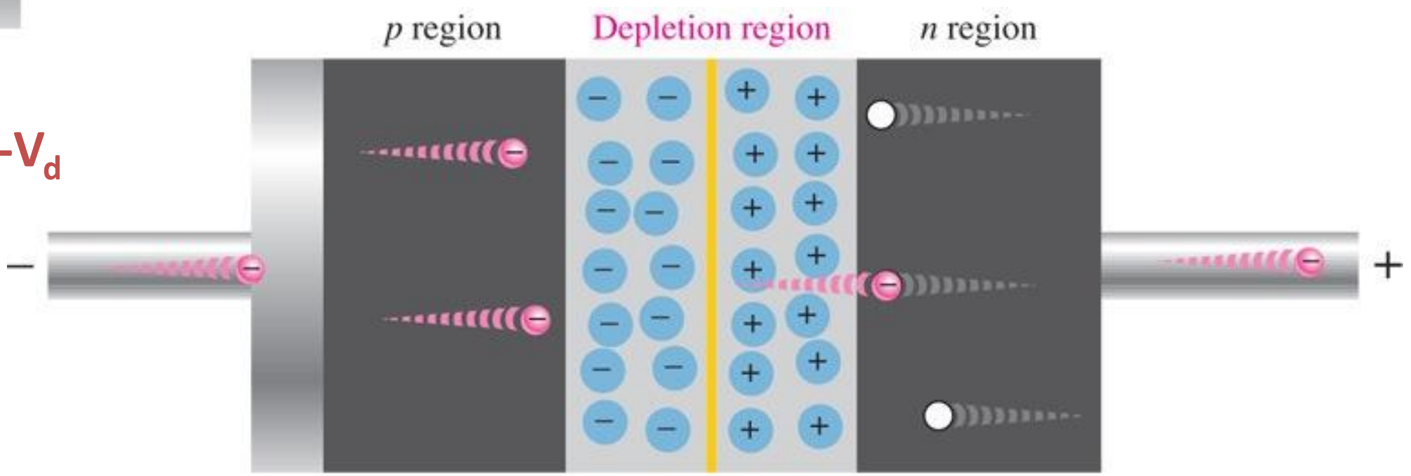
dv/dx* is dependent of *Q/W



Reverse-Biased PN Junction → $V_d < 0$

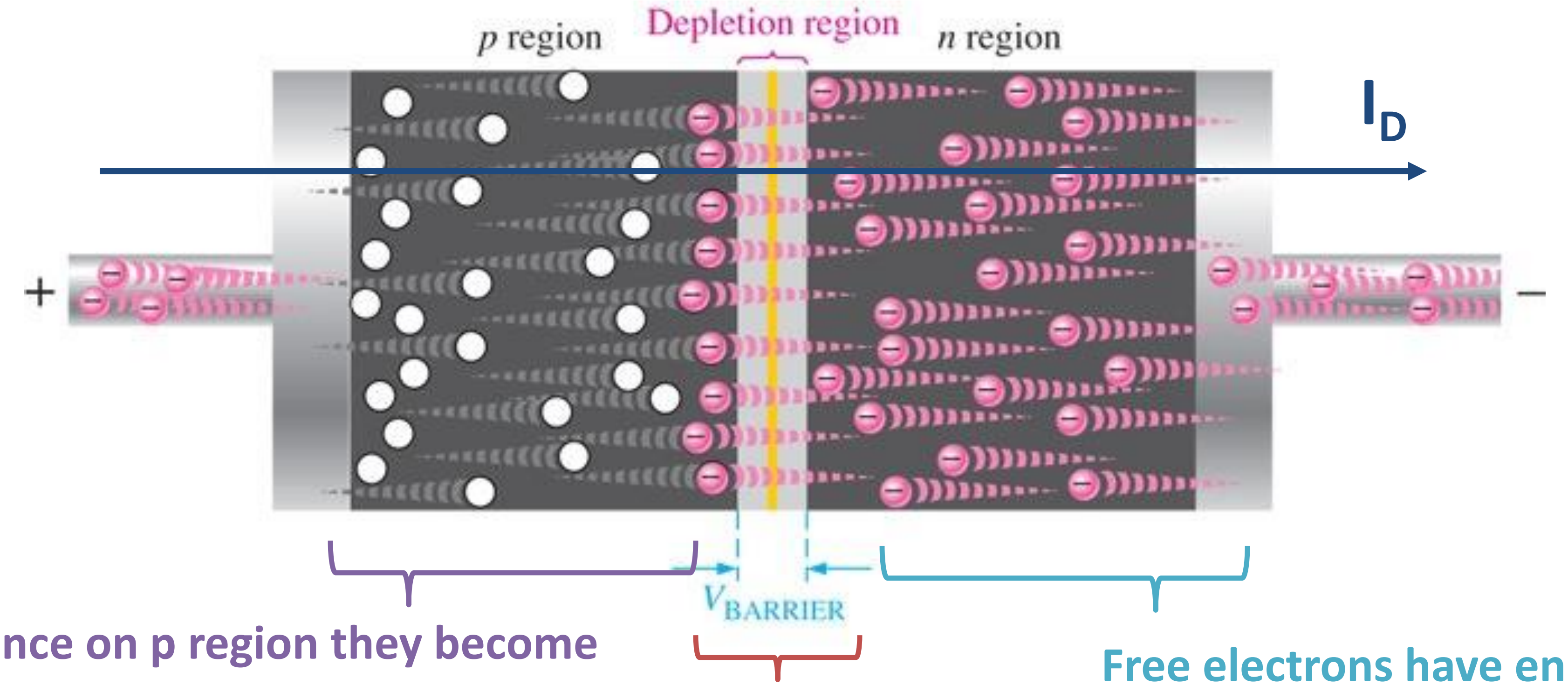


- Widening of the depletion region until $V_0 = -V_d$
- Depletion of majority carriers



- The transition current essentially ceases
- A extremely small current exists do minority carries produced thermally

Forward-Biased PN Junction → $V_d > |V_0|$



Once on p region they become minority carries

Barrier is reduced

Free electrons have enough energy to diffuse across the barrier

Hole current will move the minority carries towards the positive terminal → **Thus a steady state current will be established!**

Qualitative PN Junction Operation

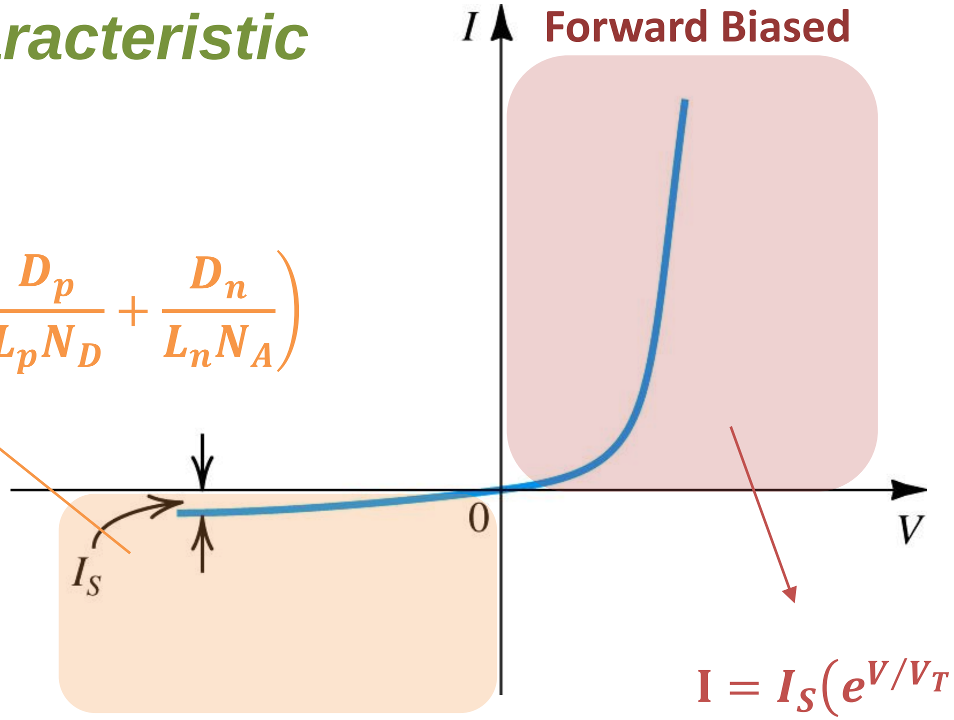
Reverse biased case (↑V_R)

- barrier voltage increases (↑V_0)
    - Diffusion decreases… ∴ ↓ I_D
    - @ V_R > 1V, $I_D \approx 0$A
- the drift current I_S is unaffected
- $I_{pn} \approx I_S$ (small non-zero current)

Forward biased case case (↑V_F)

- barrier voltage decreases (↓V_0)
    - Diffusion increases … ∴ ↑I_D
- the drift current I_S is unaffected
- $I_{pn} \approx I_D - I_S$ (a significant current)

I-V Characteristic



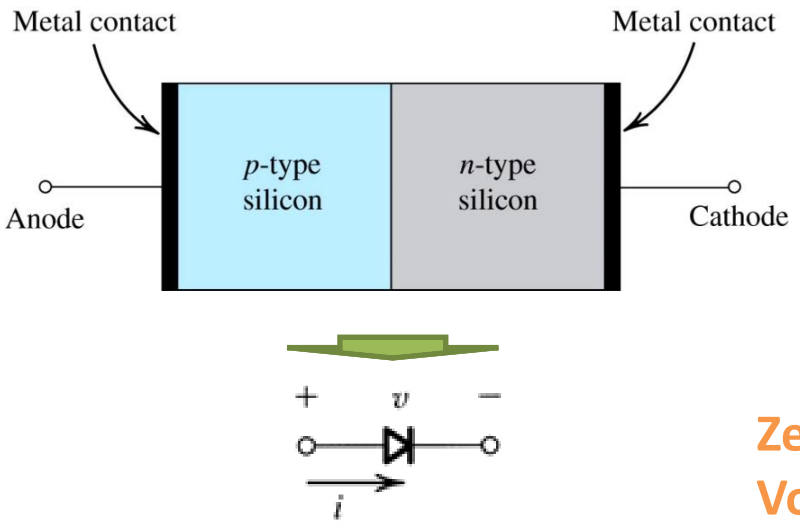
Forward Biased

$$I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D}+\frac{D_n}{L_nN_A}\right)$$

$$\mathrm{I} = I_S\left(e^{V/V_T}-1\right)$$

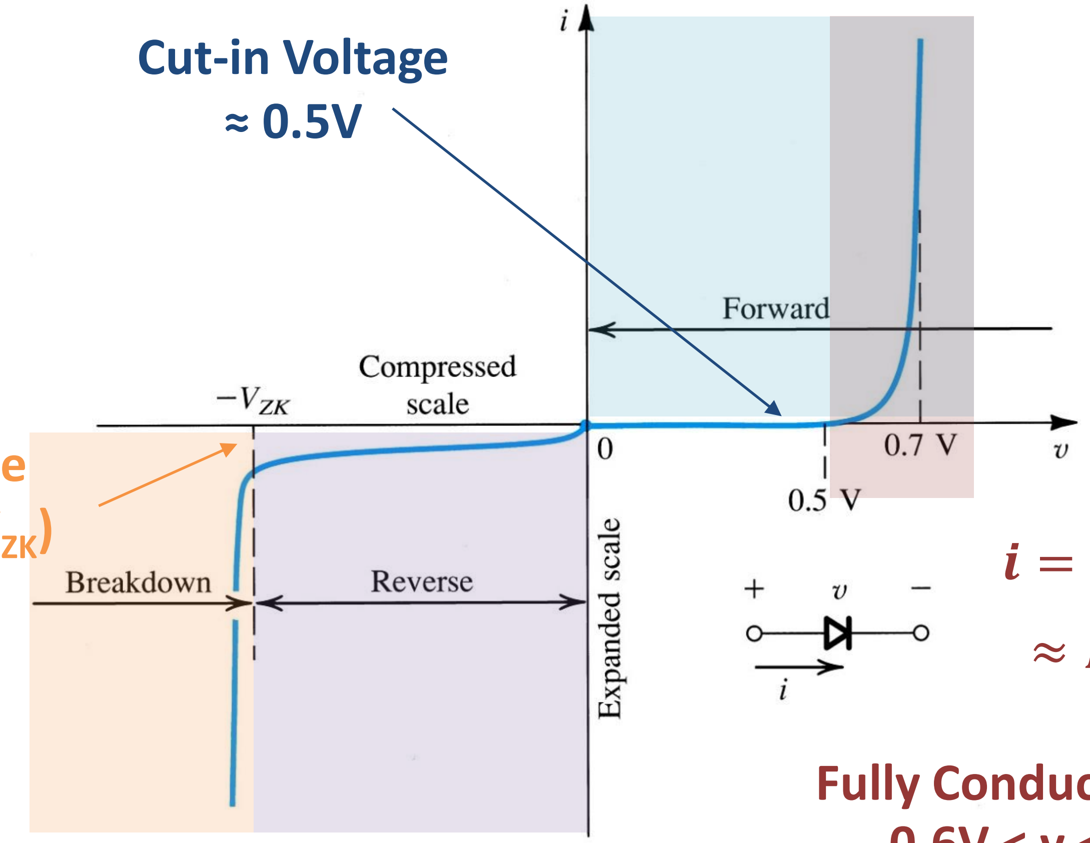
Reverse Biased

Terminal Characteristics of Diodes



Characteristic Regions

- **Forward Bias: $v > 0$**
- **On $v \geq 0.5\text{V}$**
- **Reverse Bias: $v < 0$**
- **Breakdown: $v << 0$**



Cut-in Voltage
≈ 0.5V

Zener-Knee Voltage (V_{ZK})

$$i = I_S\left(e^{v/V_T} - 1\right)$$

$$\approx I_S e^{v/V_T}$$

$$i = -I_S e^{-|v|/V_T}$$

$$i \approx -I_S$$

Fully Conducting Region
$0.6\text{V} < v < 0.8\text{V}$

- I_S → saturation current
- V_T → thermal voltage

Diode Models

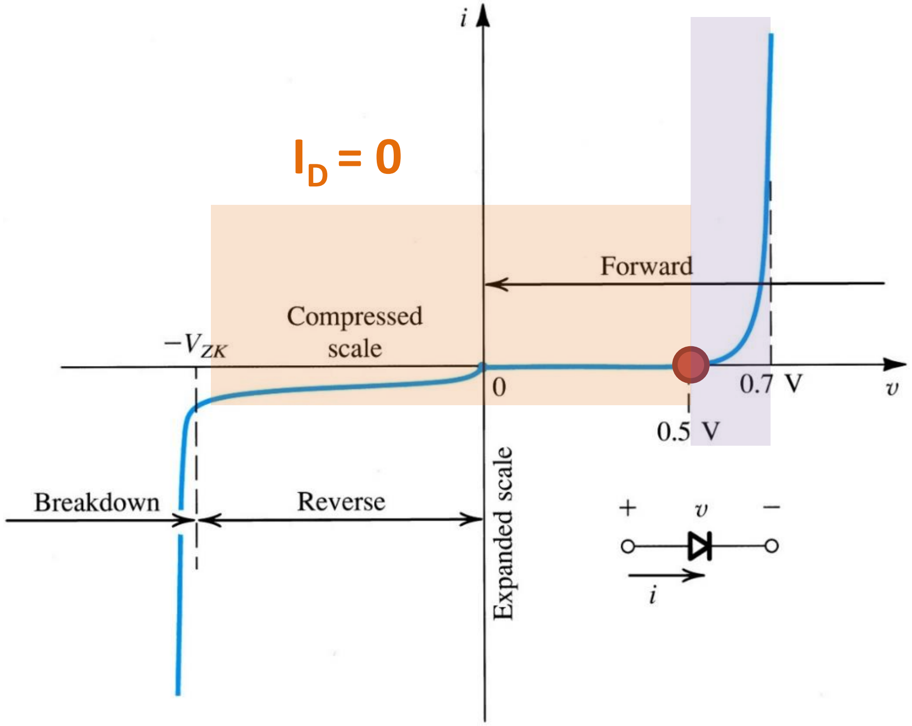
DC Analysis

- **Ideal Model**
- **Constant-Voltage-Drop Model**
- **Exponential Model**
  - **Graphical Analysis**
  - **Numerical Analysis**

AC Analysis

- **Small Signal Model**

Your simulation results are as good as your model!!!!



Exponential Model

$$for\ v < 0.5 \rightarrow I_D \approx 0$$

$$for\ v \geq 0.5 \rightarrow I_D \approx I_S e^{v_D/V_T}$$

Problem 4.23

The circuit provided below utilizes three identical diodes having $I_s = 10^{-16}$A. Find the value of the current I required to obtain an output voltage $V_0 = 2.4$V. If a current of 1mA is drawn away from the output terminal by a load, what is the change in the output voltage.