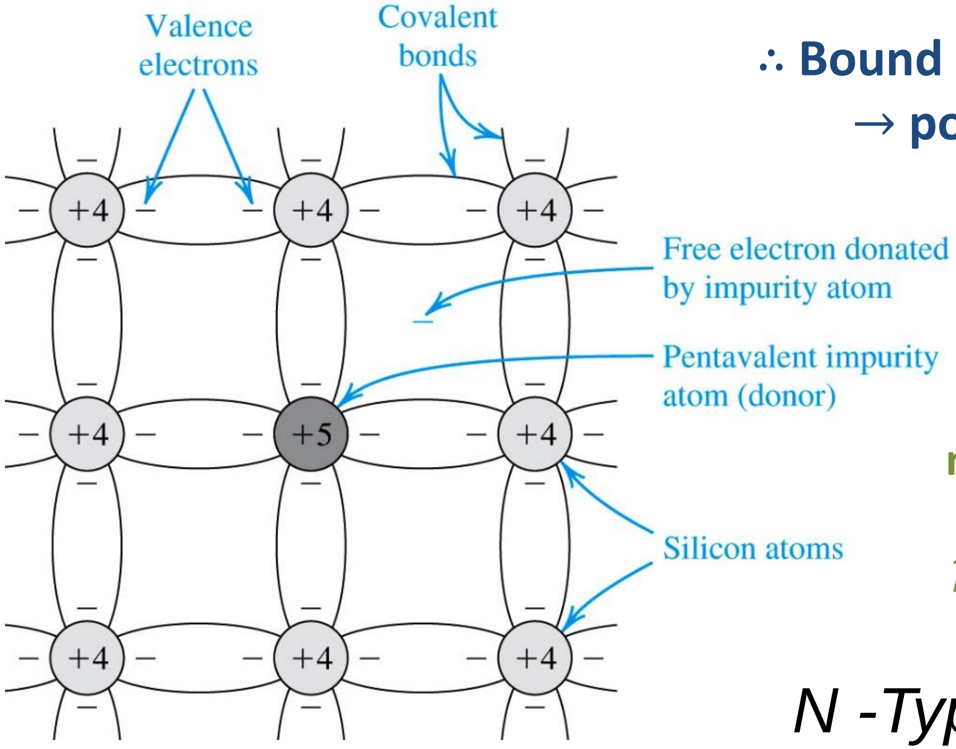
Last Lecture → Doped Semiconductor

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



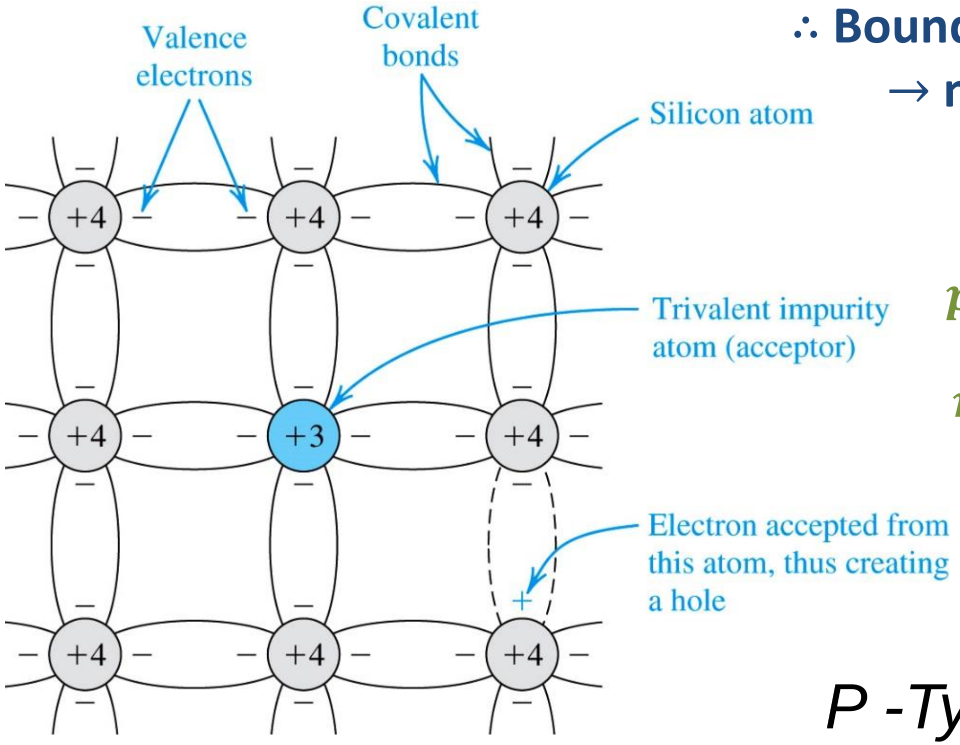
∴ Bound charge → positive

$$n_n \simeq N_D$$

$$p_n \simeq \frac{{n_i}^2}{N_D}$$

N -Type

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



∴ Bound charge → negative

$$p_p \simeq N_A$$

$$n_p \simeq \frac{{n_i}^2}{N_D}$$

P -Type

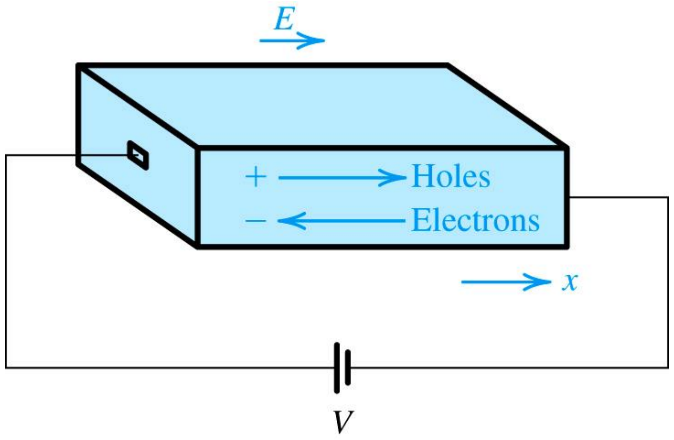
Last Lecture → Current Flow

… 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!*



Semiconductor Characteristics

- **Ohm's Law [A/cm²]**

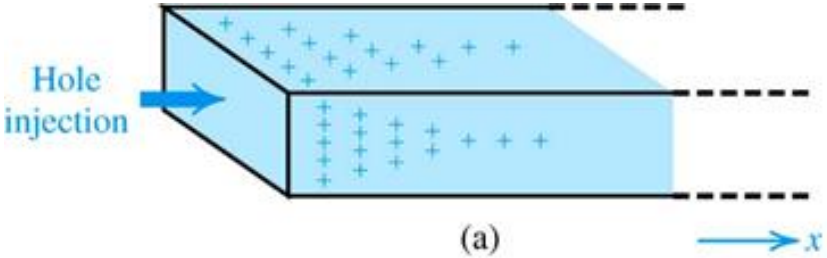
$$J = \sigma E$$

- **Conductivity [1/ Ω·cm]**

$$\sigma = q\left(p\mu_p + n\mu_n\right)$$

- **Resistivity [Ω·cm]**

$$\rho = \frac{1}{q\left(p\mu_p + n\mu_n\right)}$$



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

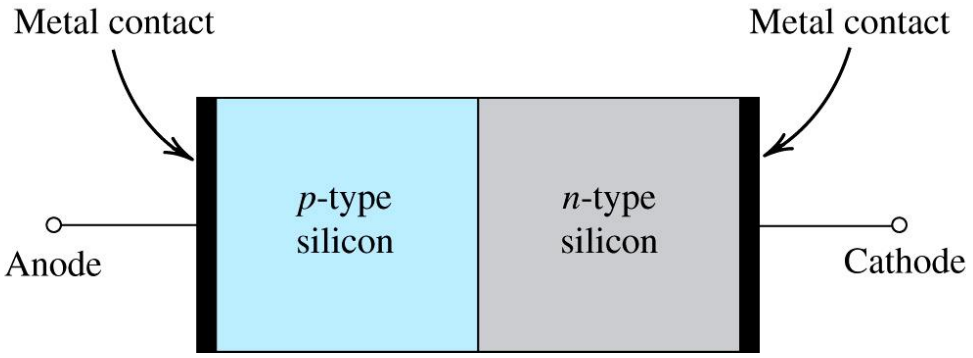
A young designer, aiming to develop intuition concerning conducting paths within an integrated circuit, examines the end-to-end resistance of a connecting bar 10µm long, 3µm wide, and 1µm thick, made of various materials. The designer considers:

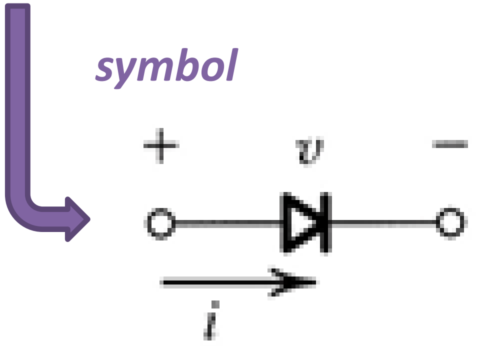
a) intrinsic silicon
b) n-doped silicon with $N_D=10^{16}/cm^3$
c) n-doped silicon with $N_D=10^{18}/cm^3$
d) p-doped silicon with $N_A=10^{16}/cm^3$
e) Aluminum with resistivity of 2.8 µΩ·cm.

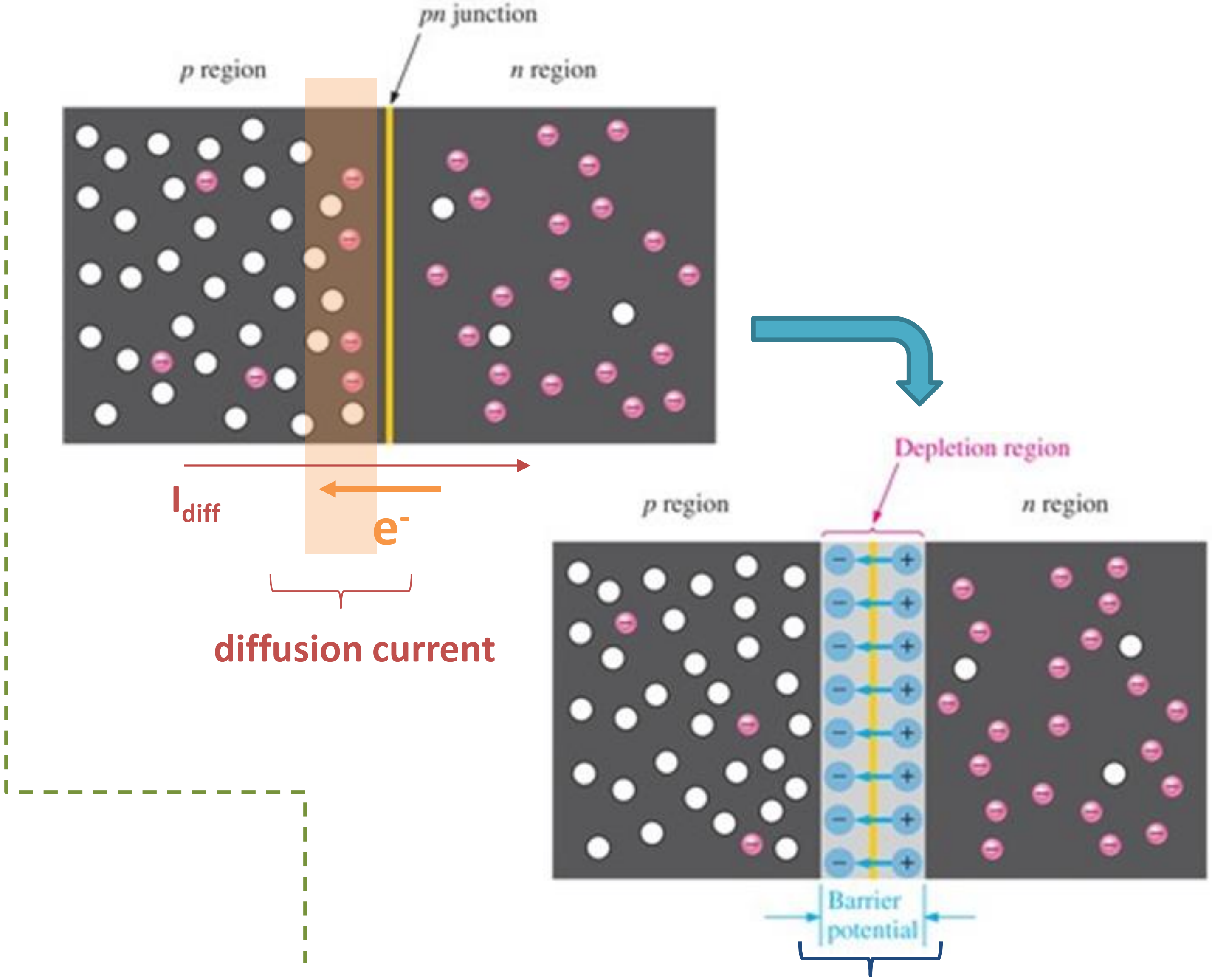
Find the resistance in each case. For intrinsic silicon use the data in Table 3.1. For doped silicon, assume $\mu_n=2.5\cdot\mu_p=1200cm^2/V\cdot s$. (Recall that $R=\rho L/A$)

The PN Junction

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



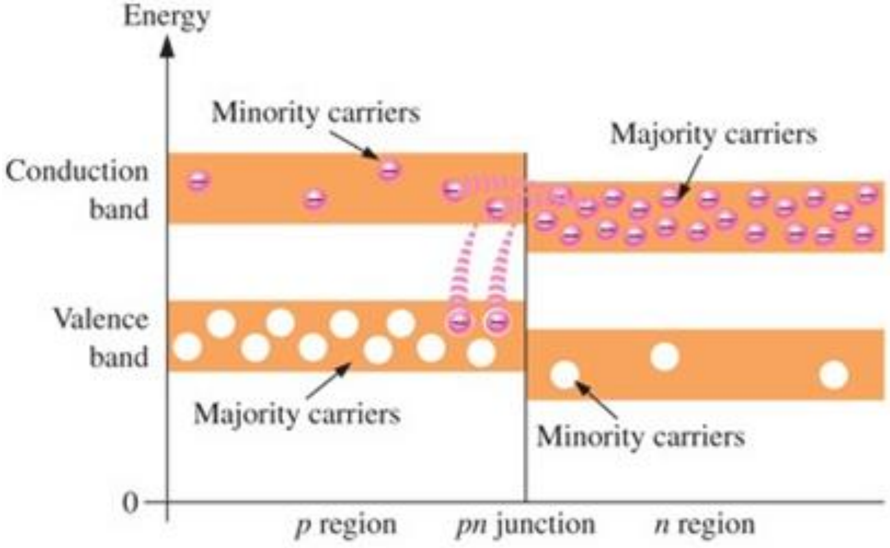




diffusion current

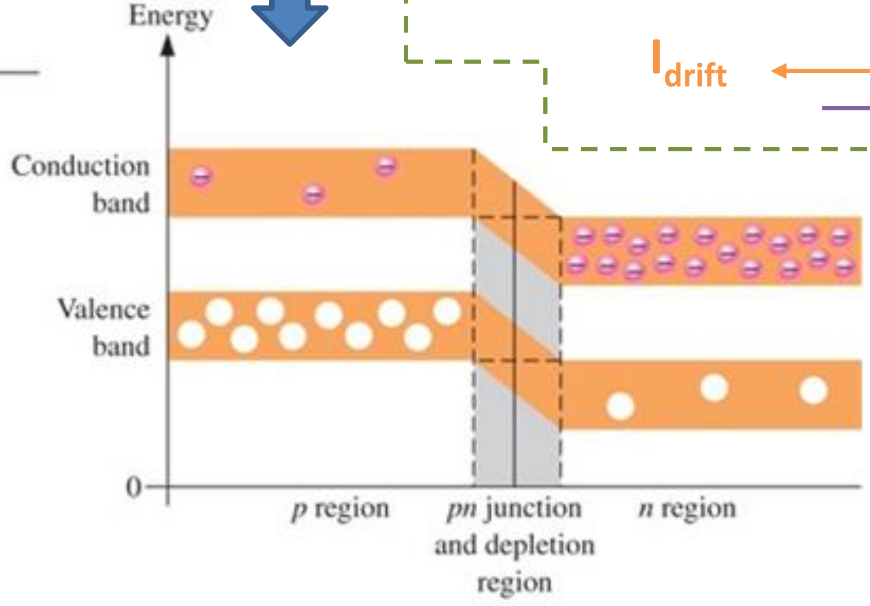
uncovered bound charges!

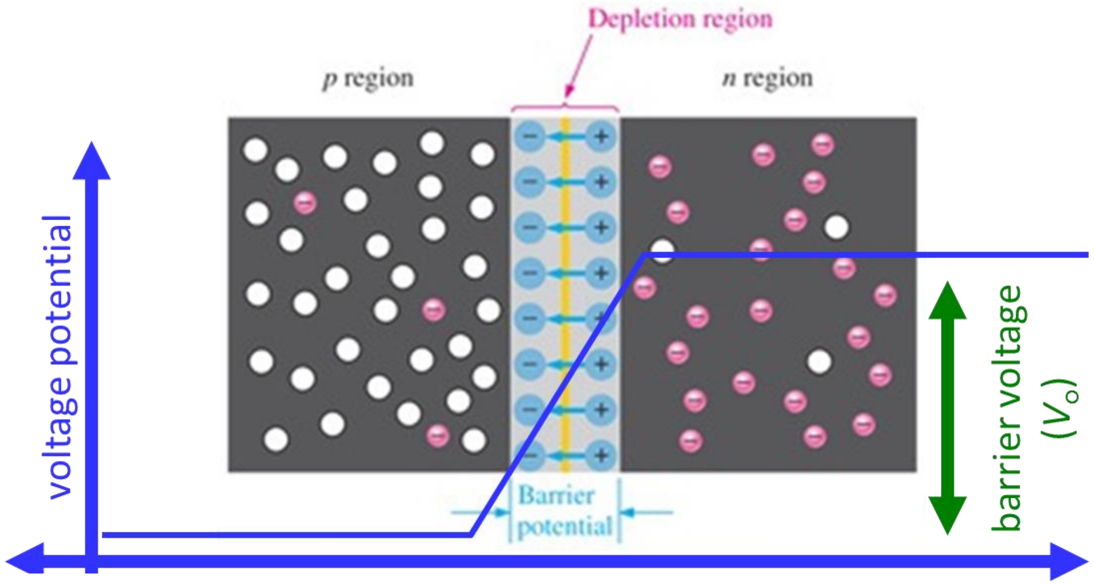
The Equilibrium PN Junction



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

Diffusion





location (x)

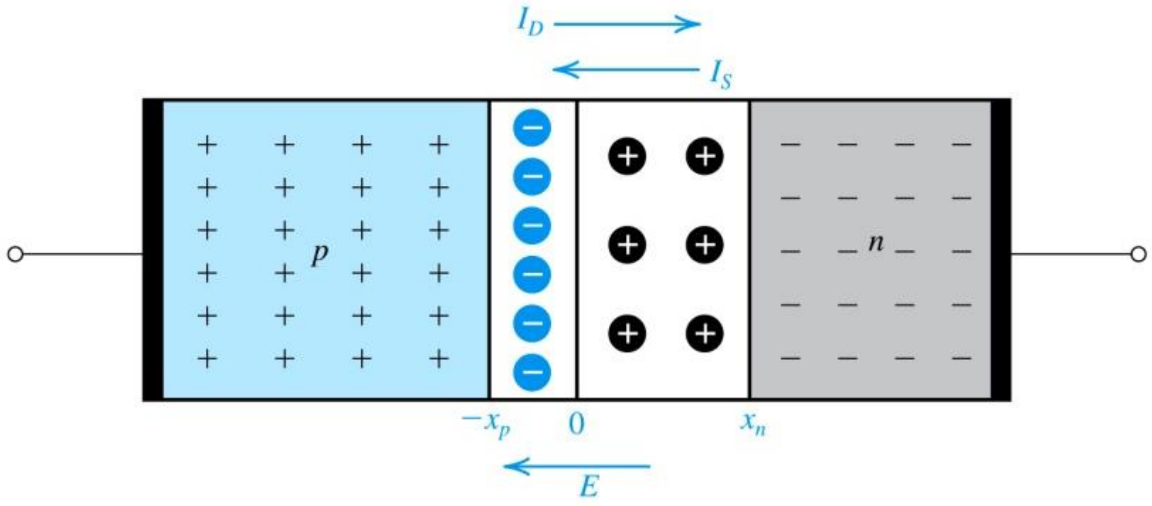
I_{drift}

$I_{difussion}$

@ equilibrium net flow is zero!

- **The energy level of the n region decreases.**
- **The depletion region acts like an "energy hill".**

The Equilibrium PN Junction → $N_A > N_D$

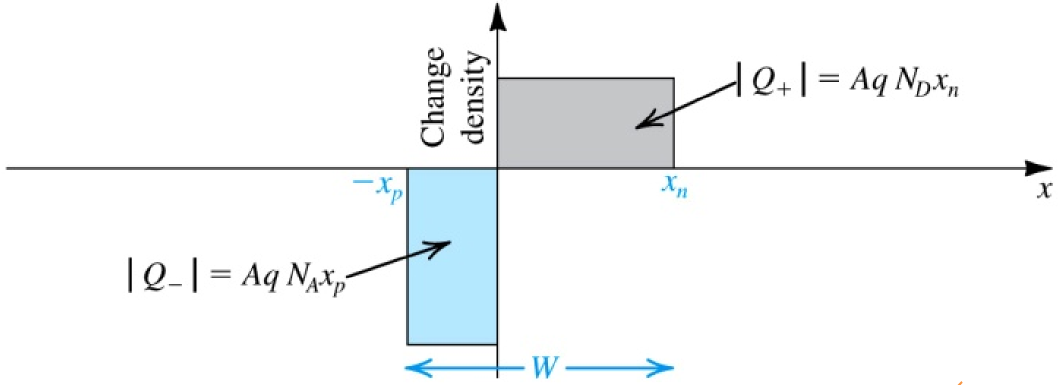


- The depletion region will extend further in to region with “less” doping.
- However, the “number” of uncovered charges is the same.

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

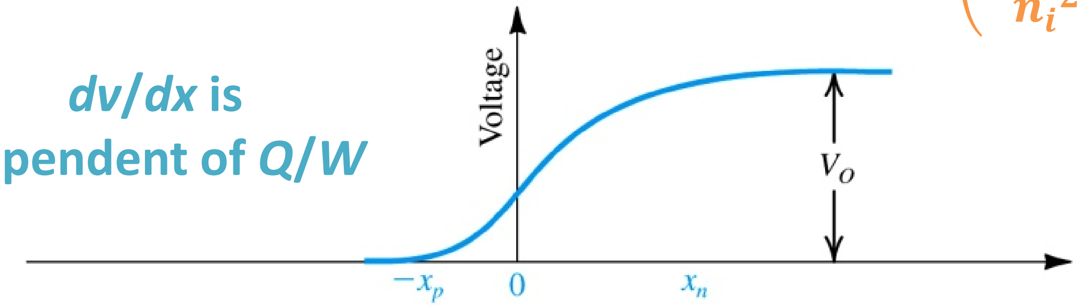
$$W = x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_A} + \frac{1}{N_D}\right][V_0 + V_R]}$$

charge is equal, but width is different

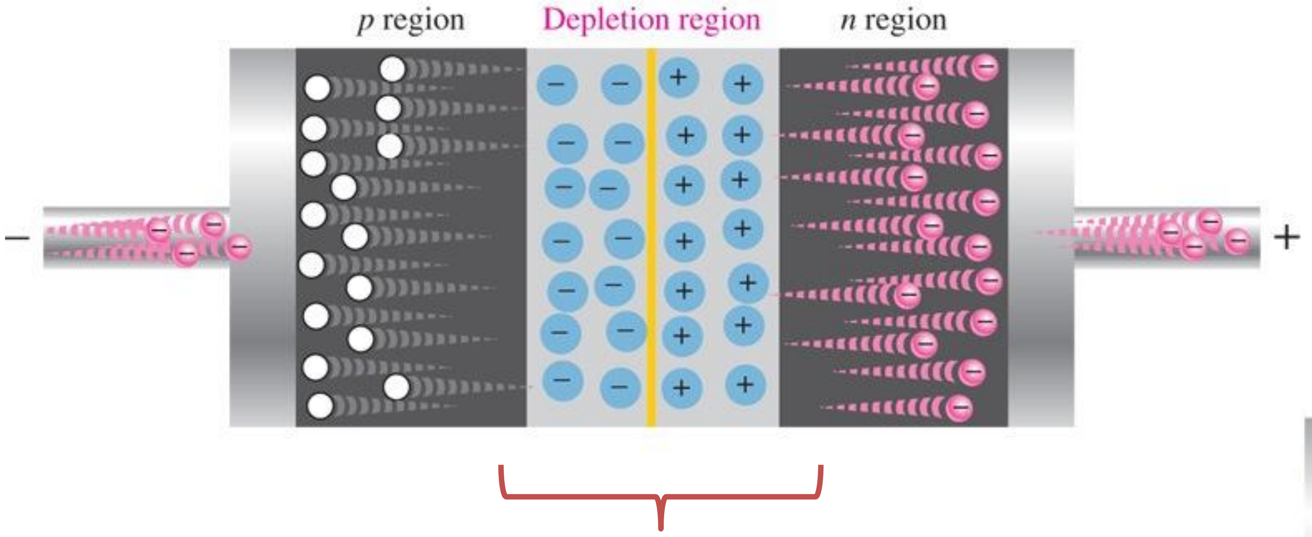


$$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

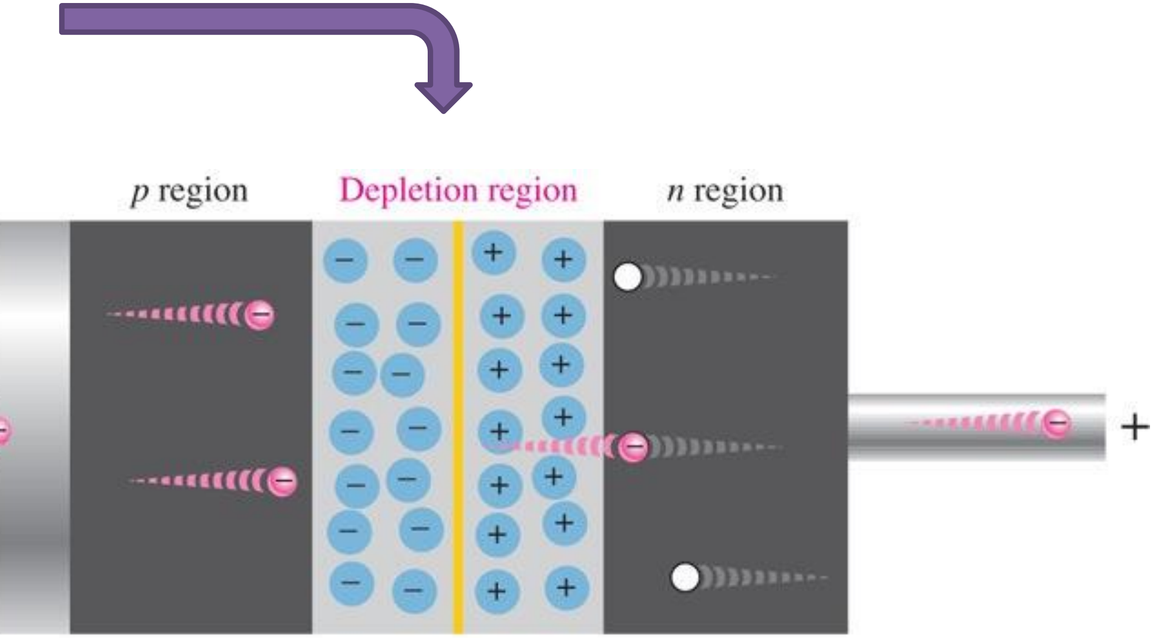
dv/dx **is dependent of** ***Q/W***



Reverse-Biased PN Junction

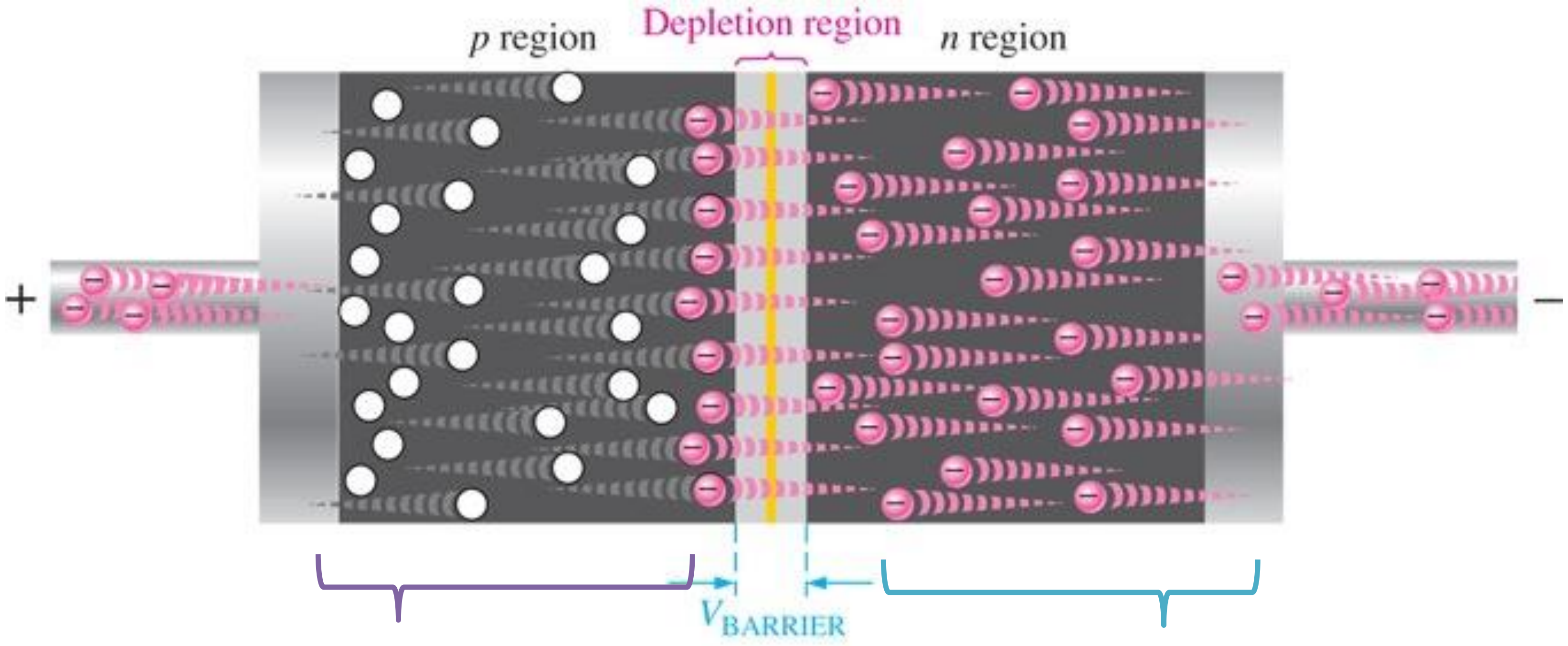


- Widening of the depletion region until $V_0 = V_{bias}$
- Depletion of majority carriers



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

Forward-Biased PN Junction



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)

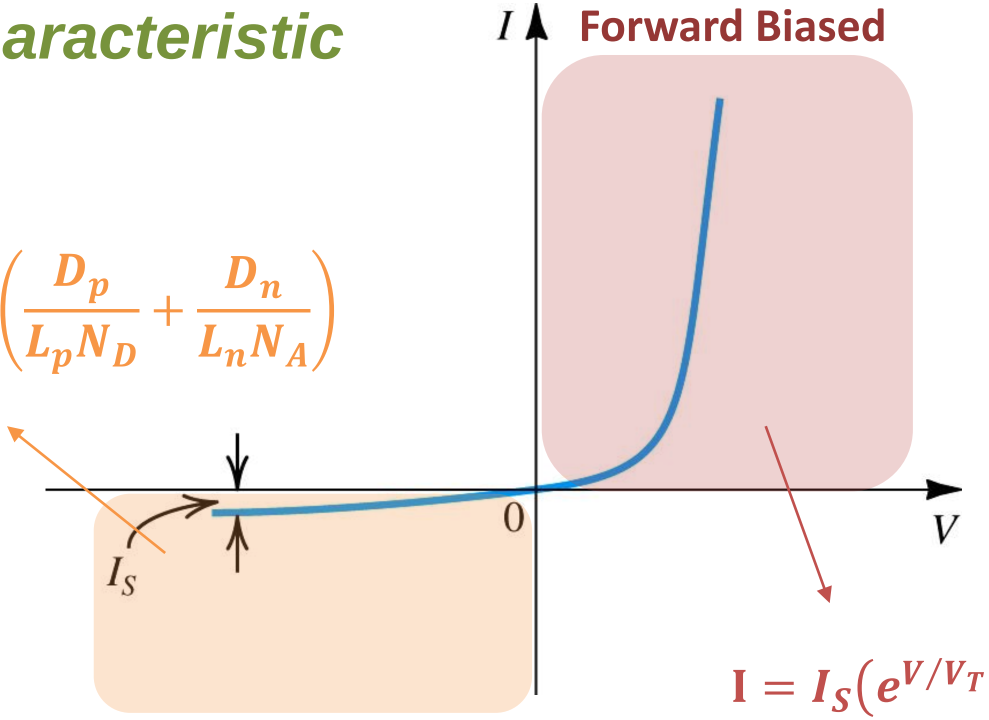
- barrier voltage increases (↑V_0)
  - Diffusion decreases… ∴ ↓I_D
  - @ $V_R > 1V$, $I_D \approx 0A$
- the drift current I_S is unaffected
- $I_{pn} \approx I_S$ (small non-zero current)

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

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



Forward Biased

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

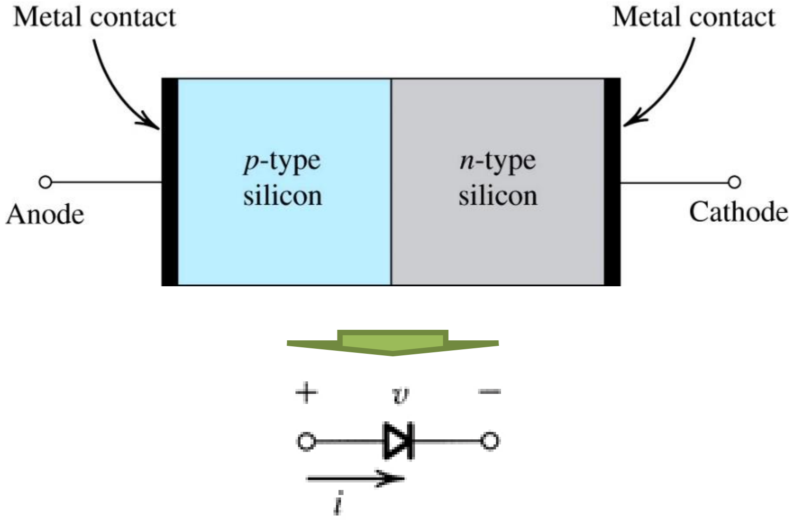
Reverse Biased

saturation current (I_S) – is the maximum reverse current which will flow through *pn*-junction (typical value is $10^{-18}A$)

Problem 3.13

If, for a particular junction, the acceptor concentration is 10^{16}/cm^3 and the donor concentration is 10^{15}/cm^3, find the junction built-in voltage. Assume $n_i = 1.5\text{x}10^{10}$/cm^3. Also, find the width of the depletion region (W) and its extent in each of the p and n regions when the junction terminals are left open. Calculate the magnitude of the charge stored on either side of the junction. Assume that the junction area is 400µm^2.

Terminal Characteristics of Diodes



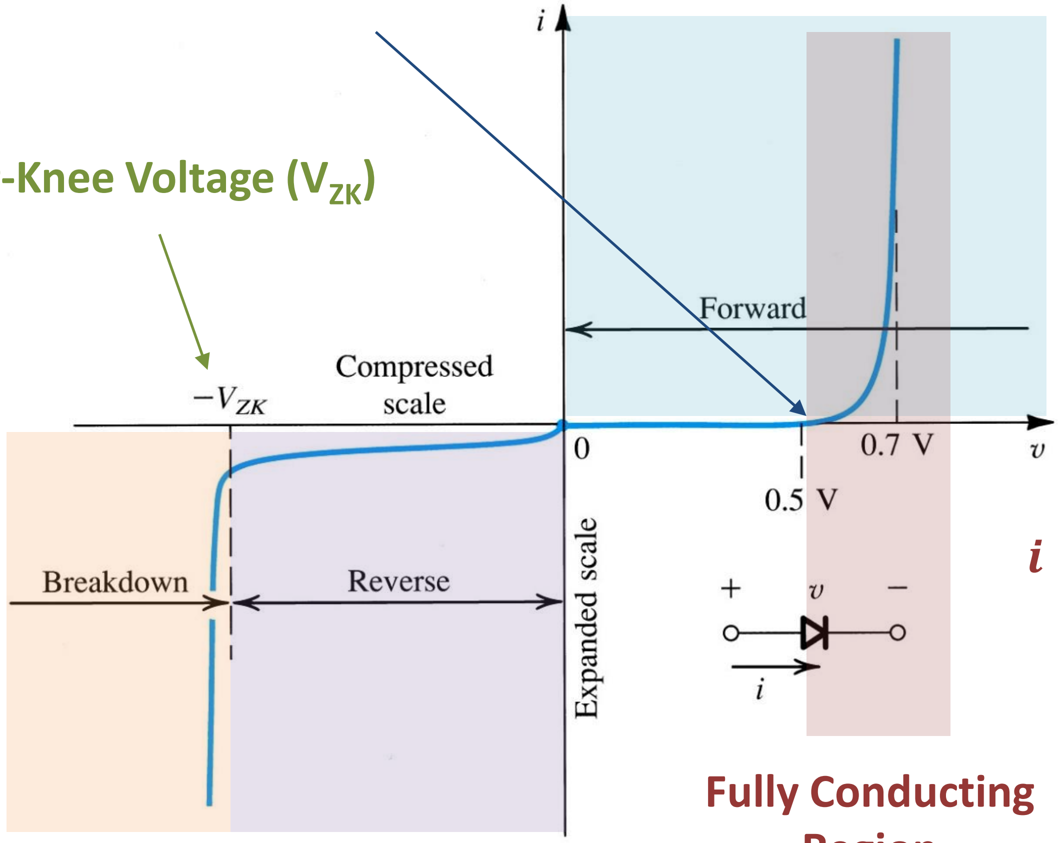
Characteristic Regions

- **Forward Bias:** v > 0
- **Reverse Bias:** v < 0
- **Breakdown:** v << 0

Cut-in Voltage ≈ 0.5V

- I_S → saturation current
- V_T → thermal voltage

Zener-Knee Voltage (V_{ZK})



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

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

Fully Conducting Region

0.6V < v < 0.8V

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

$$i \approx -I_S$$