ACCEP
Communication and Computer
Engineering Program

BENHA UNIVERSITY
FACULTY OF ENGINEERING (SHOUBRA)
ELECTRONICS AND COMMUNICATIONS ENGINEERING

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FACULTY OF ENGINEERING AT SHOUBRA

CCE 201
Solid State Electronic Devices
(2022 - 2023) term 231

Lecture 5: PN junction.

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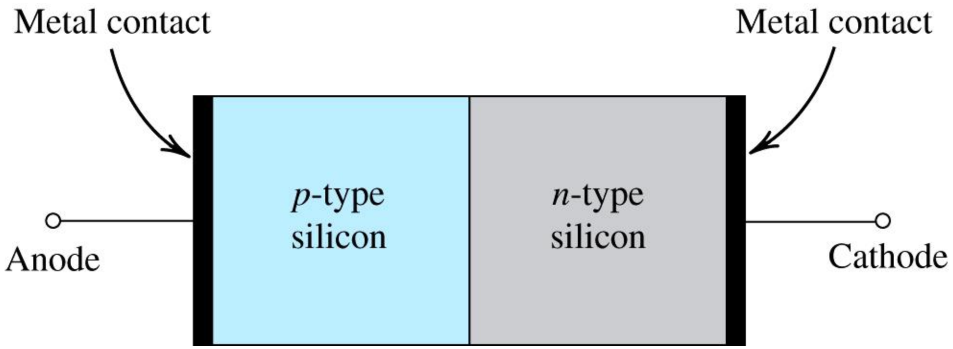
Outlines

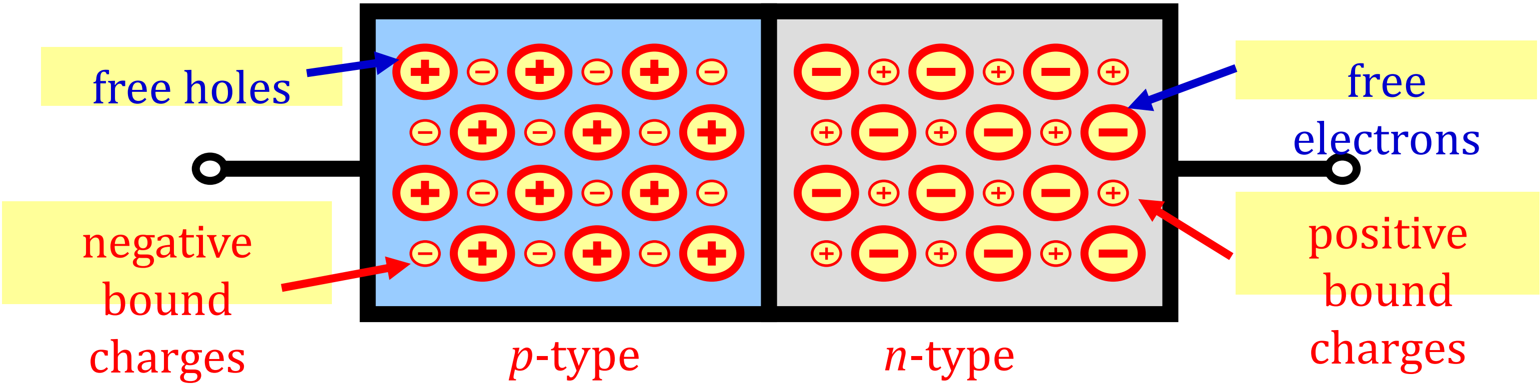
- **PN Junction with Open-Circuit Terminals.**
- The pn Junction with an Applied Voltage.
- **Summary.**

The PN Junction with Open-Circuit Terminals

- PN junction structure:
  - p-type semiconductor
  - n-type semiconductor
  - metal contact for connection

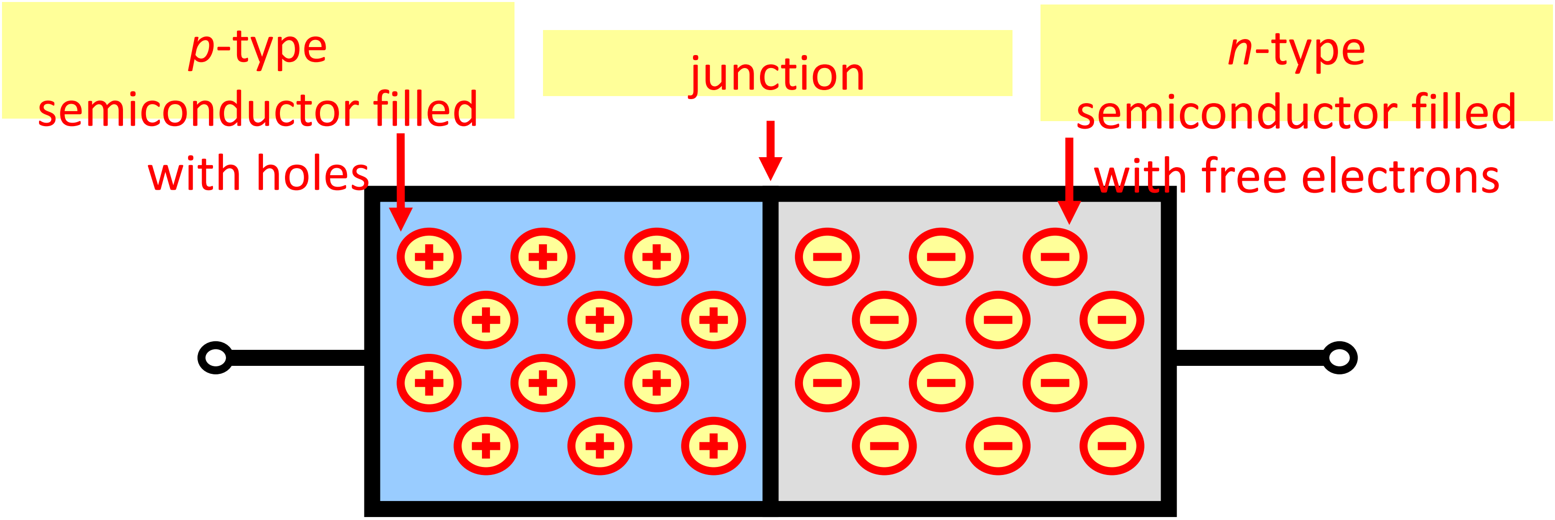


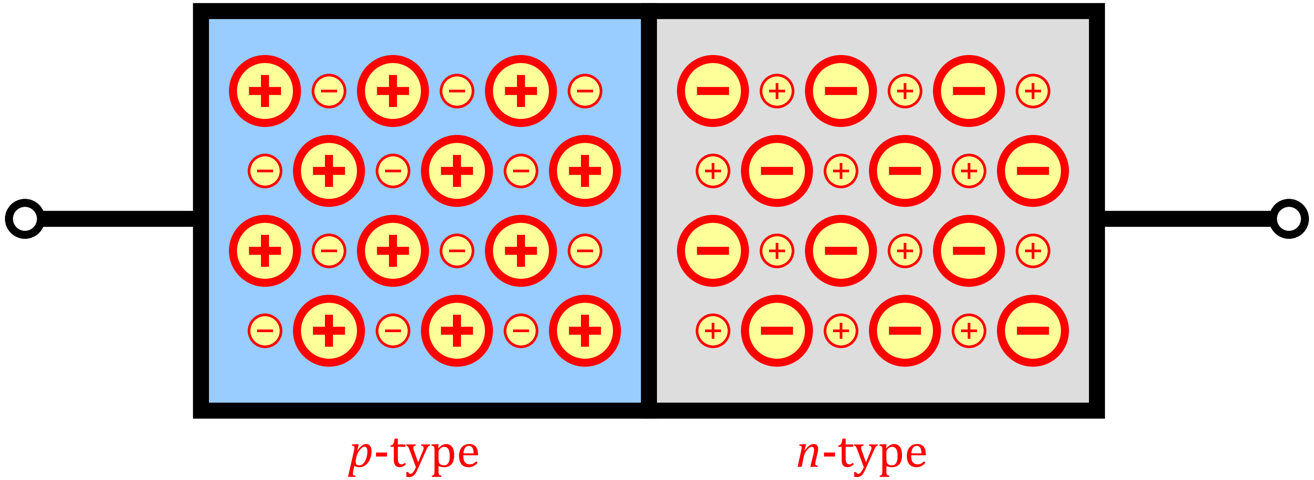
- Q: What is state of pn junction with open-circuit terminals?
  - p-type material contains majority of holes
    These holes are neutralized by equal amount of bound negative charge.
  - n-type material contains majority of free electrons
    These electrons are neutralized by equal amount of bound positive charge.
- Bound charge
  - Charge of opposite polarity to free electrons / holes of a given material.
  - Neutralizes the electrical charge of these majority carriers.
  - Does not affect concentration gradients (current).



Operation with Open-Circuit Terminals

- What happens when a pn-junction is newly formed, when the p-type and n-type semiconductors first touch one another?
  - ☐ Step #1: The p-type and n-type semiconductors are joined at the junction.
  - ☐ Step #2: Diffusion begins. Those free electrons and holes which are closest to the junction will recombine and, essentially, eliminate one another.

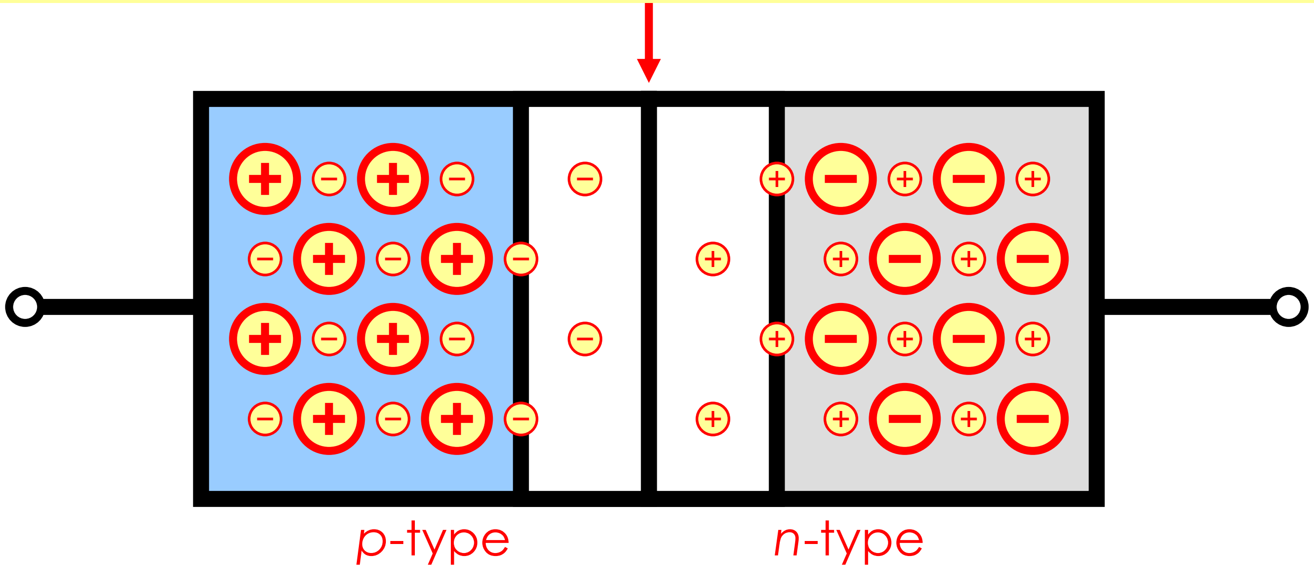




Operation with Open-Circuit Terminals

- Step #3: The depletion region begins to form – as diffusion occurs and free electrons recombine with holes.

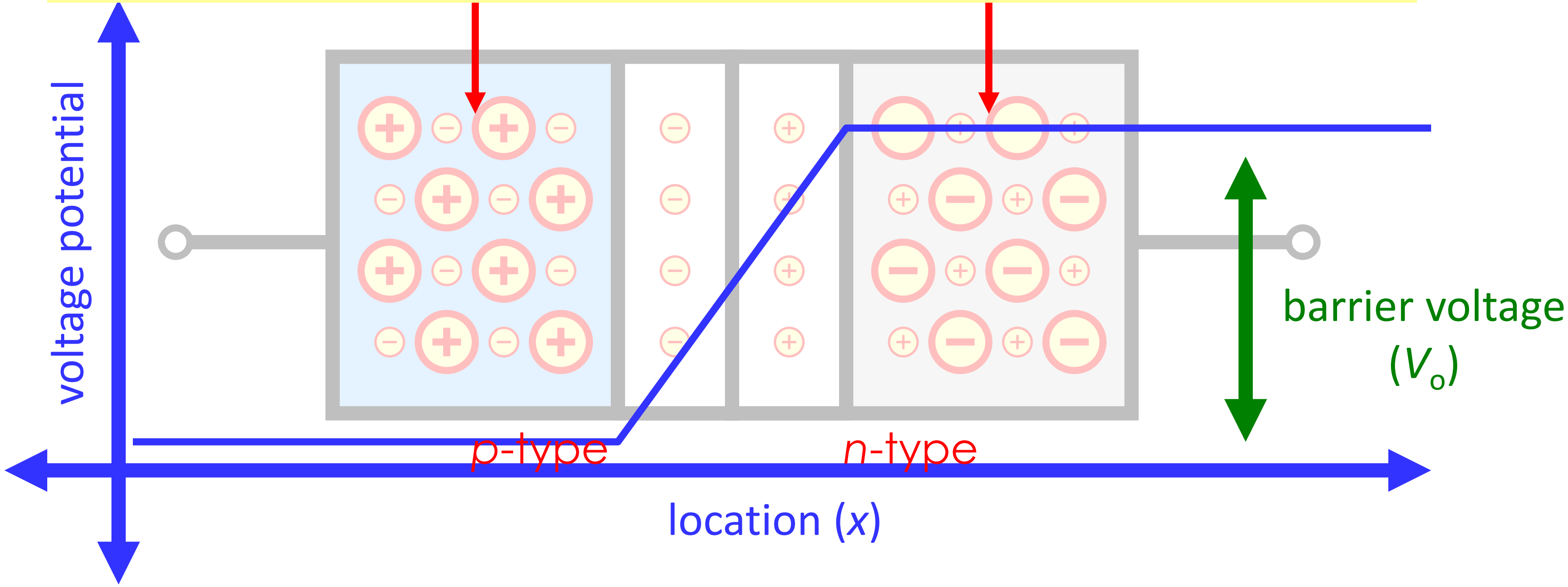
The depletion region is filled with “uncovered” bound charges – who have lost the majority carriers to which they were linked.



Operation with Open-Circuit Terminals

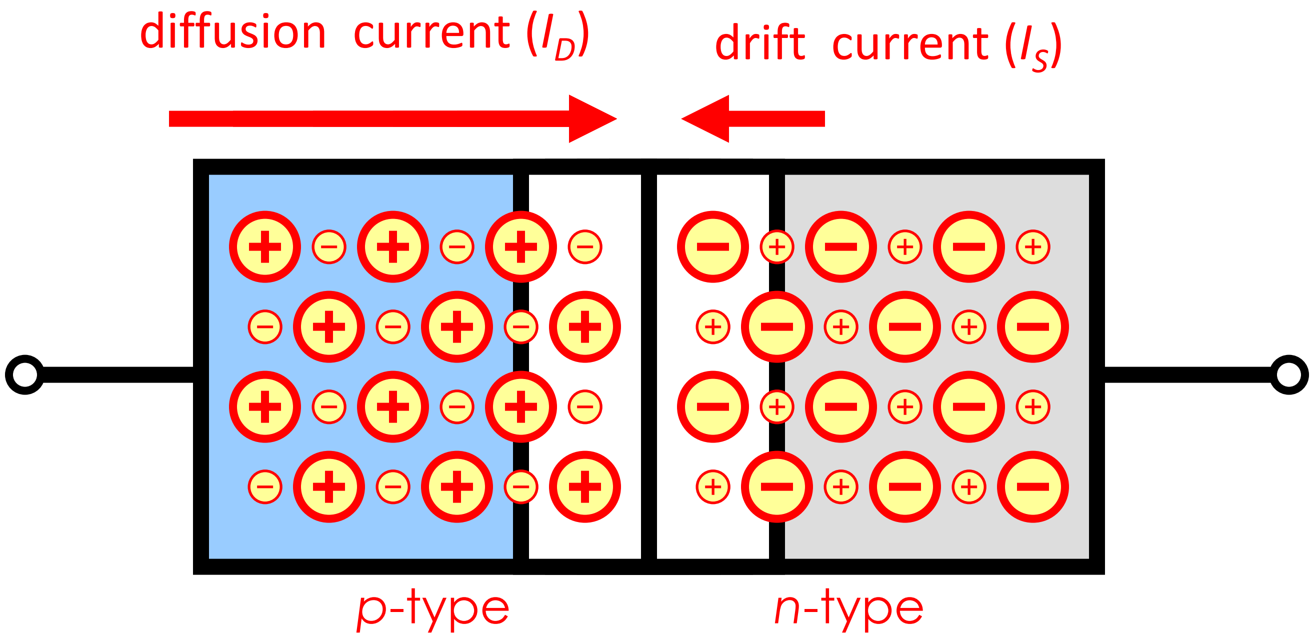
- ❑ Step #4: The "uncovered" bound charges affect a voltage differential across the depletion region. The magnitude of this barrier voltage (V0) differential grows, as diffusion continues.

No voltage differential exists across regions of the *pn*-junction outside of the depletion region because of the neutralizing effect of positive and negative bound charges.



Operation with Open-Circuit Terminals

- Step #5: The barrier voltage (V_0) is an electric field whose polarity opposes the direction of diffusion current (I_D). As the magnitude of V_0 increases, the magnitude of I_D decreases.

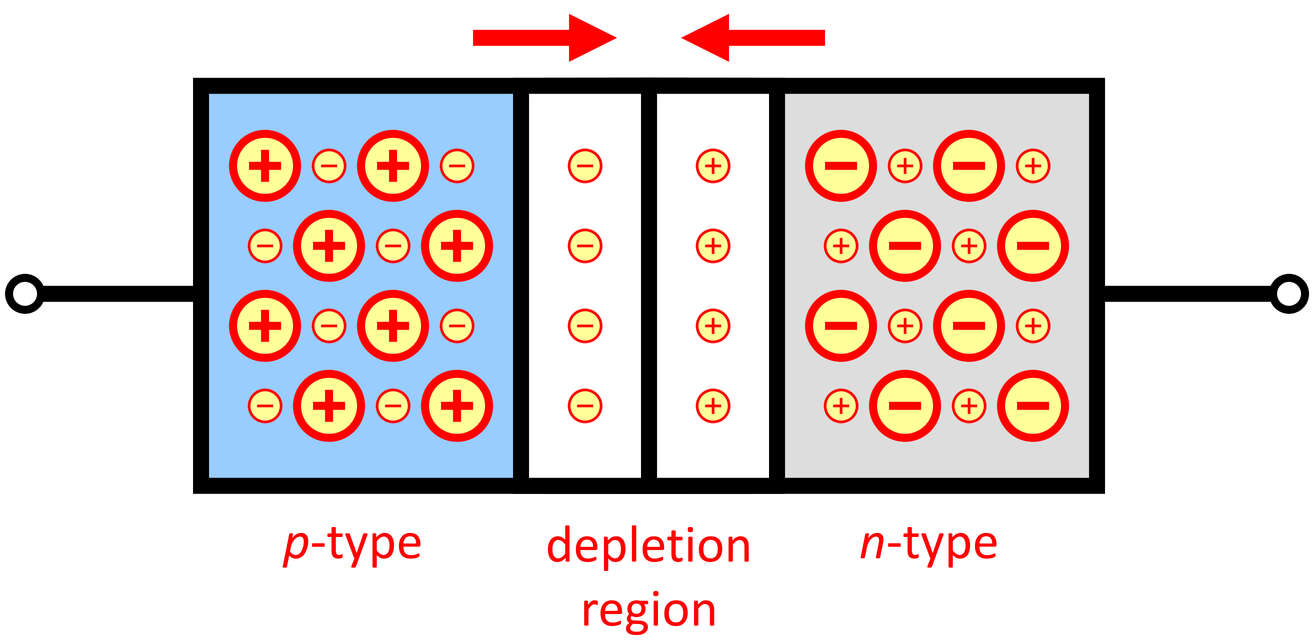


Operation with Open-Circuit Terminals

- Step #6: Equilibrium is reached, and diffusion ceases, once the magnitudes of diffusion and drift currents equal one another – resulting in no net flow.

- In addition to majority-carrier diffusion current (I_D), a component of current due to minority carrier drift exists (I_S).
- Specifically, some of the thermally generated in the p-type and n-type materials move toward and reach the edge of the depletion region.
- Therefore, they experience the electric field (V_0) in the depletion region and are swept across it.
- Unlike diffusion current, the polarity of V_0 reinforces this drift current.

Once equilibrium is achieved, no net current flow exists ($I_{net} = I_D - I_S$) within the *pn*-junction while under open-circuit condition.



Operation with Open-Circuit Terminals

- PN-junction built-in voltage (V_0) – is the equilibrium value of barrier voltage.
  - ❑ Generally, it takes on a value between 0.6 and 0.9V for silicon at room temperature.
  - ❑ This voltage is applied across depletion region, not terminals of pn junction.
  - ❑ Power cannot be drawn from V_0.

$V_0 =$ barrier voltage
$V_T =$ thermal voltage
$N_A =$ acceptor doping concentration
$N_D =$ donor doping concentration
$n_i =$ concentration of free electrons…
…in intrinsic semiconductor

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

Report 1

- ❖ Prove that the pn - junction built -in voltage is given by:

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

- ❖ Hint: it can be derived from the equality of drift current and diffusion current at equibrium.
- ❖ electron drift current = electron diffusion current.

Operation with Open-Circuit Terminals

- How is the charge stored in both sides of the depletion region defined?
- What information can be derived from this equality?

$|Q_+|$= magnitude of charghe on *n*-side of junction
q= magnitude of electric charge
A= cross-sectional area of junction
x_n= penetration of depletion region into *n*-side
N_D= concentration of donor atoms

$$\overbrace{|Q_+| = qAx_nN_D}$$

$$\underbrace{|Q_-| = qAx_pN_A}$$

$|Q_-|$= magnitude of charghe on *n*-side of junction
q= magnitude of electric charge
A= cross-sectional area of junction
x_p= penetration of depletion region into *p*-side
N_A= concentration of acceptor atoms

- ☐ In reality, the depletion region exists almost entirely on one side of the pn junction – due to great disparity between NA > ND.

$$\boxed{qAx_pN_A = qAx_nN_D \rightarrow \frac{x_n}{x_p} = \frac{N_A}{N_D}}$$

- ☐ Note that both x_p and x_n may be defined in terms of the depletion region width (W).

$$\boxed{W = x_n + x_p = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0}} \rightarrow \boxed{\begin{aligned} x_n &= W\frac{N_A}{N_A + N_D} \\ x_p &= W\frac{N_D}{N_A + N_D} \end{aligned}} \rightarrow \boxed{\begin{aligned} Q_J &= |Q_\pm| = Aq\left(\frac{N_AN_D}{N_A + N_D}\right)W \\ Q_J &= A\sqrt{2\varepsilon_S q\left(\frac{N_AN_D}{N_A + N_D}\right)V_0} \end{aligned}}$$

Summary :

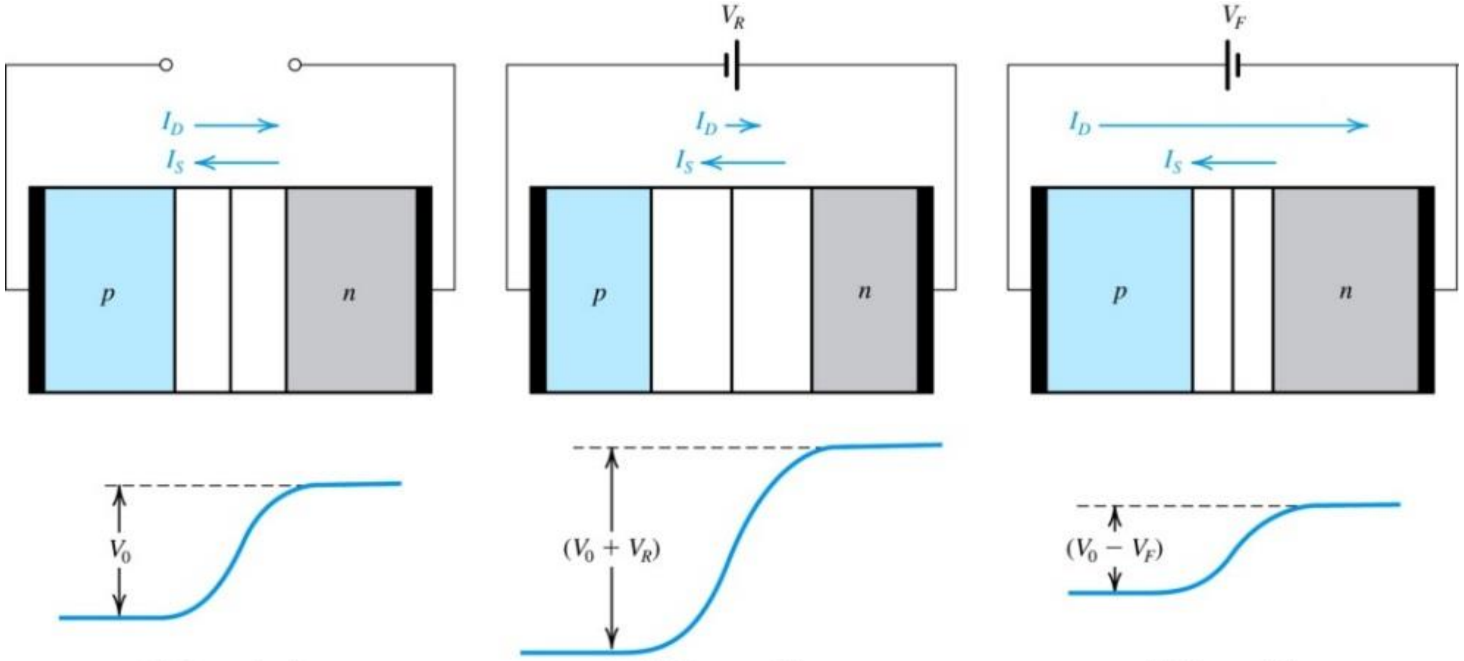
- What has been learned about the pn-junction?
  - ☐ Composition: The pn junction is composed of two silicon-based semiconductors, one doped to be p-type and the other n-type.
  - ☐ majority carriers: Are generated by doping. Holes are present on p-side, free electrons are present on n-side.
  - ☐ Bound charges: charge of majority carriers are neutralized electrically by bound charges.
  - ☐ Diffusion current ID: those majority carriers close to the junction will diffuse across, resulting in their elimination.
  - ☐ Depletion region: As these carriers disappear, they release bound charges and effect a voltage differential V0.
  - ☐ Depletion-layer voltage: As diffusion continues, the depletion layer voltage (V0) grows, making diffusion more difficult and eventually bringing it to halt.
  - ☐ Minority carriers: Are generated thermally. Free electrons are present on p-side, holes are present on n-side.
  - ☐ Drift current IS: The depletion-layer voltage (V0) facilitates the flow of minority carriers to opposite side.
  - ☐ Open circuit equilibrium ID = IS

Outlines

- PN Junction with Open-Circuit Terminals.
- The pn Junction with an Applied Voltage.
- Summary.

The pn Junction with an Applied Voltage

- pn-junction under three conditions:
  - (a) open-circuit – where a barrier voltage V_0 exists.
  - (b) reverse bias – where a dc voltage V_R is applied.
  - (c) forward bias – where a dc voltage V_F is applied.



(a) Open-circuit (Equilibrium)

(b) Reverse Bias

(c) Forward Bias

The pn Junction with an Applied Voltage

1) no voltage applied

2) voltage differential across depletion zone is V_0

3) $I_D = I_S$

1) negative voltage applied

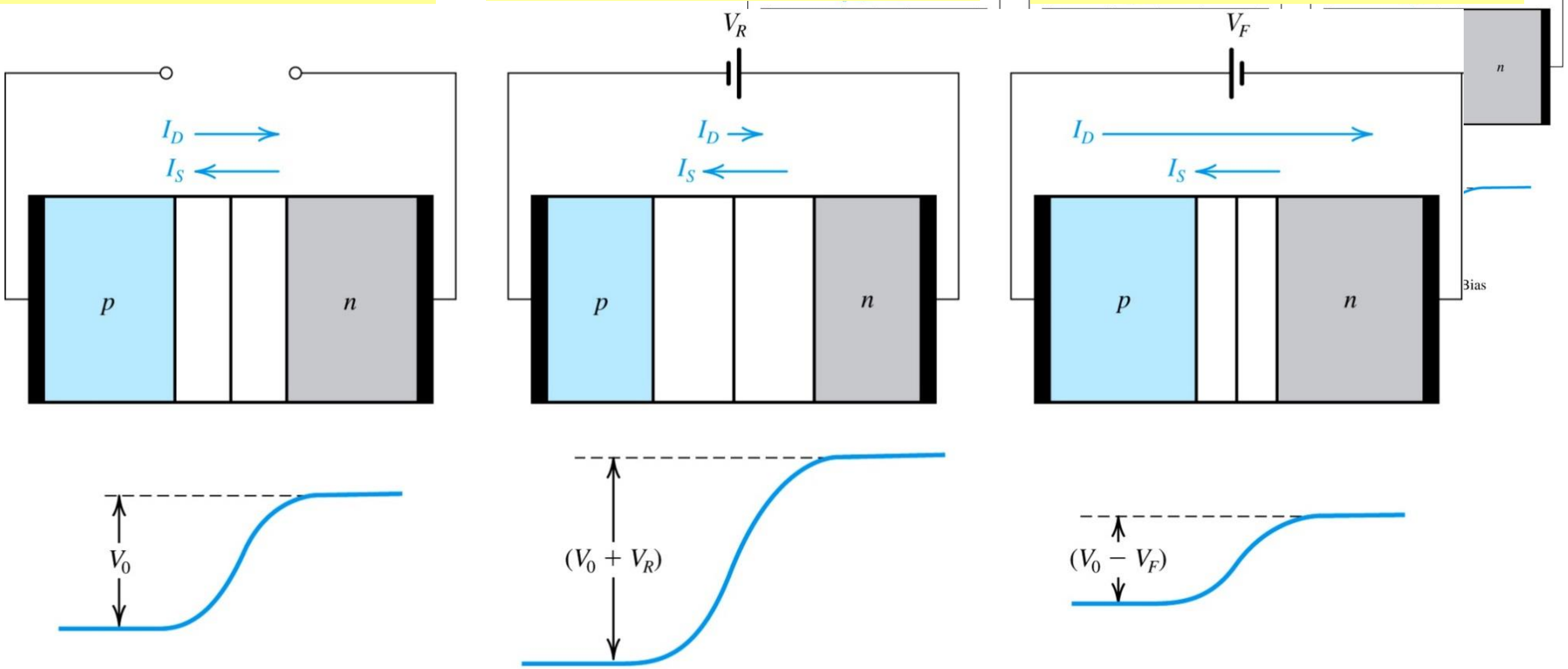
2) voltage differential across depletion zone is $V_0 + V_R$

3) $I_D < I_S$

1) positive voltage applied

2) voltage differential across depletion zone is $V_0 - V_F$

3) $I_D > I_S$

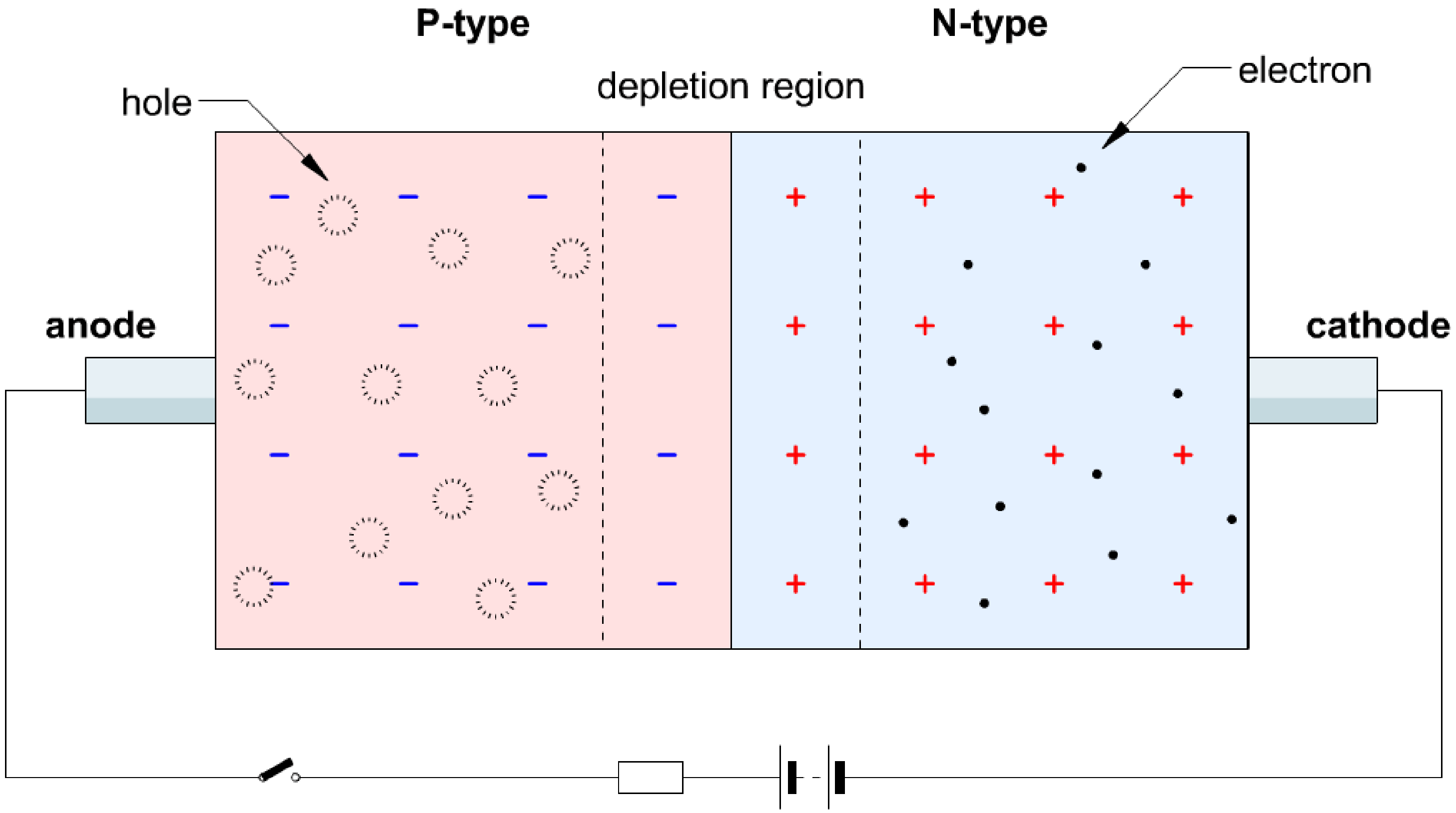


(a) Open-circuit (Equilibrium)

(b) Reverse Bias

(c) Forward Bias

The pn Junction with an Applied Voltage



The pn Junction with an Applied Voltage

reverse bias case

- the externally applied voltage V_R adds to the barrier voltage V_0
    - ...increase effective barrier
- this reduces rate of diffusion, reducing I_D
    - if $V_R > 1V$, I_D will fall to $0A$
- the drift current I_S is unaffected, but dependent on temperature
- result is that *pn* junction will conduct **small** drift current I_S

minimal current flows in reverse-bias case

forward bias case

- the externally applied voltage V_F subtracts from the barrier voltage V_0
    - ...decrease effective barrier
- this increases rate of diffusion, increasing I_D
- the drift current I_S is unaffected, but dependent on temperature
- result is that *pn* junction will conduct **significant** current I_D - I_S

significant current flows in forward-bias case

Forward-Bias Case

- Observe that decreased barrier voltage will be accompanied by...

  (1) decrease in stored uncovered charge on both sides of junction

  (2) smaller depletion region

- Width of depletion can given as:

$$W = x_n + x_p = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\underbrace{(V_0 - V_F)}_{\substack{\textbf{action:}\\ \text{replace } V_0\\ \text{with } V_0 - V_F}}}$$

ε_S = electrical permiability of silicon ($11.7\varepsilon_0 = 1.04\mathbf{E} - 12F / cm$)

$$\underbrace{Q_J = A\sqrt{2\varepsilon_S q\left(\frac{N_A N_D}{N_A + N_D}\right)\underbrace{(V_0 - V_F)}_{\substack{\textbf{action:}\\ \text{replace } V_0\\ \text{with } V_0 - V_F}}}}_{Q_J = \text{ magnitude of charge stored on either side of depletion region}}$$

Reverse-Bias Case

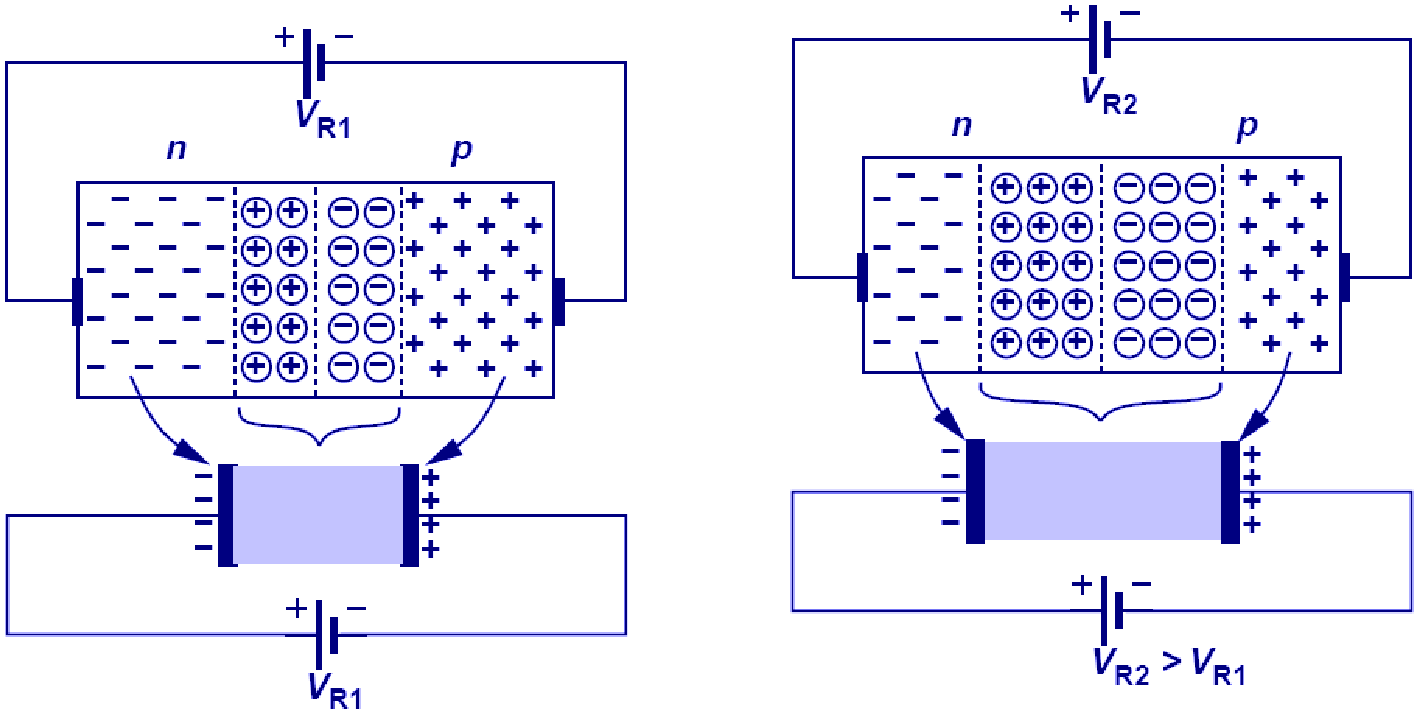
- Observe that increased barrier voltage will be accompanied by...
  - (1) increase in stored uncovered charge on both sides of junction
  - (2) Wider depletion region
- Width of depletion can given as:

$$W = x_n + x_p = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)\underbrace{(V_0+V_R)}_{\substack{\textbf{action:}\\ \text{replace } V_0\\ \text{with } V_0+V_R}}}$$

ε_S = electrical permiability of silicon ($11.7\varepsilon_0 = 1.04\mathbf{E}-12F/cm$)

$$\underbrace{Q_J = A\sqrt{2\varepsilon_S q\left(\frac{N_A N_D}{N_A+N_D}\right)\underbrace{(V_0+V_R)}_{\substack{\textbf{action:}\\ \text{replace } V_0\\ \text{with } V_0+V_R}}}}_{Q_J = \text{ magnitude of charge stored on either side of depletion region}}$$

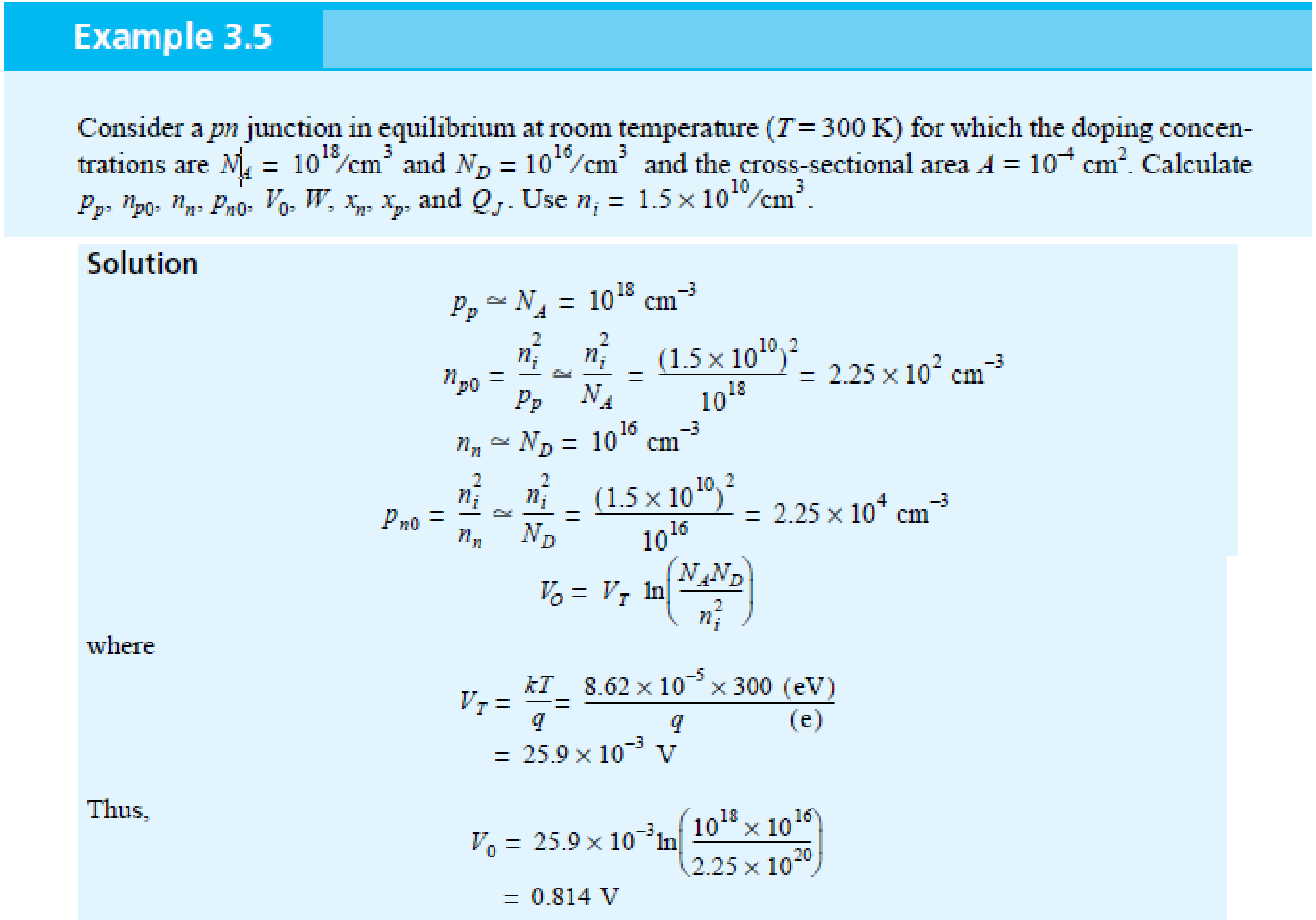
Reverse Biased Diode's Application: Voltage-Dependent Capacitor



(a)

(b)

The PN junction can be viewed as a capacitor. By varying V_R, the depletion width changes, changing its capacitance value; therefore, the PN junction is actually a voltage-dependent capacitor.



Example 3.5

Consider a *pn* junction in equilibrium at room temperature ($T = 300$ K) for which the doping concentrations are $N_A = 10^{18}/\text{cm}^3$ and $N_D = 10^{16}/\text{cm}^3$ and the cross-sectional area $A = 10^{-4}\ \text{cm}^2$. Calculate p_p, n_{p0}, n_n, p_{n0}, V_0, W, x_n, x_p, and Q_J. Use $n_i = 1.5 \times 10^{10}/\text{cm}^3$.

Solution

$$p_p \simeq N_A = 10^{18}\ \text{cm}^{-3}$$

$$n_{p0} = \frac{n_i^2}{p_p} \simeq \frac{n_i^2}{N_A} = \frac{(1.5 \times 10^{10})^2}{10^{18}} = 2.25 \times 10^2\ \text{cm}^{-3}$$

$$n_n \simeq N_D = 10^{16}\ \text{cm}^{-3}$$

$$p_{n0} = \frac{n_i^2}{n_n} \simeq \frac{n_i^2}{N_D} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4\ \text{cm}^{-3}$$

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

where

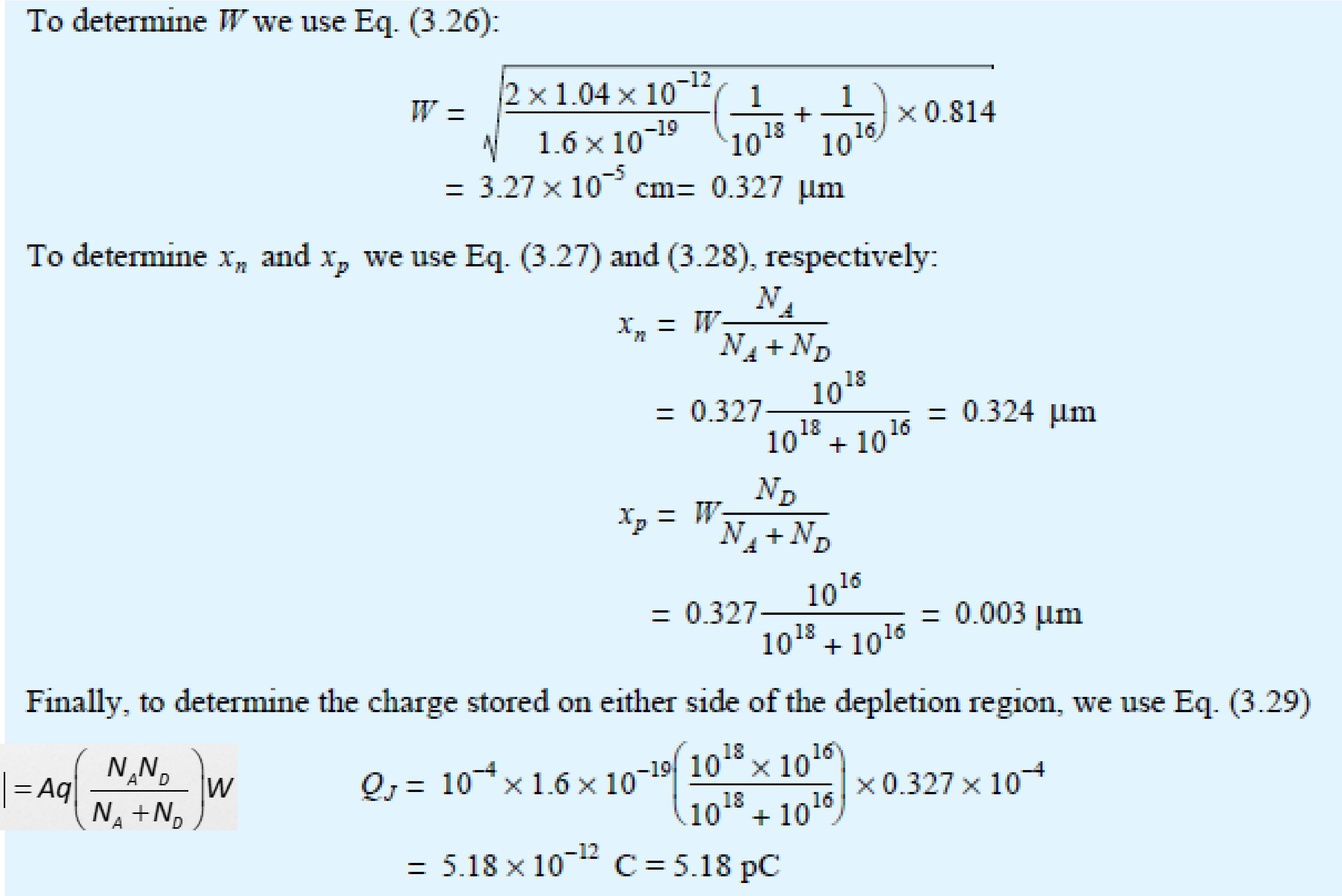
$$V_T = \frac{kT}{q} = \frac{8.62 \times 10^{-5} \times 300\ (\text{eV})}{q\ \ \ \ (\text{e})}$$

$$= 25.9 \times 10^{-3}\ \text{V}$$

Thus,

$$V_0 = 25.9 \times 10^{-3} \ln\left(\frac{10^{18} \times 10^{16}}{2.25 \times 10^{20}}\right)$$

$$= 0.814\ \text{V}$$



To determine W we use Eq. (3.26):

$$W = \sqrt{\frac{2\times 1.04\times 10^{-12}}{1.6\times 10^{-19}}\left(\frac{1}{10^{18}}+\frac{1}{10^{16}}\right)\times 0.814}$$

$$= 3.27\times 10^{-5}\ \text{cm} = 0.327\ \mu\text{m}$$

To determine x_n and x_p we use Eq. (3.27) and (3.28), respectively:

$$x_n = W\frac{N_A}{N_A+N_D}$$

$$= 0.327\frac{10^{18}}{10^{18}+10^{16}} = 0.324\ \mu\text{m}$$

$$x_p = W\frac{N_D}{N_A+N_D}$$

$$= 0.327\frac{10^{16}}{10^{18}+10^{16}} = 0.003\ \mu\text{m}$$

Finally, to determine the charge stored on either side of the depletion region, we use Eq. (3.29)

$$Q_J = |Q_\pm| = Aq\left(\frac{N_A N_D}{N_A+N_D}\right)W$$

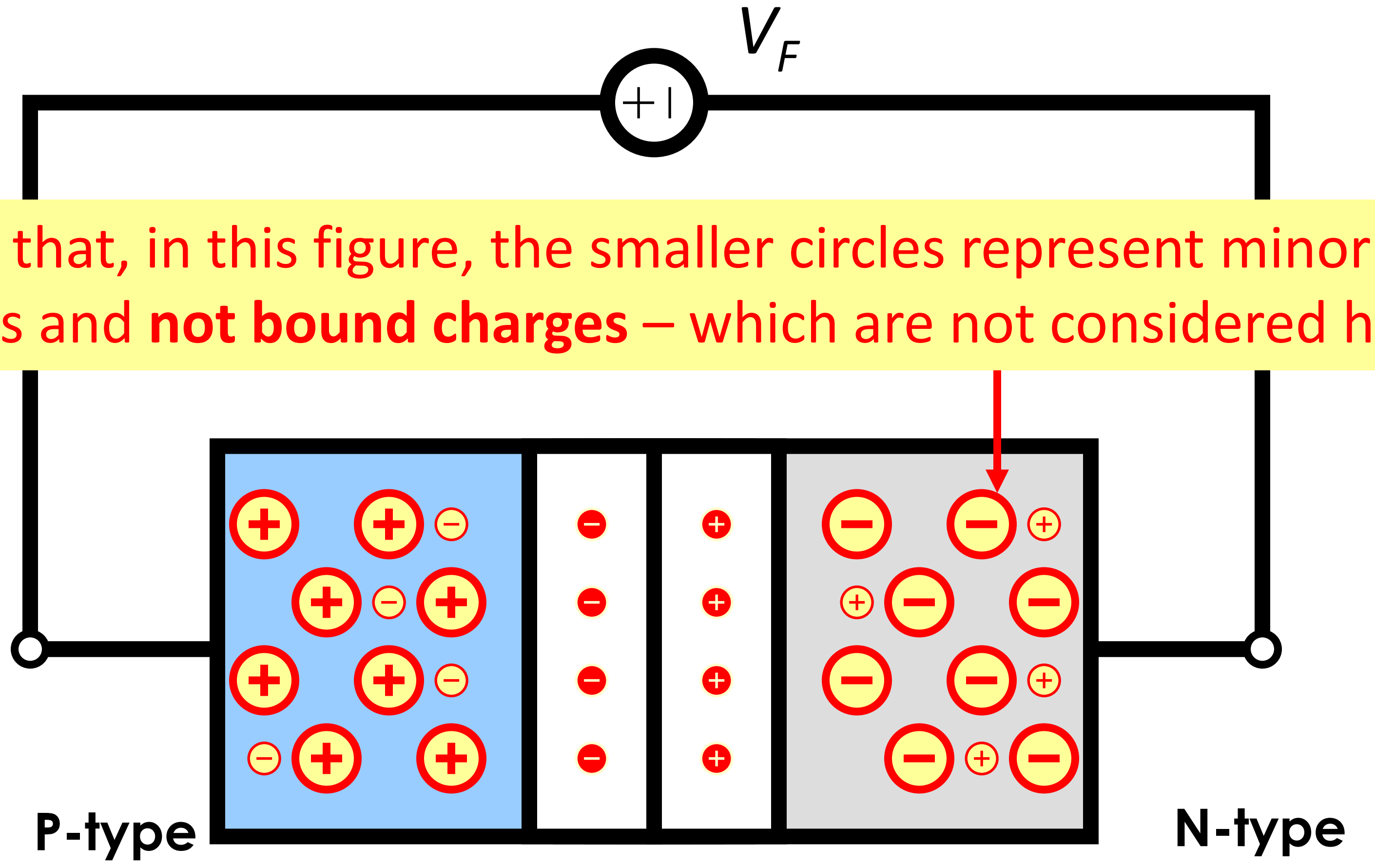
$$Q_J = 10^{-4}\times 1.6\times 10^{-19}\left(\frac{10^{18}\times 10^{16}}{10^{18}+10^{16}}\right)\times 0.327\times 10^{-4}$$

$$= 5.18\times 10^{-12}\ \text{C} = 5.18\ \text{pC}$$

The Current-Voltage Relationship of the Junction

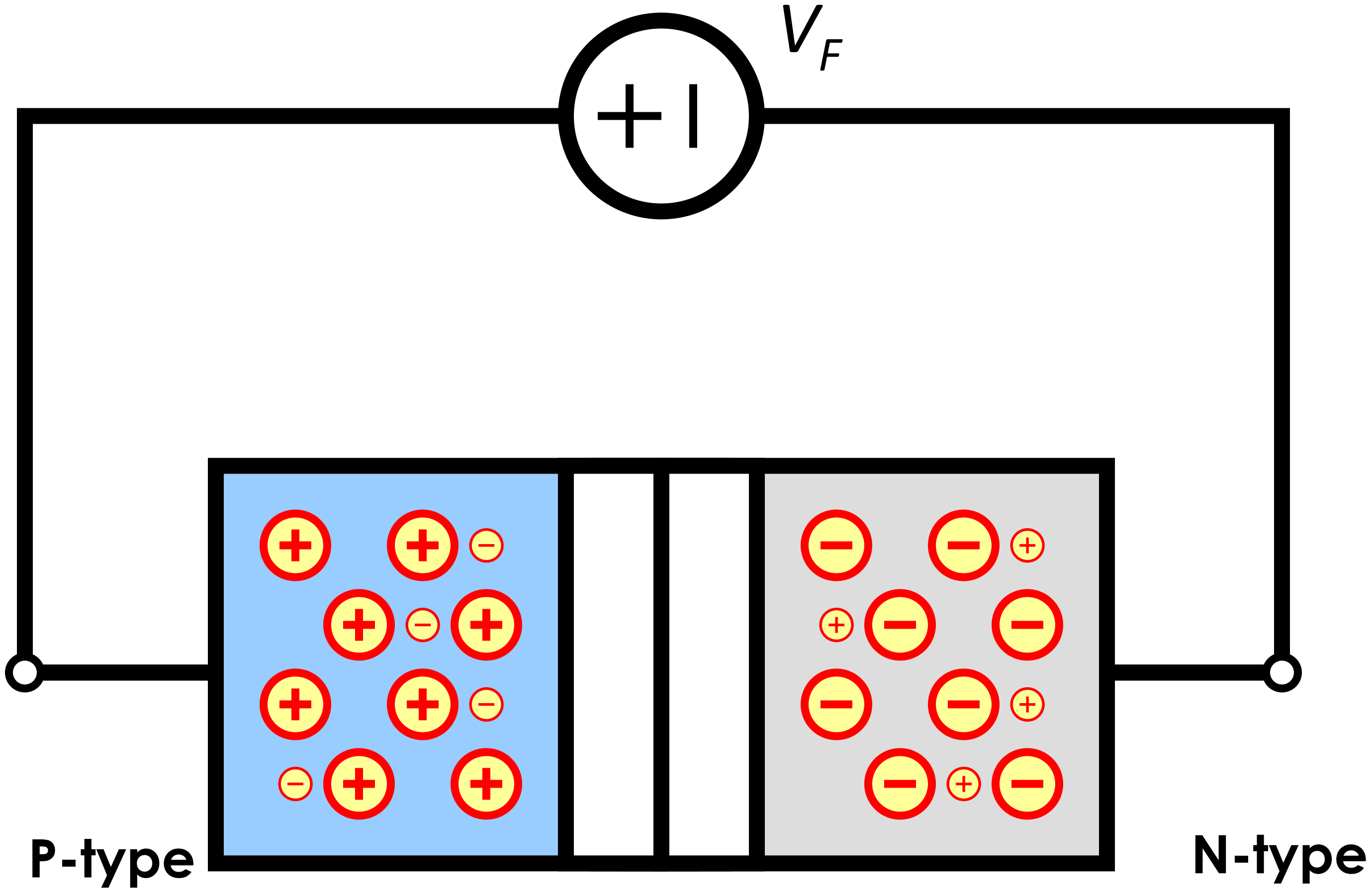
- What happens, exactly, when a forward-bias voltage (VF) is applied to the pn-junction? step #1: Initially, a small forward-bias voltage (V_F) is applied. It, because of its polarity, pushes majority (holes in *p*-region and electrons in *n*-region) toward the junction and reduces width of the depletion zone.

Note that, in this figure, the smaller circles represent minority carriers and **not bound charges** – which are not considered here.



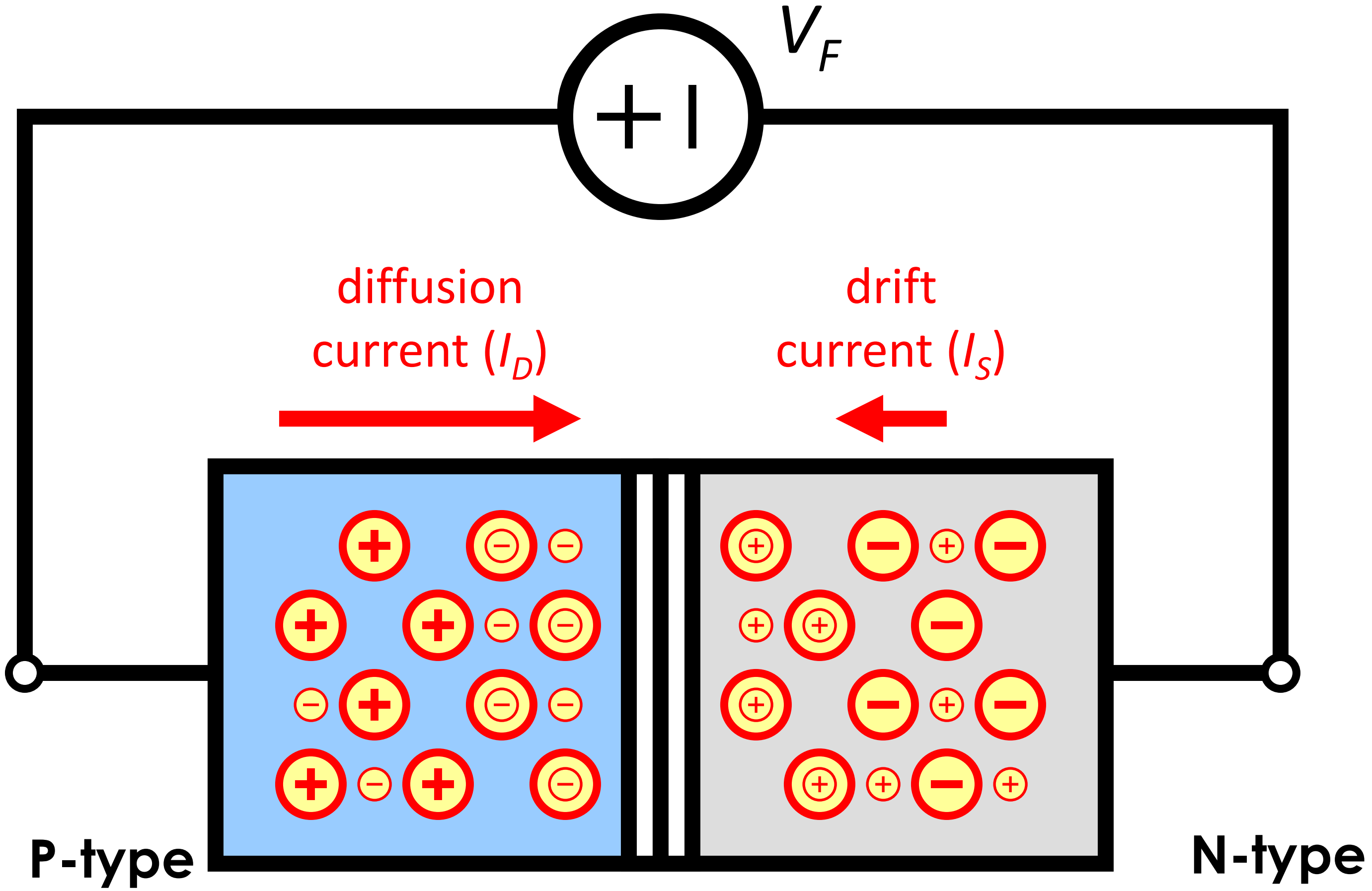
The Current-Voltage Relationship of the Junction

- step #2: As the magnitude of V_F increases, the depletion zone becomes thin enough such that the barrier voltage (V_0 – V_F) cannot stop diffusion current – as described in previous slides.



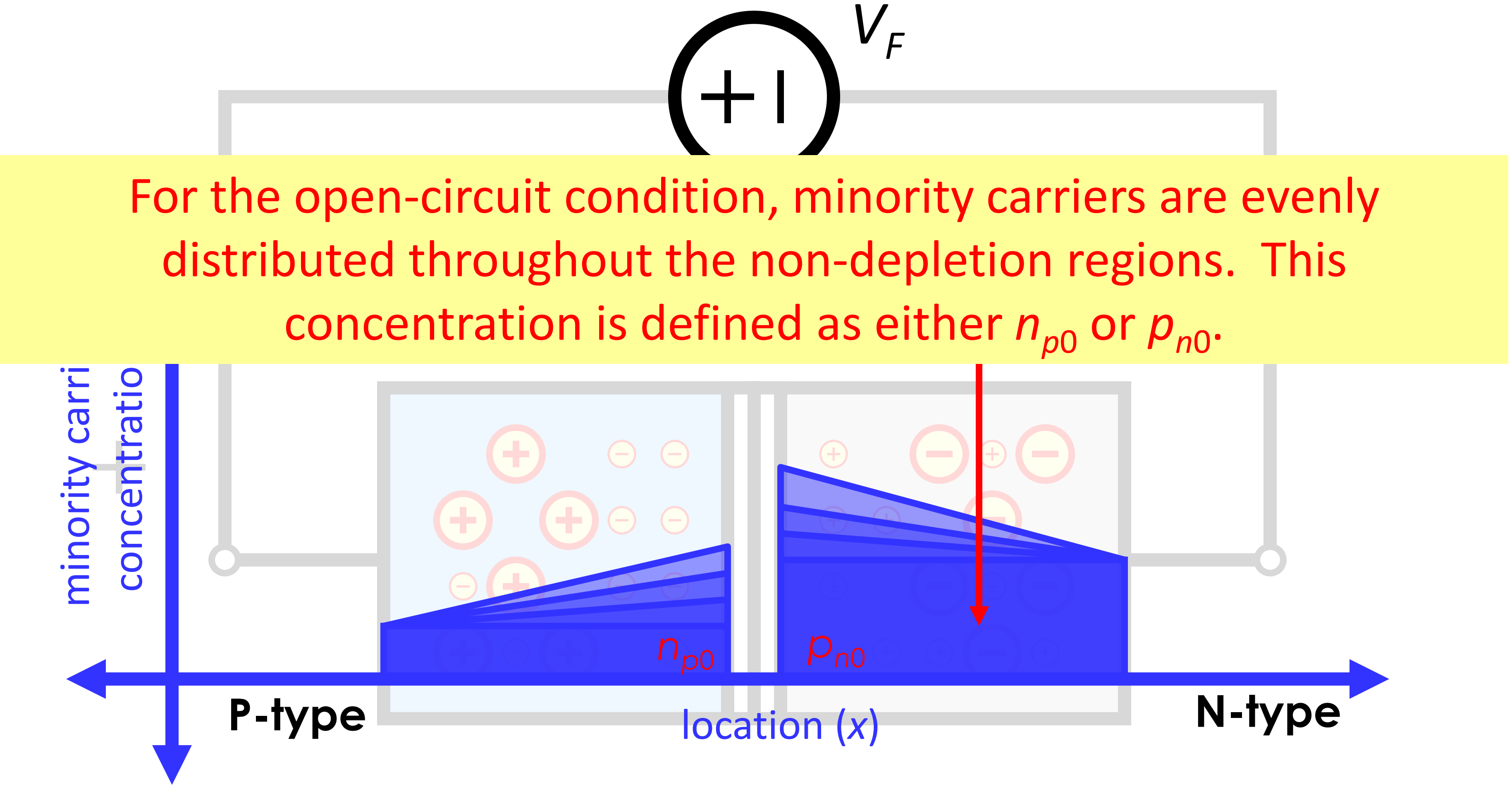
The Current-Voltage Relationship of the Junction

- step #3: Majority carriers (free electrons in *n*-region and holes in *p*-region) cross the junction and become minority charge carriers in the near-neutral region.



The Current-Voltage Relationship of the Junction

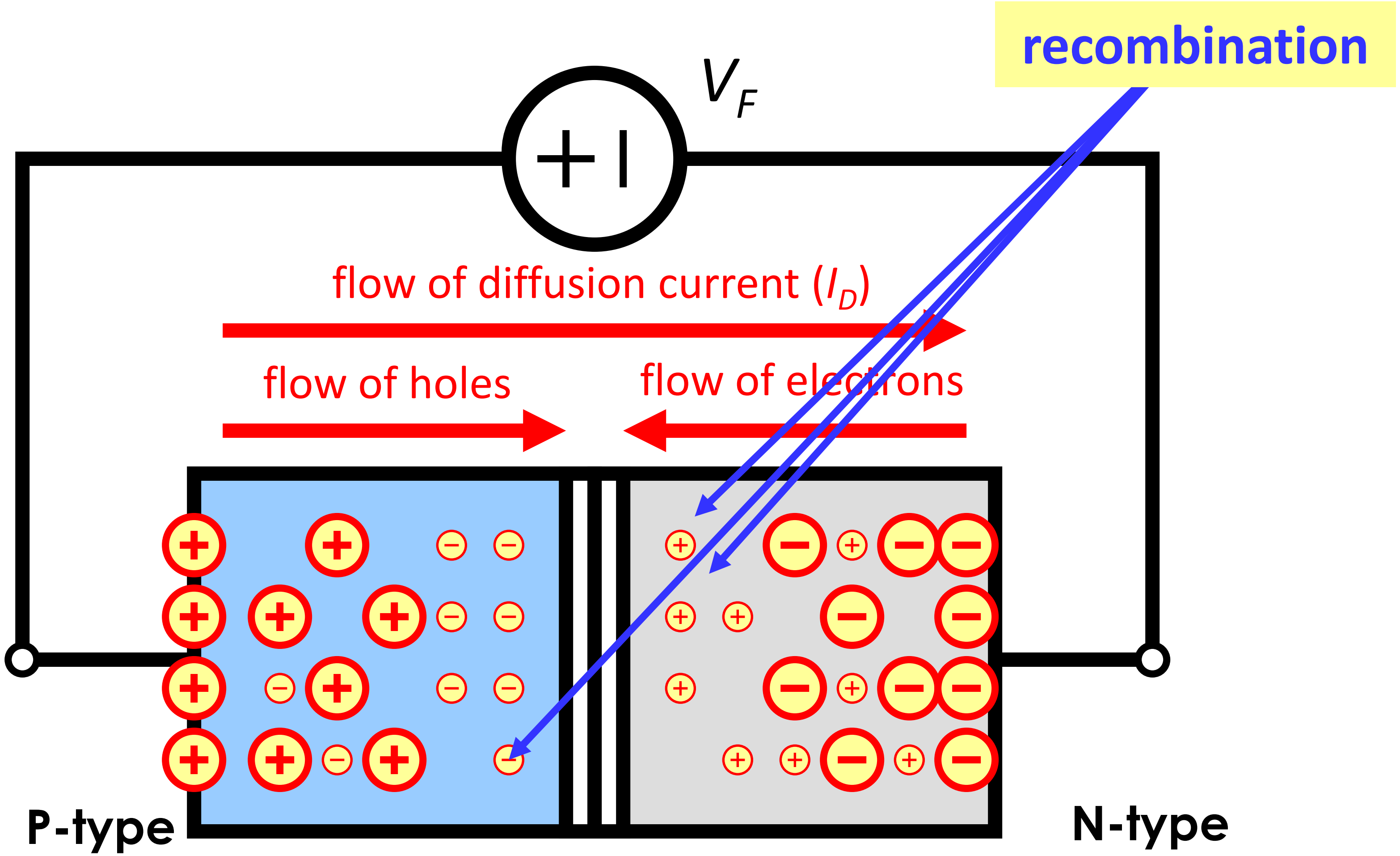
- step #4: The concentration of minority charge carriers increases on either side of the junction. A steady-state gradient is reached as rate of majority carriers crossing the junction equals that of recombination.



For the open-circuit condition, minority carriers are evenly distributed throughout the non-depletion regions. This concentration is defined as either n_{p0} or p_{n0}.

The Current-Voltage Relationship of the Junction

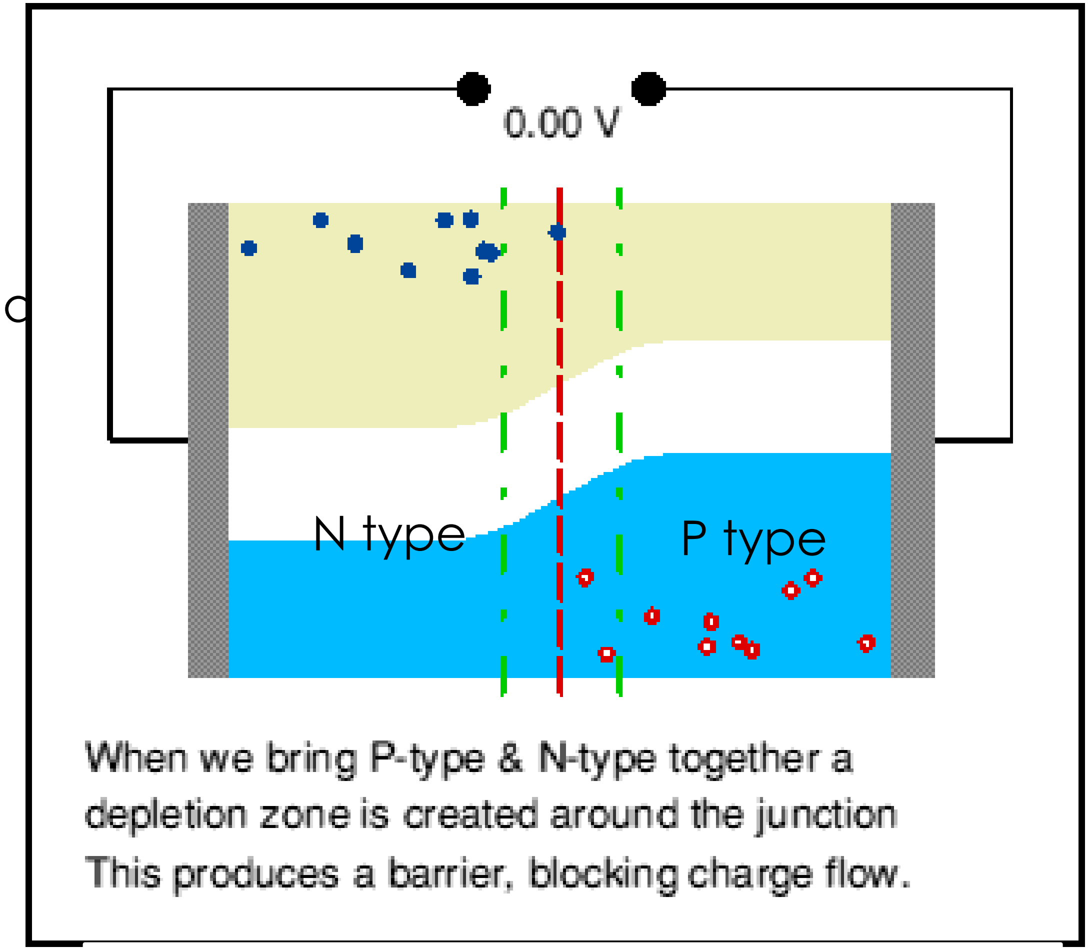
- step #5: Diffusion current is maintained – in spite low diffusion lengths (e.g. microns) and recombination – by constant flow of both free electrons and holes towards the junction.



The Current-Voltage Relationship of the Junction

Conduction band

Valence band



When we bring P-type & N-type together a depletion zone is created around the junction This produces a barrier, blocking charge flow.

The Current-Voltage Relationship of the Junction

For forward-biased case, how is diffusion current (I_D) defined?

$$I = \underbrace{\left(Aqn_i^2 \left[\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right] \right)}_{I_S} \left(e^{V/V_T} - 1\right) = I_S\left(e^{V/V_T} - 1\right)$$

- **saturation current (I_S)** – is the maximum reverse current which will flow through *pn*-junction.
  - It is proportional to cross-section of junction (A).
  - Typical value is $10^{-18} A$.

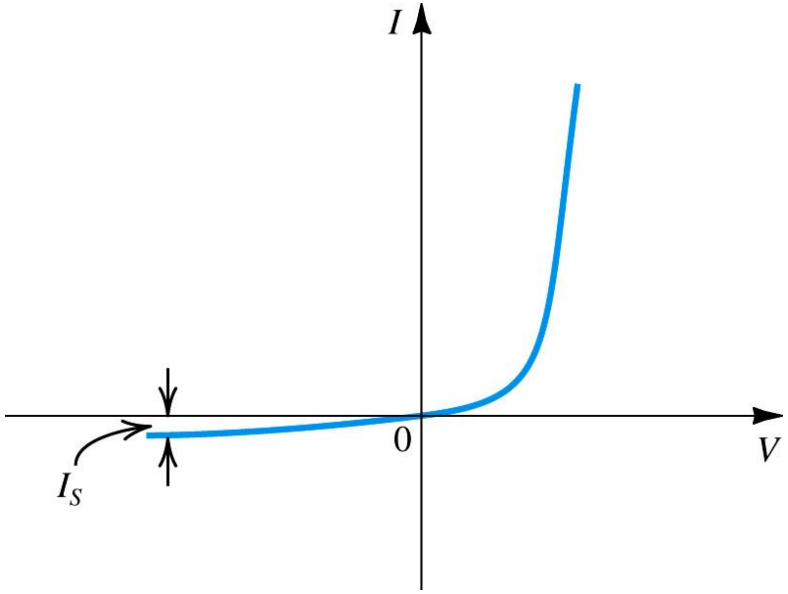
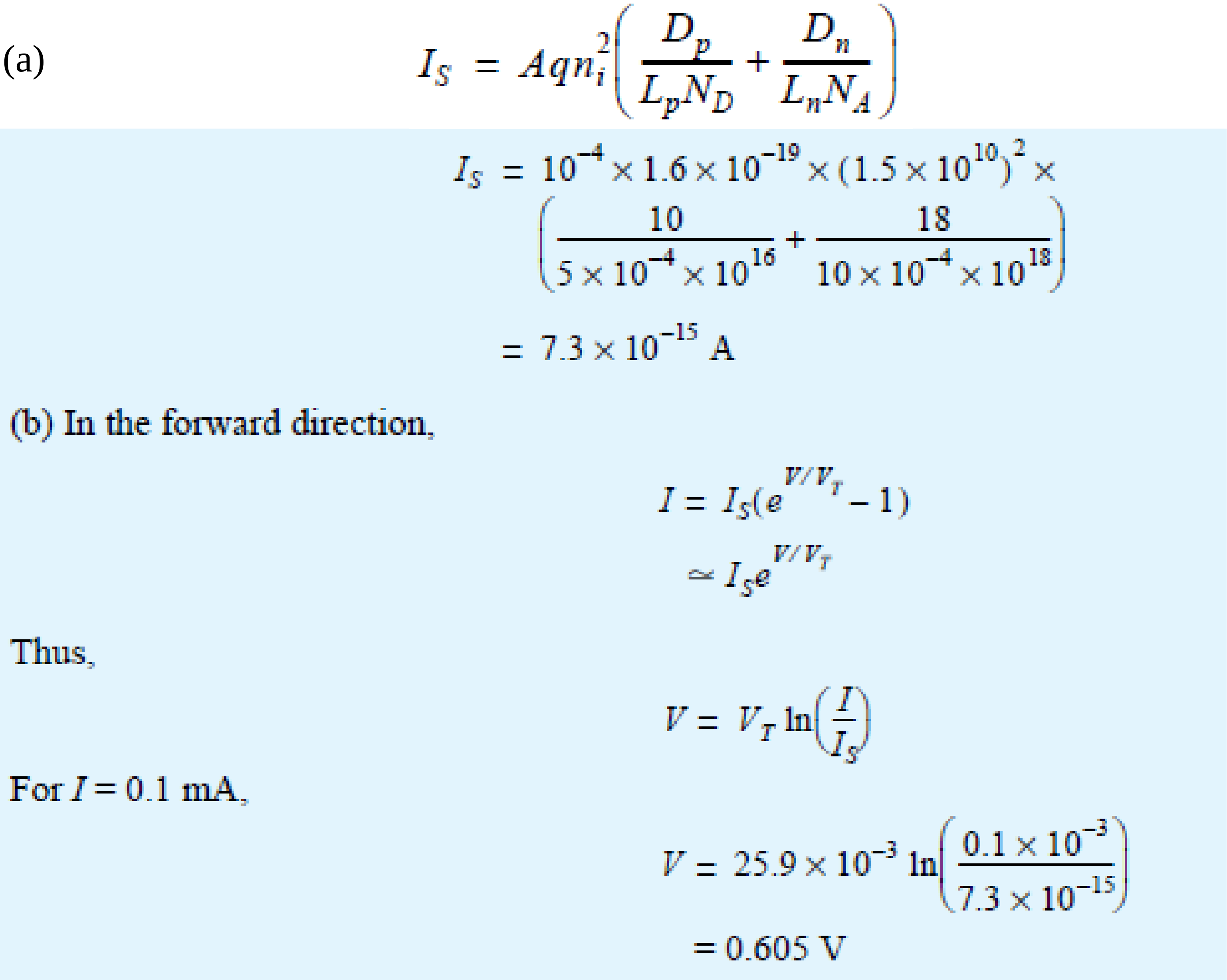


Figure 13: The *pn* junction *I*–*V* characteristic.

Example 6: *pn*-Junction

- Consider a forward-biased *pn* junction conducting a current of $I = 0.1mA$ with following parameters:
  - $N_A = 10^{18}/cm^3$, $N_D = 10^{16}/cm^3$, A = $10^{-4}cm^2$, $n_i = 1.5\mathbf{e}^{10}/cm^3$, $L_p = 5um$, $L_n = 10um$, D_p (*n*-region) = $10cm^2/s$, D_n (*p*-region) = $18cm^2/s$
- **Q(a):** Calculate I_S.
- **Q(b):** Calculate the forward bias voltage (V).
- **Q(c):** Component of current I due to hole injection and electron injection across the junction.



(a)

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

$$I_S = 10^{-4} \times 1.6 \times 10^{-19} \times (1.5 \times 10^{10})^2 \times \left(\frac{10}{5 \times 10^{-4} \times 10^{16}} + \frac{18}{10 \times 10^{-4} \times 10^{18}}\right)$$

$$= 7.3 \times 10^{-15}\ \text{A}$$

(b) In the forward direction,

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

$$\simeq I_S e^{V/V_T}$$

Thus,

$$V = V_T \ln\left(\frac{I}{I_S}\right)$$

For $I = 0.1$ mA,

$$V = 25.9 \times 10^{-3} \ln\left(\frac{0.1 \times 10^{-3}}{7.3 \times 10^{-15}}\right)$$

$$= 0.605\ \text{V}$$

(c) The hole-injection component of I can be found using Eq. (3.37)

$$I_p = Aq\frac{D_p}{L_p}\; p_{n0}(e^{V/V_T}-1)$$

$$= Aq\frac{D_p}{L_p}\;\frac{n_i^2}{N_D}(e^{V/V_T}-1)$$

Similarly I_n can be found using Eq. (3.39),

$$I_n = Aq\frac{D_n}{L_n}\;\frac{n_i^2}{N_A}(e^{V/V_T}-1)$$

Thus,

$$\frac{I_p}{I_n} = \left(\frac{D_p}{D_n}\right)\left(\frac{L_n}{L_p}\right)\left(\frac{N_A}{N_D}\right)$$

For our case,

$$\frac{I_p}{I_n} = \frac{10}{18}\times\frac{10}{5}\times\frac{10^{18}}{10^{16}} = 1.11\times 10^2 = 111$$

Thus most of the current is conducted by holes injected into the n region.

Specifically,

$$I_p = \frac{111}{112}\times 0.1 = 0.0991\ \text{mA}$$

$$I_n = \frac{1}{112}\times 0.1 = 0.0009\ \text{mA}$$

This stands to reason, since the p material has a doping concentration 100 times that of the n material.

END OF LECTURE

BEST WISHES