***pn* Junction**

1. Introduction
2. Open-Circuit Conditions
3. Reverse-Bias Conditions
4. Breakdown Region
5. Forward-Bias Conditions
6. Terminal Current-Voltage Characteristics
7. Depletion Capacitance and Diffusion Capacitance
8. Modeling the Diode
9. The *pn* Junction Circuit: Rectifier

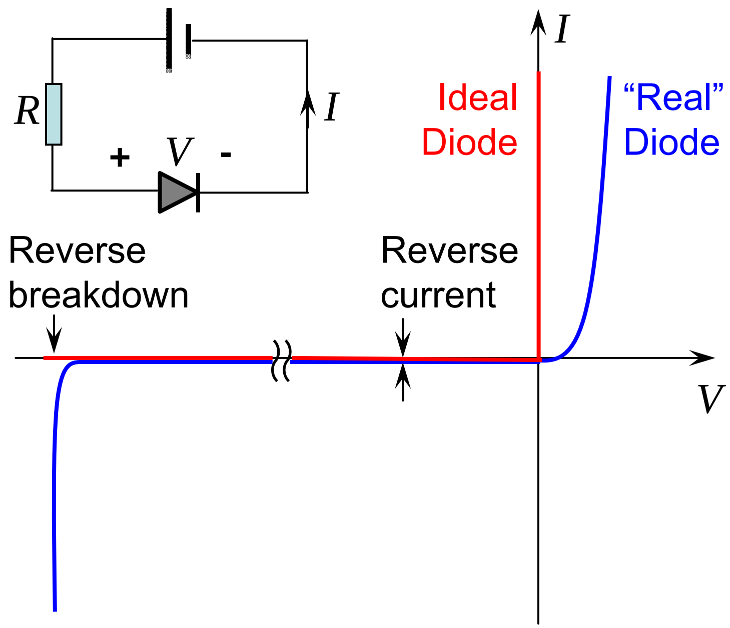
Reference

- A.D. Sedra & K.C. Smith, “Microelectronic Circuits – Theory and Application”, 5th Edition (International Version), Oxford University Press, Chapter 2.

pn Junction - Introduction

Why study *pn* junctions?

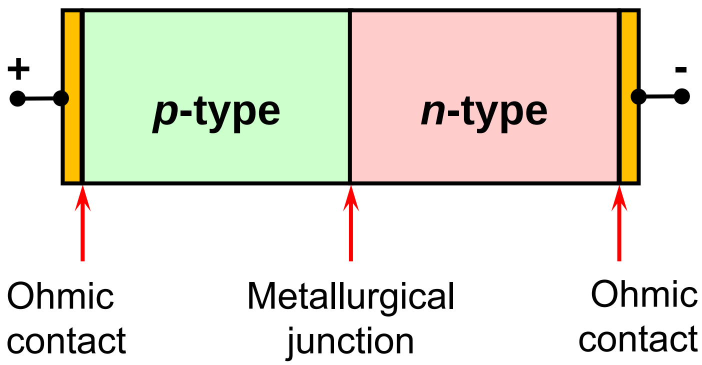
- The semiconductor diode is basically a *pn* junction.
- Diode is the simplest and most fundamental *nonlinear* circuit element. It allows a current to flow through it easily in one direction, but not in the opposite direction (unlike a resistor).
  - As such, it can be used in a rectifier circuit, to convert ac into dc.



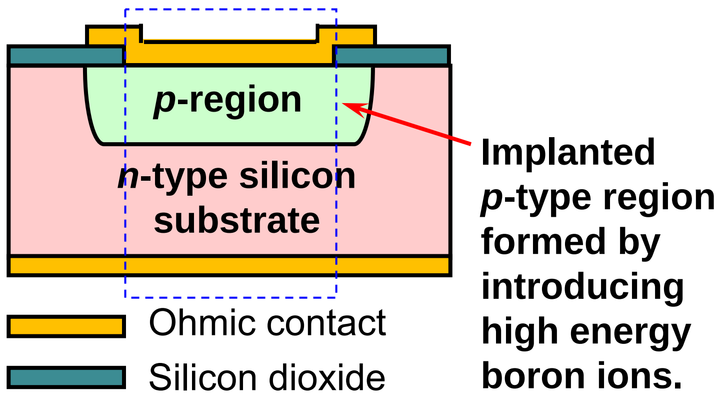
- The *pn* junction is the basic element of bipolar junction transistors (BJTs) and field-effect transistors (FETs), which are widely used in electronic circuits.

pn Junction - Introduction & Definitions

Junction – the joining together of two dissimilar materials, *e.g.,* metal-semiconductor junction, *pn* junction (semiconductor diode).



Simplified physical structure of a pn junction



Realistic cross-section of fabricated silicon *pn* junction diode

pn junction - a *p*-type semiconductor region in close contact with an *n*-type semiconductor region on the same single-crystal semiconductor material (e.g., Si).

Metallurgical junction - the interface between the *p*- and *n*-doped regions.

Ohmic contact – a metal-semiconductor junction which allows electrical current to pass freely through the semiconductor.

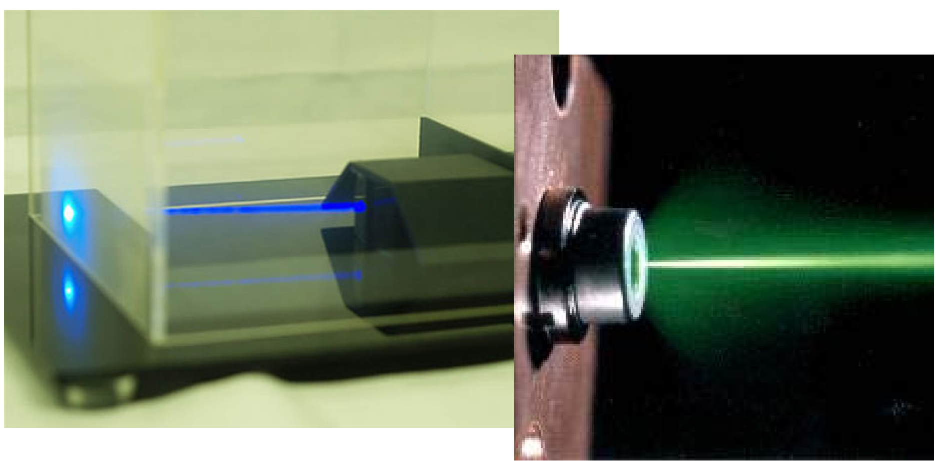
In this course, we will deal with a simplified structure for analysis purposes.

pn Junction - Introduction

Some special semiconductor diodes -

Light Emitting Diodes (LEDs)

Laser Diodes



Solar Cells

pn **Junction**

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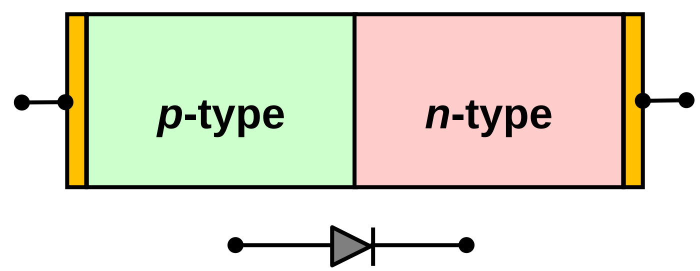
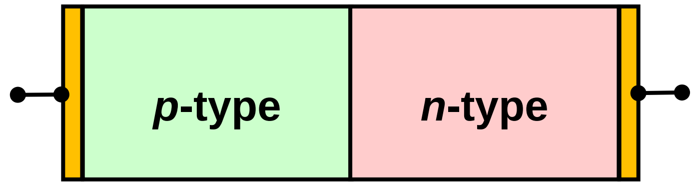
pn Junction – Open-Circuit Conditions

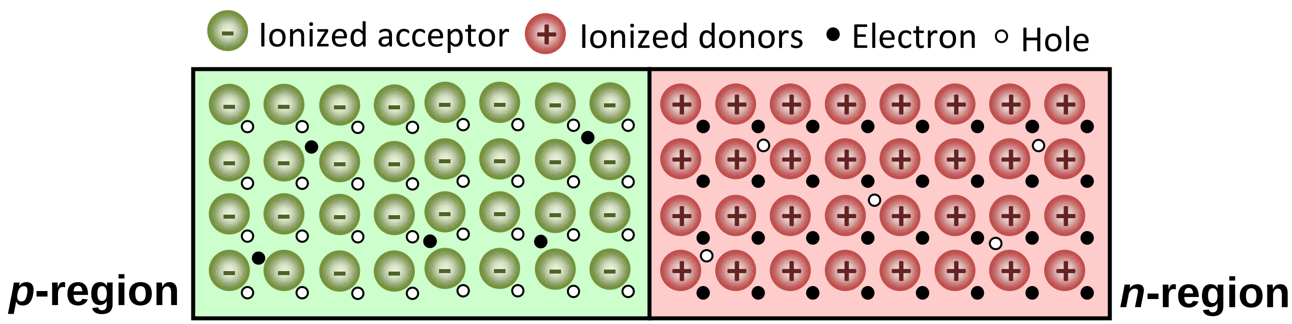
- We begin with a *pn* junction under open-circuit conditions, i.e., external terminals are left open or not connected to a voltage source
  - Hence, there is no net current flow through it



- Assumptions:
  - Room temperature operation (T = 300 K or 27 °C)
  - Steady state conditions
  - *p*-type region is doped with acceptor concentration of N_A (>> n_i)
  - *n*-type region is doped with donor concentration of N_D (>> n_i)
- Consider what happens when a *p*-type semiconductor first makes contact with an *n*-type material. This is a thought process as a *pn* junction is not formed this way. However, this approach is useful to help us understand some of the important principles in *pn* junctions.

pn Junction – Open-Circuit Conditions



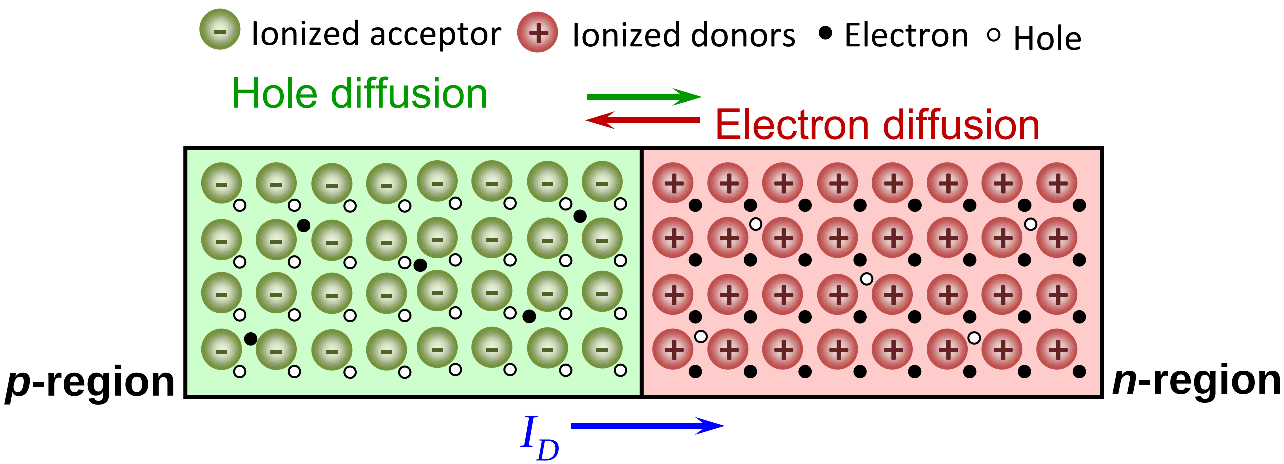


- The *p*-region has
  - N_A negative bound ionized acceptors
  - $p_{p0} \approx N_A$ positive holes (many - majority carriers)
  - $n_{p0} \approx n_i^2/N_A$ negative electrons (few - minority carriers)
- Hence, electrically neutral

- The *n*-region has
  - N_D positive bound ionized donors
  - $n_{n0} \approx N_D$ negative electrons (many - majority carriers)
  - $p_{n0} \approx n_i^2/N_D$ positive holes (few - minority carriers)
- Hence, electrically neutral

- Clearly, there are equivalent phenomena for electrons and holes in *pn* junction. Lectures will only focus on one carrier. Explanation for both carriers are included in the appendix for your reference.

pn Junction – Open-Circuit Conditions



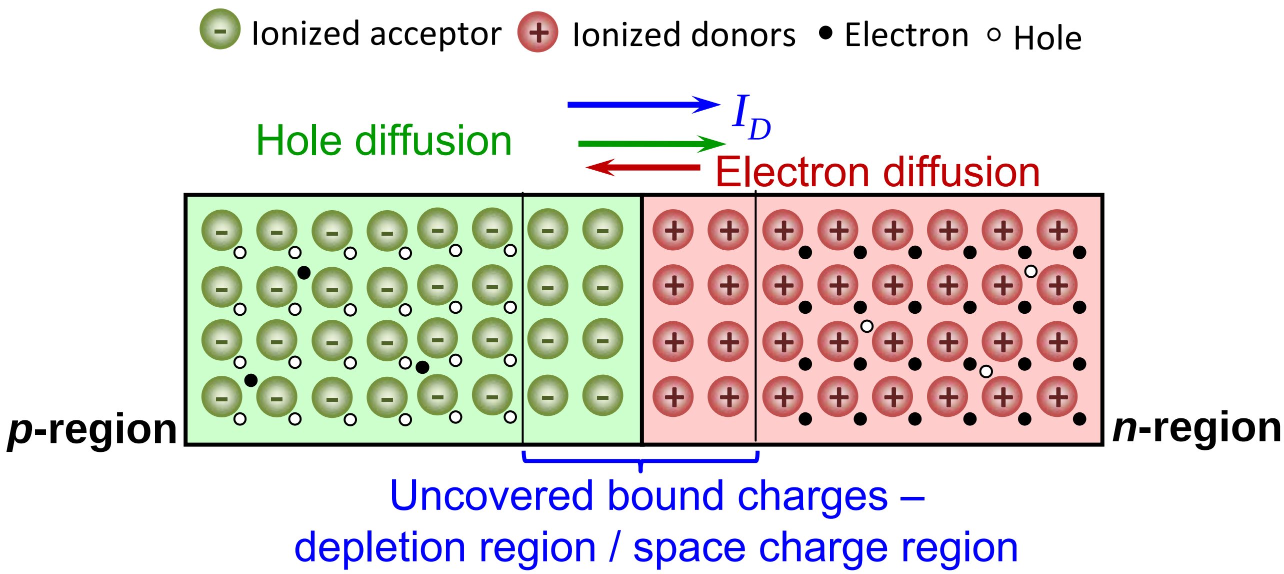
- The *n*-region has many more electrons ($n_{n0} \approx N_D$) than the *p*-region ($n_{p0} \approx n_i^2/N_A$), meaning electron concentration gradient exists across the metallurgical junction.

- Hence, electrons diffuse from the *n*-region to the *p*-region

- Similarly, holes diffuse from the *p*-region to the *n*-region

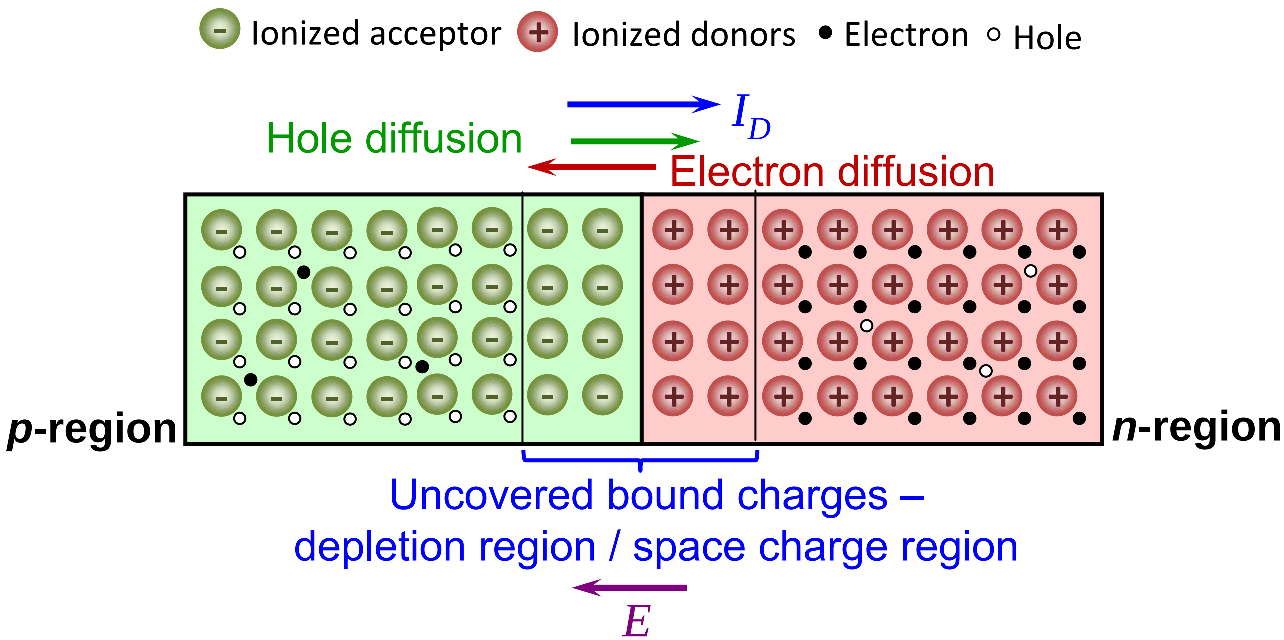
- The hole and electron diffusions add to form the diffusion current I_D (from the *p*-region to *n*-region). Note that I_D is due to majority carriers.

pn Junction – Open-Circuit Conditions



- Holes (from the *p*-region) that diffuse across the (metallurgical) junction into the *n*-region recombine with some of the majority electrons there
- Hence, some electrons in the *n*-region near the (metallurgical) junction disappear, resulting in the bound positive ionized donors being no longer neutralized by electrons (i.e., uncovered)
- Considering both electrons and holes, the region near the junction comprises uncovered bound positive ionized donors (in the n-region) and negative ionized acceptors (in the p-region) and is depleted of electrons and holes.

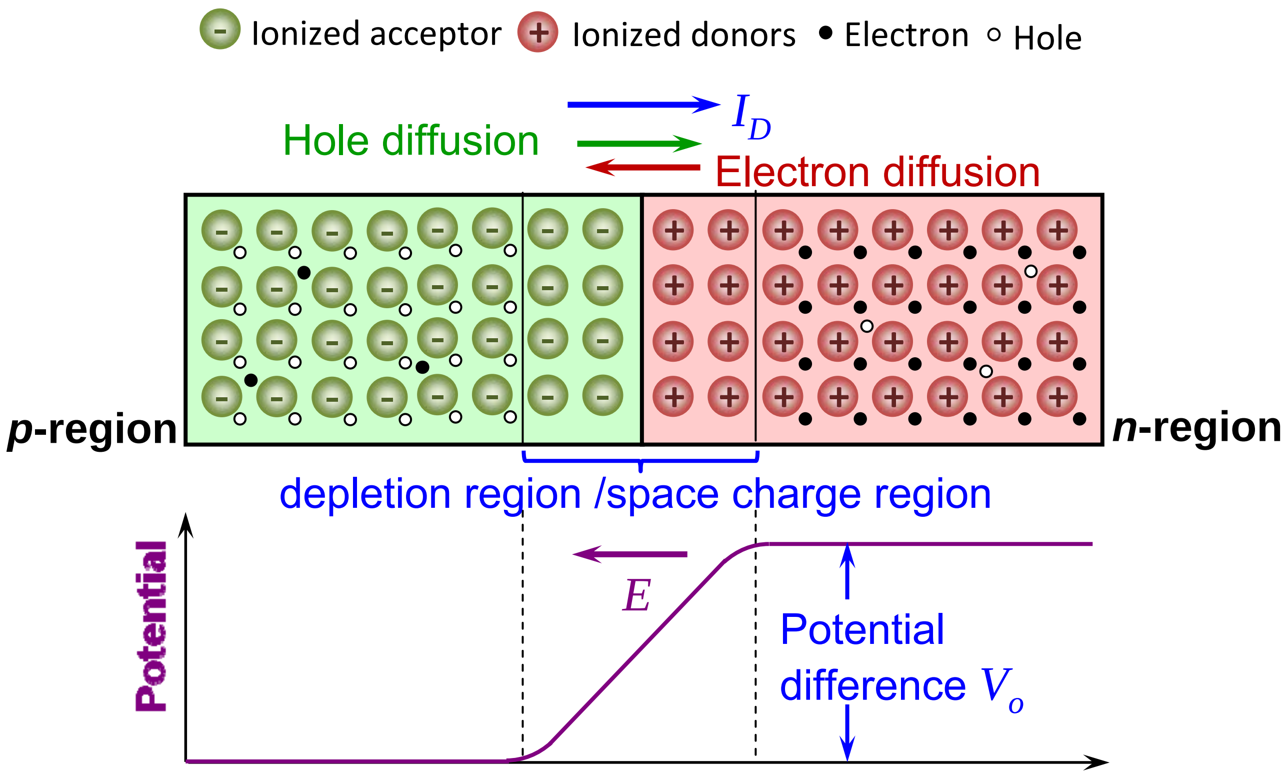
pn Junction – Open-Circuit Conditions



- The region near the junction is depleted of electrons and holes, hence is known as the depletion region. It is also called the space charge region as it has fixed donor/acceptor charges.

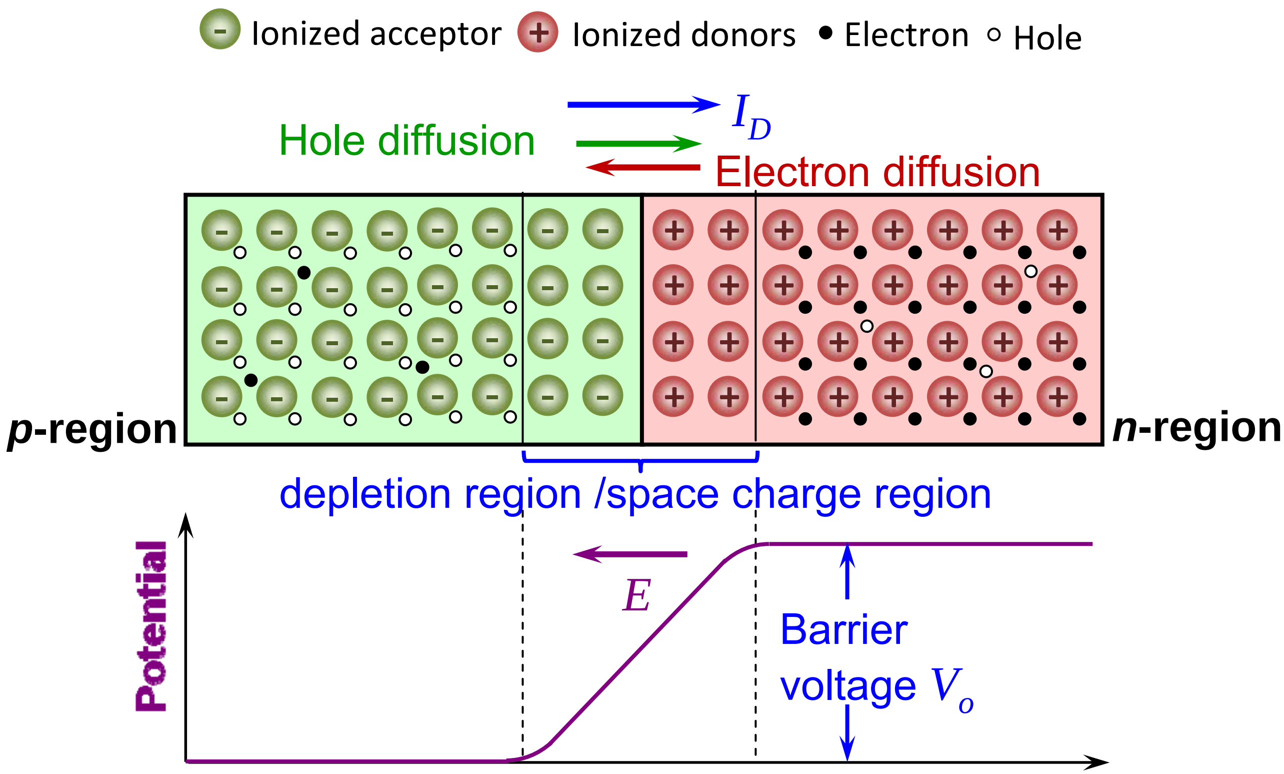
- The depletion region has 2 sides with different types of charges (negative in the *p*-side and positive in the *n*-side) and they cause an electric field, E, to establish across the depletion region, in the direction from the *n*-side to the *p*-side.

pn Junction – Open-Circuit Conditions



- With an established electric field, E, across the depletion region in the direction from the *n*-side to the *p*-side, a potential difference (voltage), V_o, results across the depletion region, with the *n*-side at a higher potential than the *p*-side.

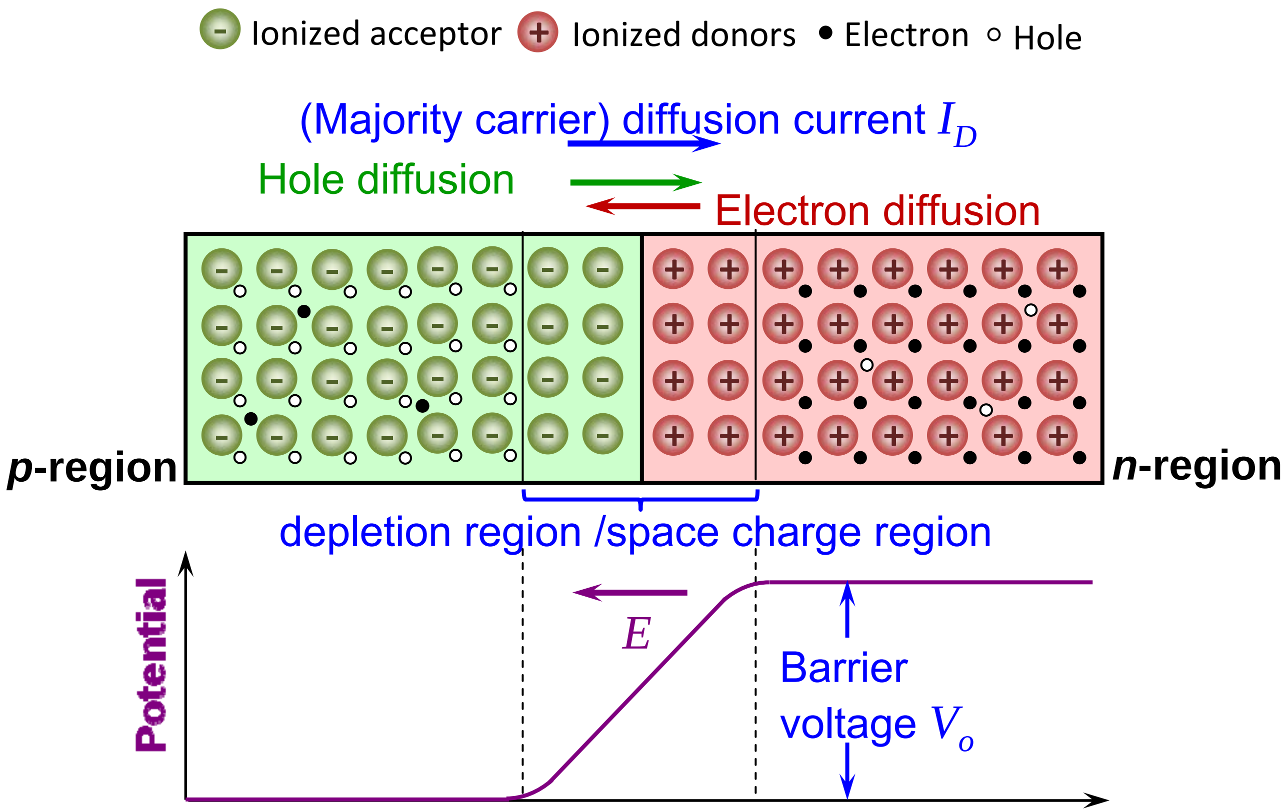
pn Junction – Open-Circuit Conditions



- The established electric field, E, across the depletion region opposes the diffusion of holes into the *n*-region, and electrons into the *p*-region.

- The potential difference (voltage) across the depletion region (V_o) acts a barrier that must be overcome by holes diffusing into the *n*-region and by electrons diffusing into the *p*-region. Hence, V_o is known as the barrier voltage.

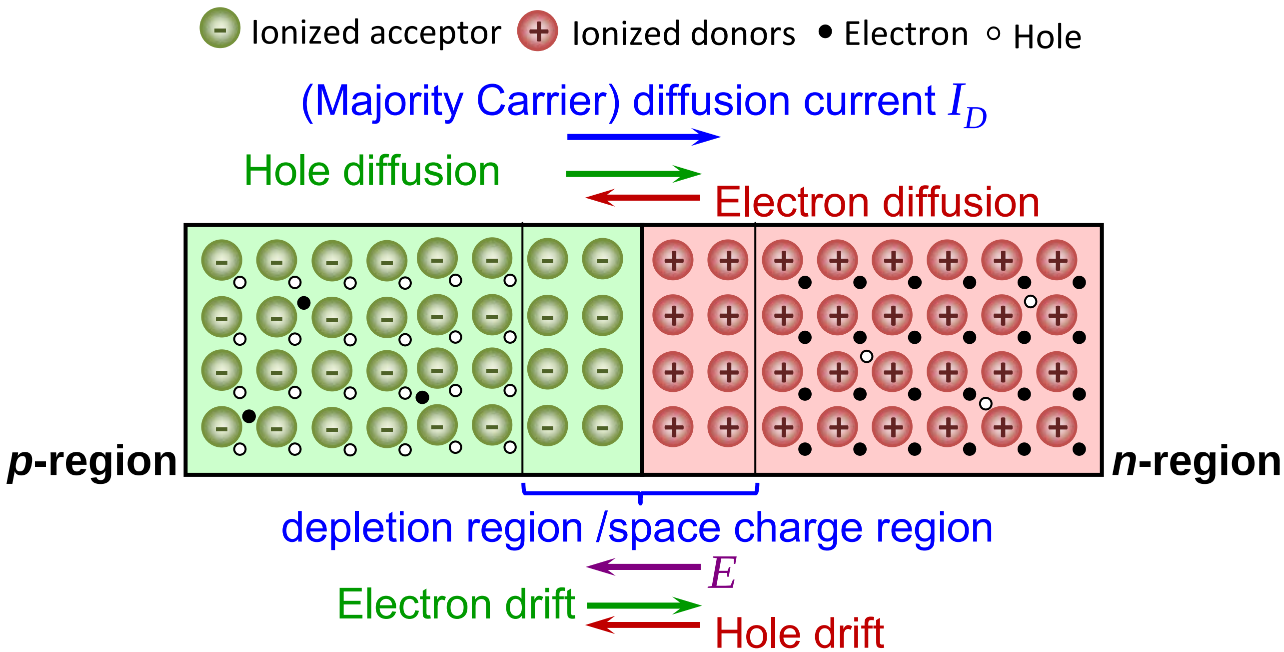
pn Junction – Open-Circuit Conditions



- Larger barrier voltage V_o across the depletion region, corresponding to a higher electric field E, opposes (majority carrier) diffusion, hence a smaller diffusion current I_D resulted. This means a smaller number of carriers are able to overcome the barrier.

- (Majority carrier) diffusion current I_D depends strongly on barrier voltage V_o.

pn Junction – Open-Circuit Conditions

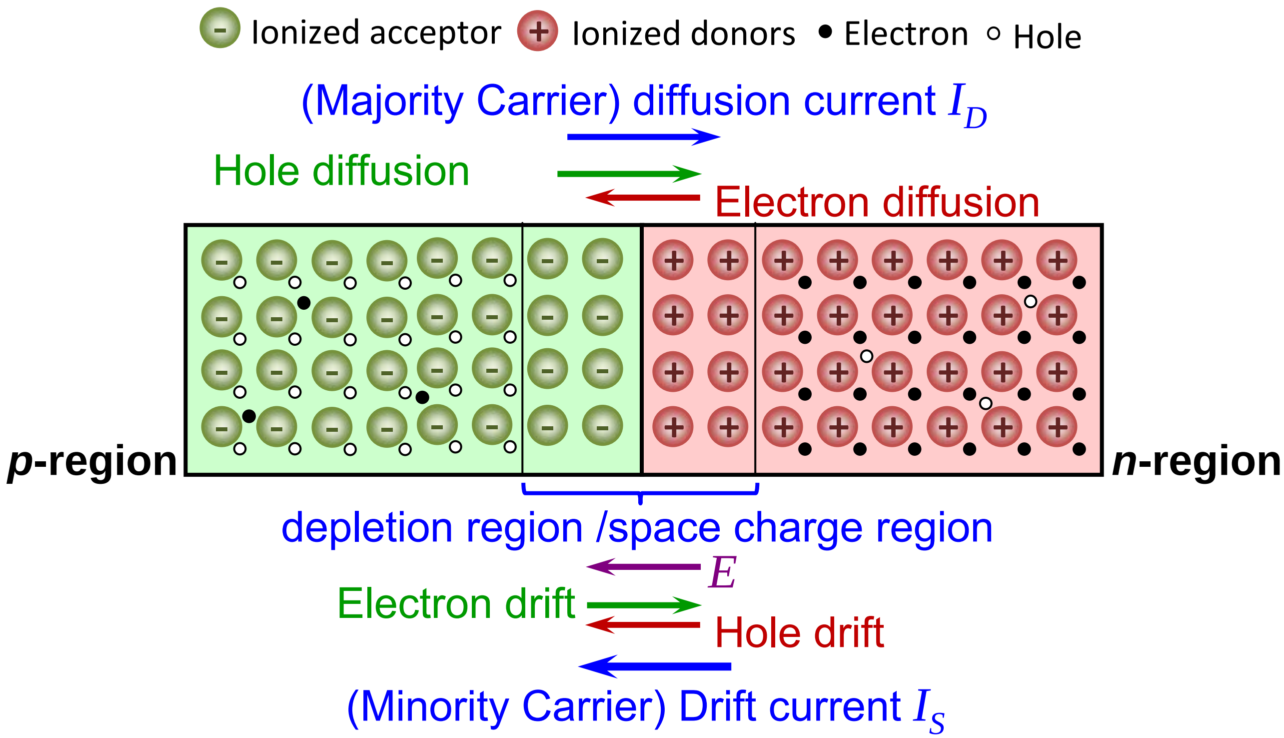


- As an electric field E is present across the depletion region, drift of carriers can happen.

- Some thermally generated minority holes in the *n*-region diffuse through the *n*-region to the edge of the depletion region, where holes experience the electric field E and are swept across the depletion region into the *p*-region (drift of holes).

- Similarly, drift of minority electrons from the *p*-region into *n*-region also occurs, as shown by the green arrow.

pn Junction – Open-Circuit Conditions

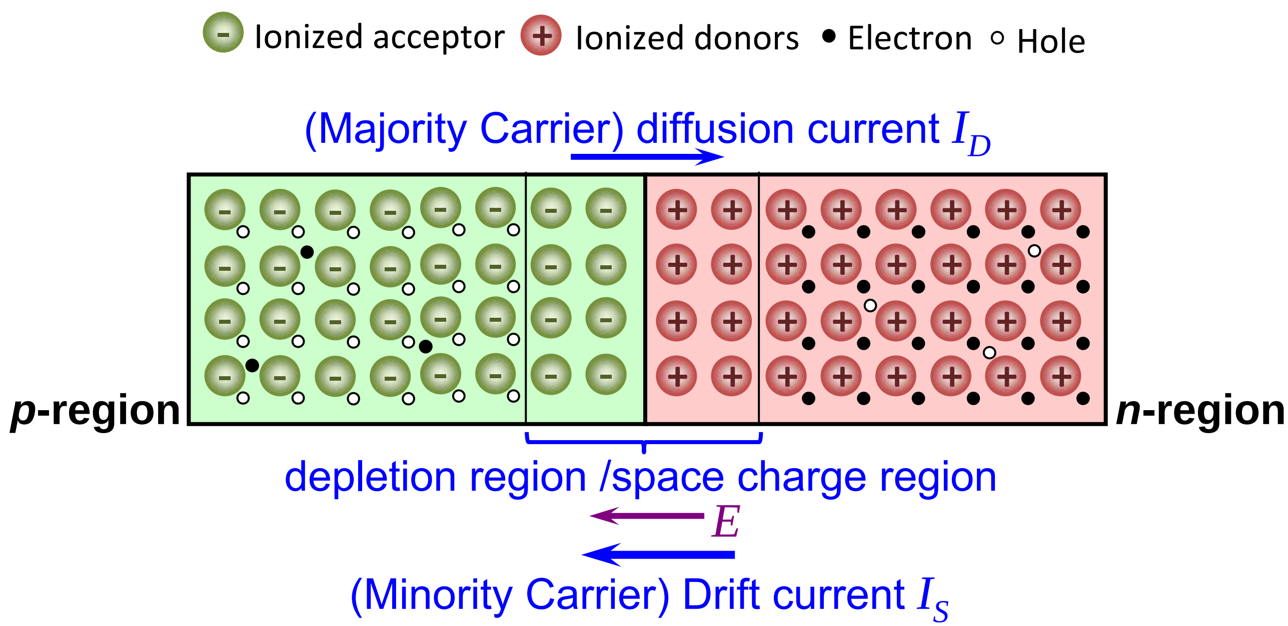


- Electrons moved by drift from *p*-region to *n*-region and holes moved by drift from *n*-region to *p*-region add to form the drift current I_S (from the *n*-region to *p*-region).

- The drift current I_S is carried by thermally generated minority carriers that are swept across the depletion region by the electric field E. Hence, its value is strongly dependent on temperature
  – higher temperature, more thermally generated minority carriers, higher I_S.

- The drift current I_S is independent on the value of the barrier voltage V_o.

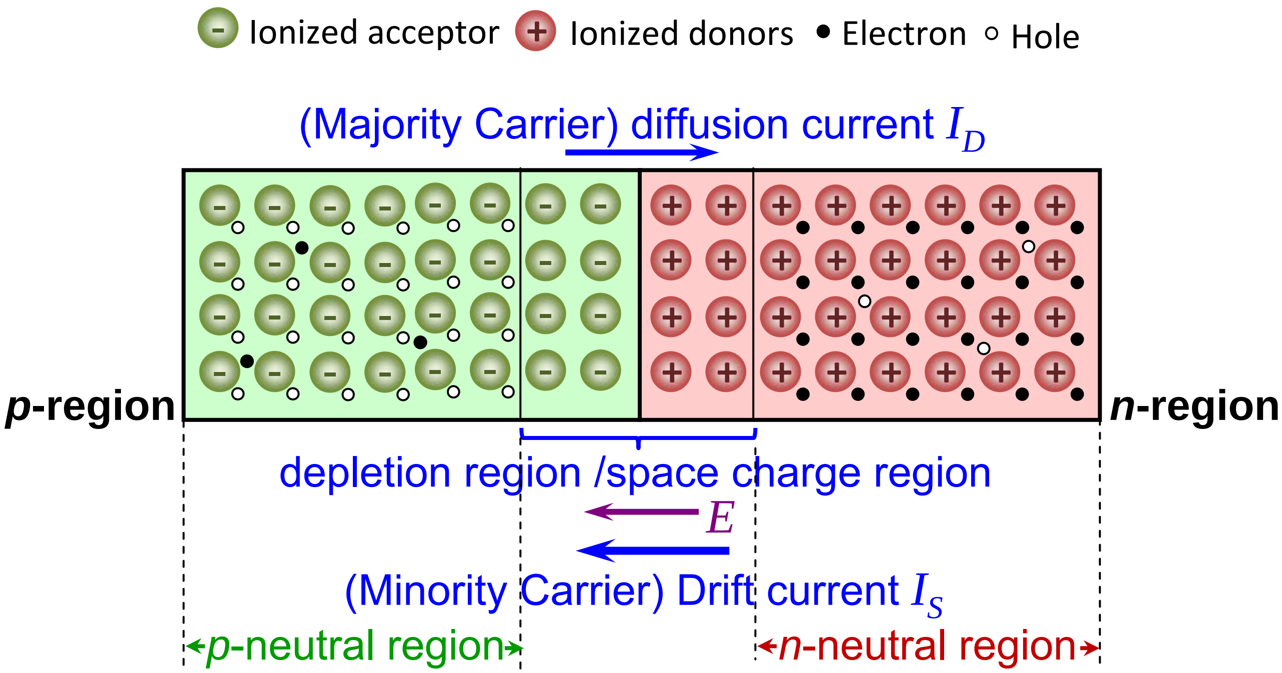
pn Junction – Open-Circuit Conditions



- Under open-circuit conditions, no external current exists. Hence, the two opposite currents across the junction are equal in magnitude: $I_D = I_S$

- Above equilibrium condition is maintained by the barrier voltage V_o. If I_D exceeds I_S, more bound charges are uncovered on both sides of junction, leading to a wider depletion region and higher voltage V_o across it. This in turn causes I_D to decrease until equilibrium is achieved with $I_D = I_S$.

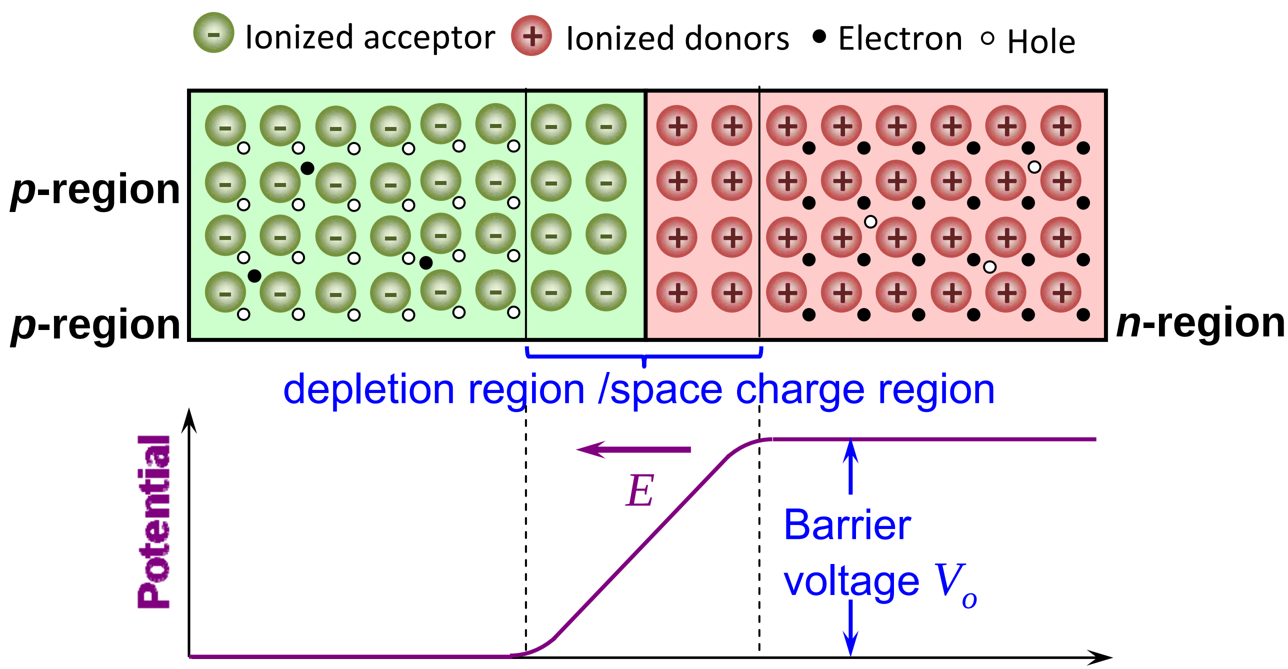
pn Junction – Open-Circuit Conditions



- Similarly, if I_S exceeds I_D, amount of uncovered bound charges will decrease, the depletion region will narrow and the barrier voltage V_o will decrease. This in turn causes I_D to increase until equilibrium is achieved with $I_D = I_S$.

- The width of the depletion region (or the amount of bound charge therein) is just enough to give $I_D = I_S$. Beyond the depletion region, the *p*-region and *n*-region remain electrically neutral.

pn Junction – Open-Circuit Conditions



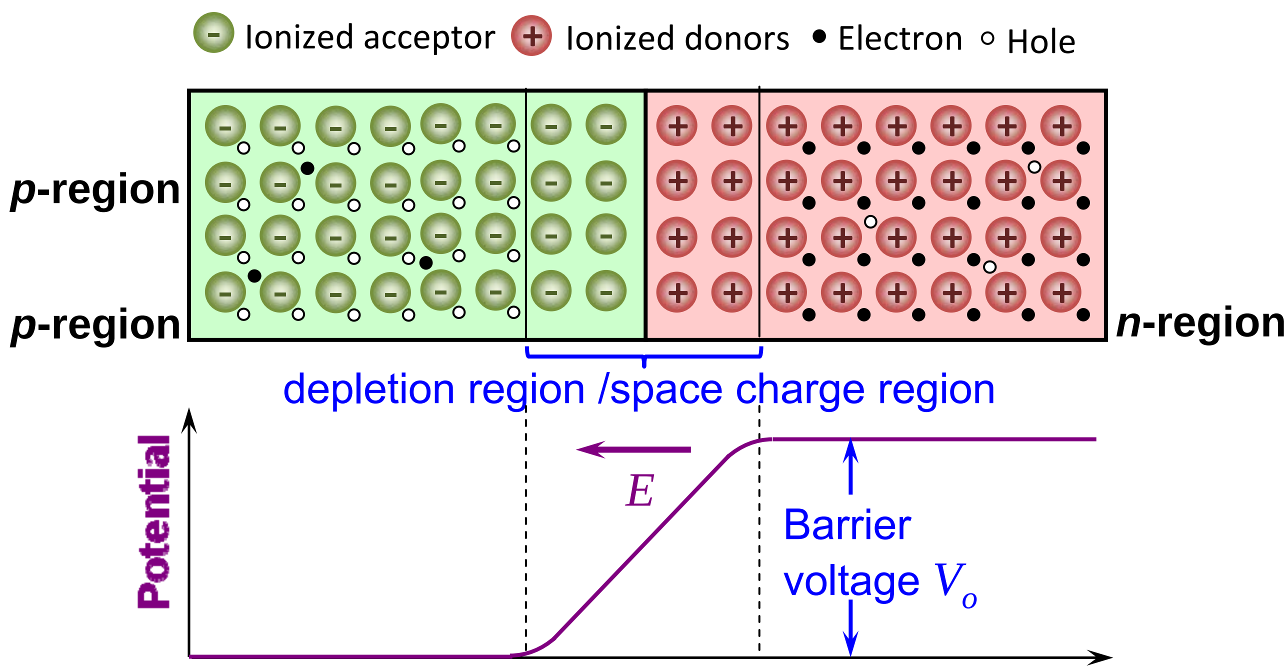
Junction Built-in Voltage (Barrier Voltage)

- With no external voltage applied, the barrier voltage V_o across the *pn* junction can be shown to be given by

$$V_o = \frac{kT}{q} ln\left(\frac{N_A N_D}{n_i^2}\right) = V_T \; ln\left(\frac{N_A N_D}{n_i^2}\right) \qquad (2.1)$$

- $V_T = \dfrac{kT}{q} = 0.0259\,\mathrm{V} \approx 0.025\,\mathrm{V}$ at $T = 300\,\mathrm{K}$ is the thermal voltage.

pn Junction – Open-Circuit Conditions

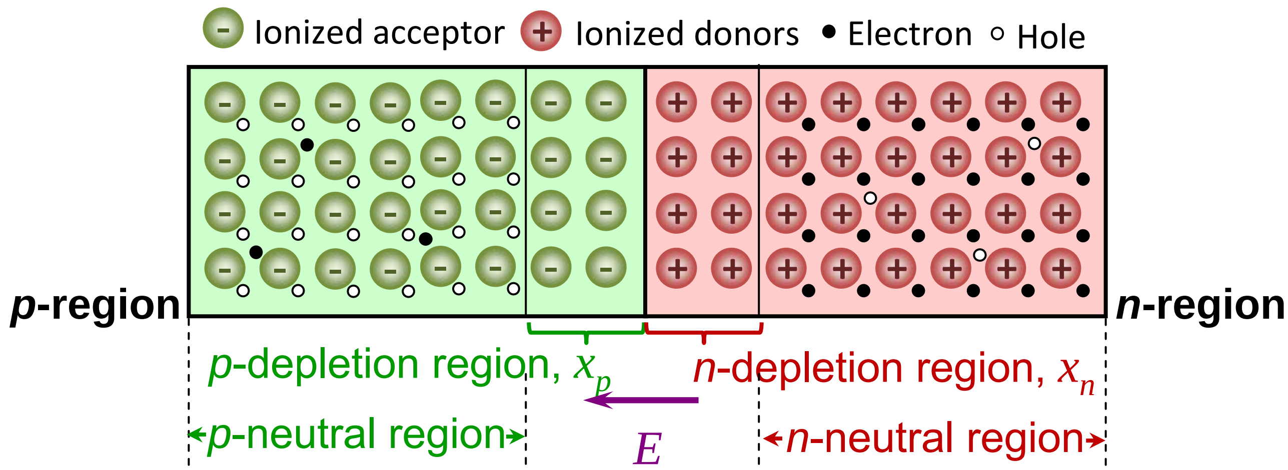


Junction Built-in Voltage (Barrier Voltage)

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

- V_o is also known as the junction built-in voltage (an internal voltage). It depends on the doping concentrations of the *pn* junction (N_A, N_D) and is typically between 0.6 to 0.8 V for silicon at room temperature.

pn Junction – Open-Circuit Conditions



<u>Width of the depletion region</u>

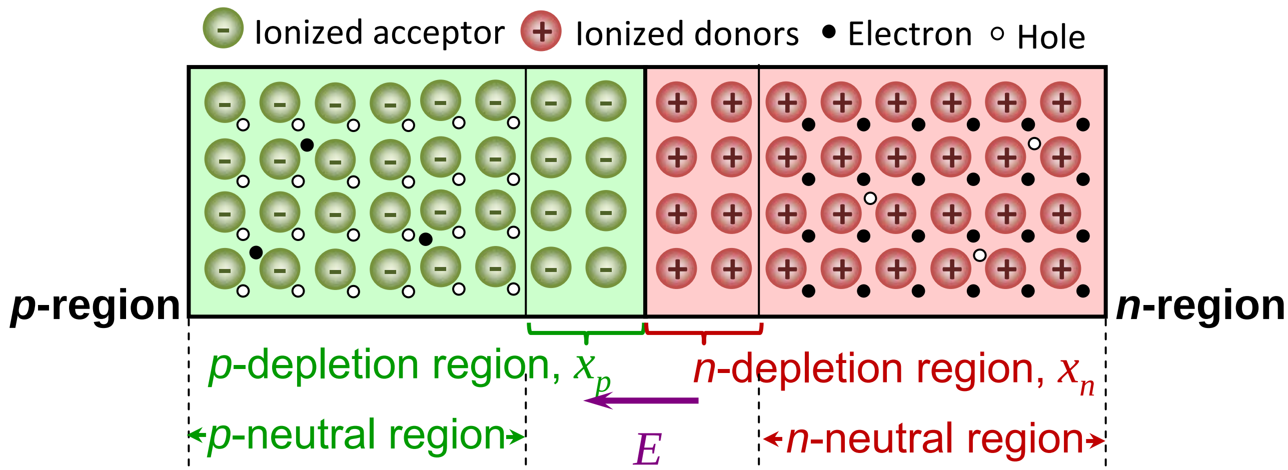
- Depletion region exists in both the *p*-region (of width x_p with negative ionized acceptors) and *n*-region (of width x_n with positive ionized donors), and the two sides have equal amounts of charge:

$$q_j = qx_pAN_A = qx_nAN_D \quad \left(\text{or} \quad \frac{x_p}{x_n} = \frac{N_D}{N_A} \right), \qquad (2.2)$$

where A is the cross-sectional area of the *pn* junction.

•Higher N_A than N_D means $x_p < x_n$ and vice versa.

pn Junction – Open-Circuit Conditions



Width of the depletion region

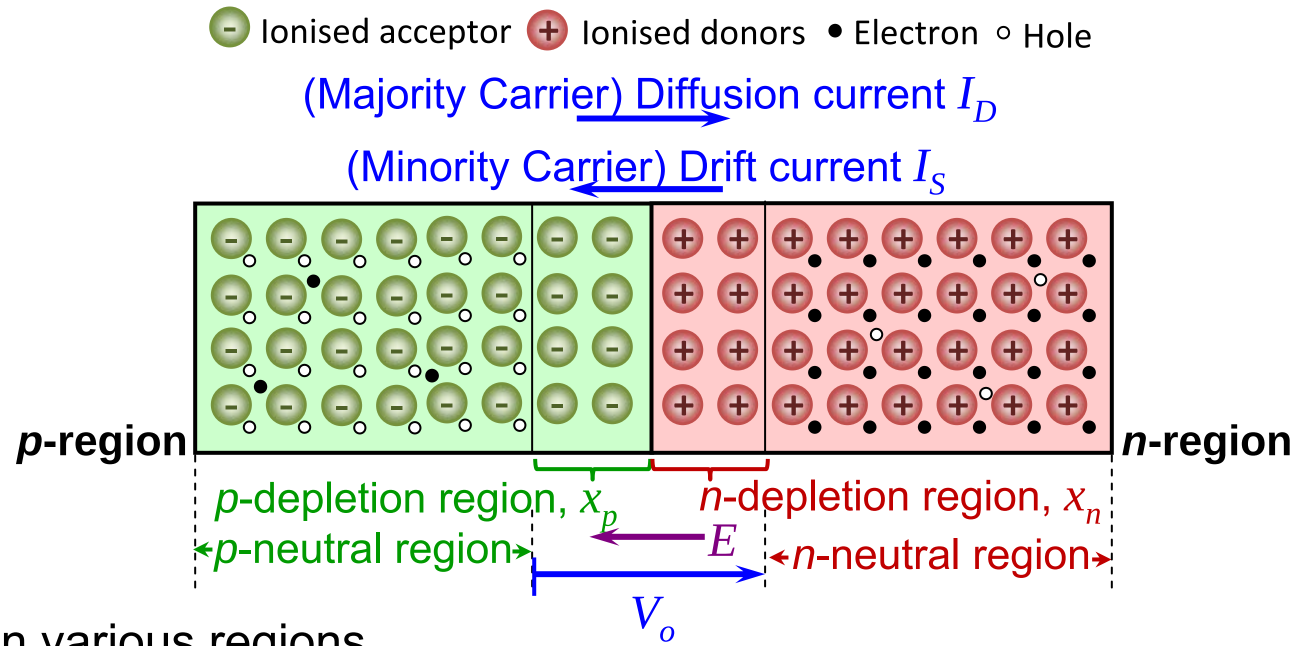
- The (total) width of the depletion region W_{dep} of an open-circuited *pn* junction can be shown to be

$$W_{dep} = x_p + x_n = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_A} + \frac{1}{N_D}\right]V_o} \quad (2.3)$$

- ε_s is the permittivity of semiconductor = 11.7ε_o = 1.04×10^{-12} F/cm for silicon. ε_o is the permittivity of free space = 8.854 $\times10^{-14}$ F/cm.

- Higher N_A and N_D lead to smaller W_{dep}.

pn Junction – Open-Circuit Conditions



Charges in various regions

	Region			
Charge type	*p*-neutral	*p*-depletion	*n*-depletion	*n*-neutral
Acceptors (-*q*)	N_A	N_A	0	0
Donors (+*q*)	0	0	N_D	N_D
Holes (+*q*)	N_A	~0	~0	$<<< N_D$
Electrons (-*q*)	$<<< N_A$	~0	~0	N_D
Charge (C)	0	$- qAx_pN_A$	$+ qAx_nN_D$	0

pn Junction – Open-Circuit Conditions

Exercise

For a Si *pn* junction with N_A = 10^{17} cm^{-3} and N_D = 10^{16} cm^{-3}, find at T = 300 K, the built-in voltage, and the width of the depletion region, including the distance it extends into the *p*-side and *n*-side of the junction under open-circuit conditions. Use n_i = 1.5x10^{10} cm^{-3}.

$$V_o = V_T \, ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.025 \cdot ln\left(\frac{10^{17} \cdot 10^{16}}{\left[1.5 \times 10^{10}\right]^2}\right) = 0.728 \text{ V}$$

$$W_{dep} = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_A} + \frac{1}{N_D}\right] V_o}$$

$$= \sqrt{\frac{2(11.7)(8.854 \times 10^{-14})}{1.602 \times 10^{-19}}\left[\frac{1}{10^{17}} + \frac{1}{10^{16}}\right](0.728)}$$

$$= 0.32 \times 10^{-4} \text{ cm} = 0.32 \text{ µm}$$

pn Junction – Open-Circuit Conditions

$$W_{dep} = x_p + x_n \quad \textbf{and} \quad \frac{x_p}{x_n} = \frac{N_D}{N_A}$$

$$\Rightarrow W_{dep} = x_p + \frac{N_A}{N_D} x_p = x_p \left(\frac{N_D + N_A}{N_D} \right)$$

$$\therefore \quad x_p = \left(\frac{N_D}{N_A + N_D} \right) W_{dep} \quad , \quad x_n = \left(\frac{N_A}{N_A + N_D} \right) W_{dep}$$

$$x_p = \left(\frac{10^{16}}{10^{17} + 10^{16}} \right) \times 0.32\ \mu\text{m} = 0.029\ \mu\text{m}$$

$$x_n = \left(\frac{10^{17}}{10^{17} + 10^{16}} \right) \times 0.32\ \mu\text{m} = 0.29\ \mu\text{m}$$

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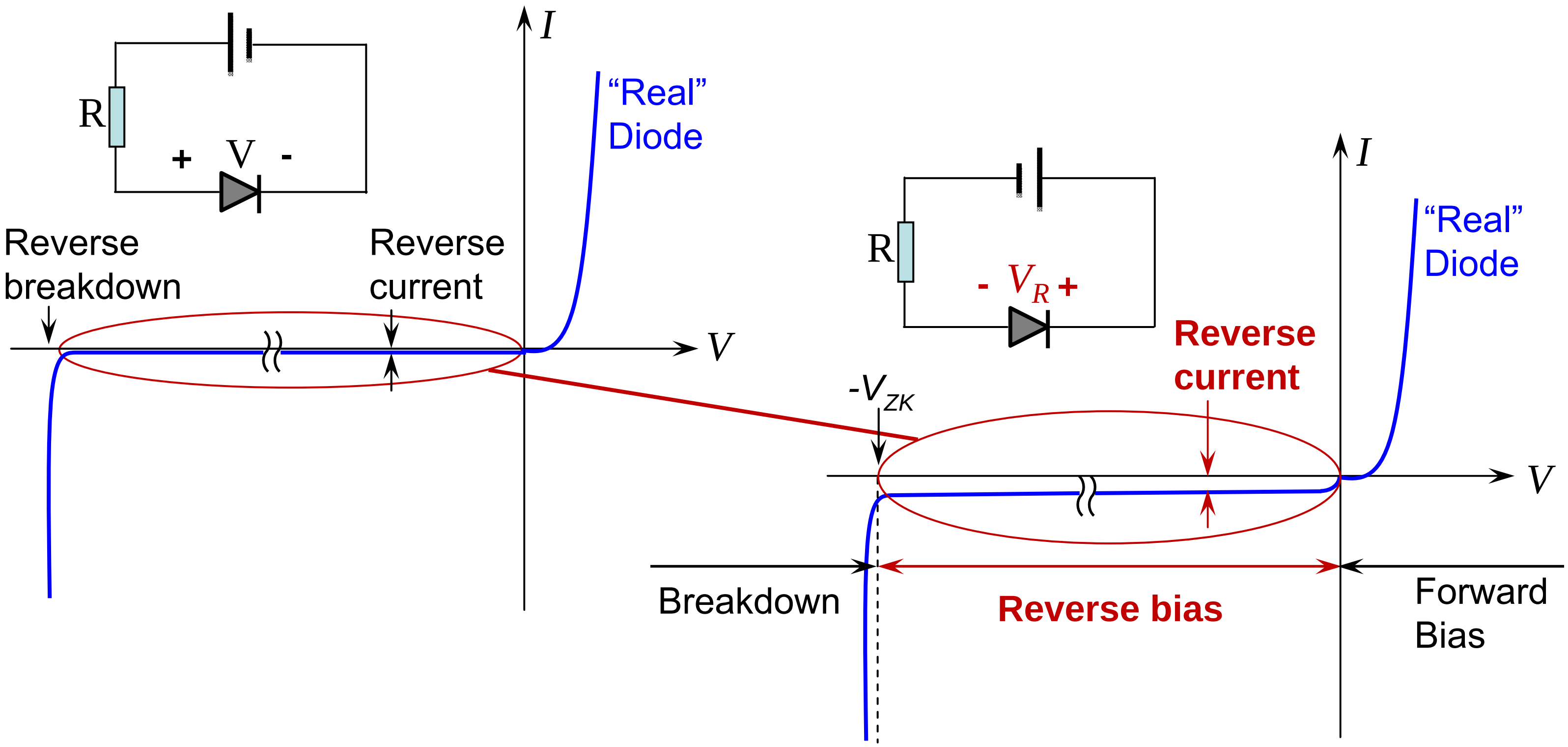
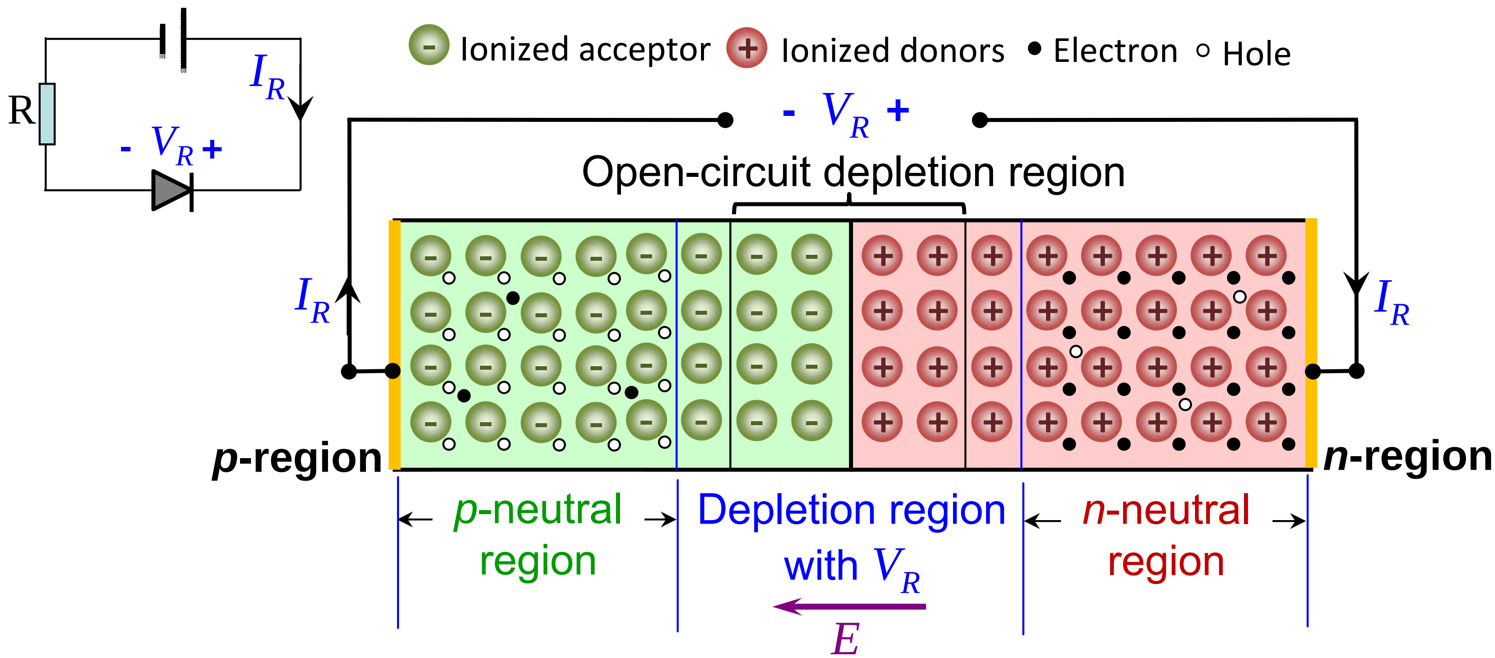
pn Junction - Reverse-Bias Conditions



- Under reverse-bias, an external voltage supply is applied such that the voltage across the *pn* junction V_R is lower (or negative) at the *p*-region with respect to the *n*-region.

- We will consider the reverse bias region where V_R is less than the breakdown (knee) voltage V_{ZK}. For $V_R < V_{ZK}$, the (reverse) current flowing through the *pn* junction is very small, but not zero.

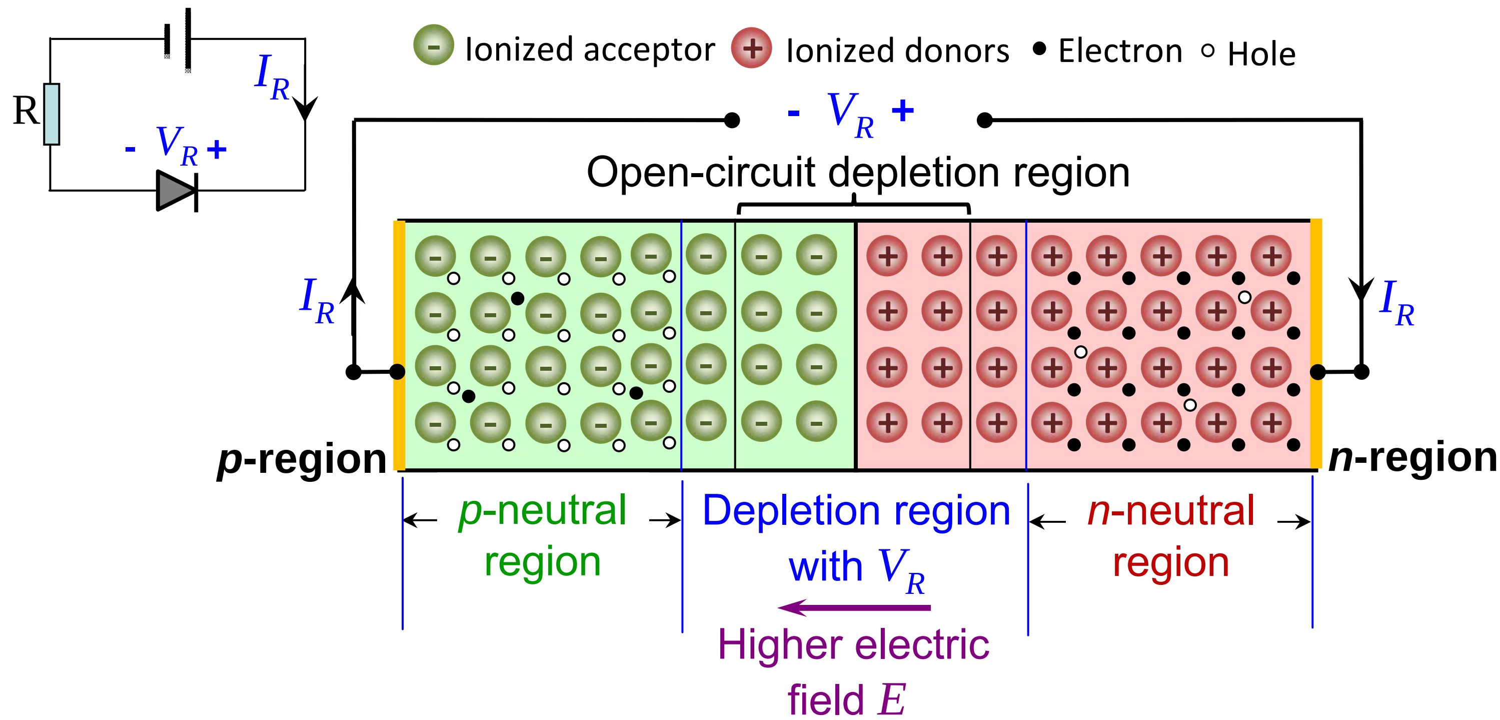
pn Junction – Reverse-Bias Conditions



- Holes in the (neutral) *p*-region will be attracted by the negative voltage of V_R to leave the *p*-region and flow through the external circuit.
- Above causes the uncovered negative bound charge (ionized acceptors) to increase.

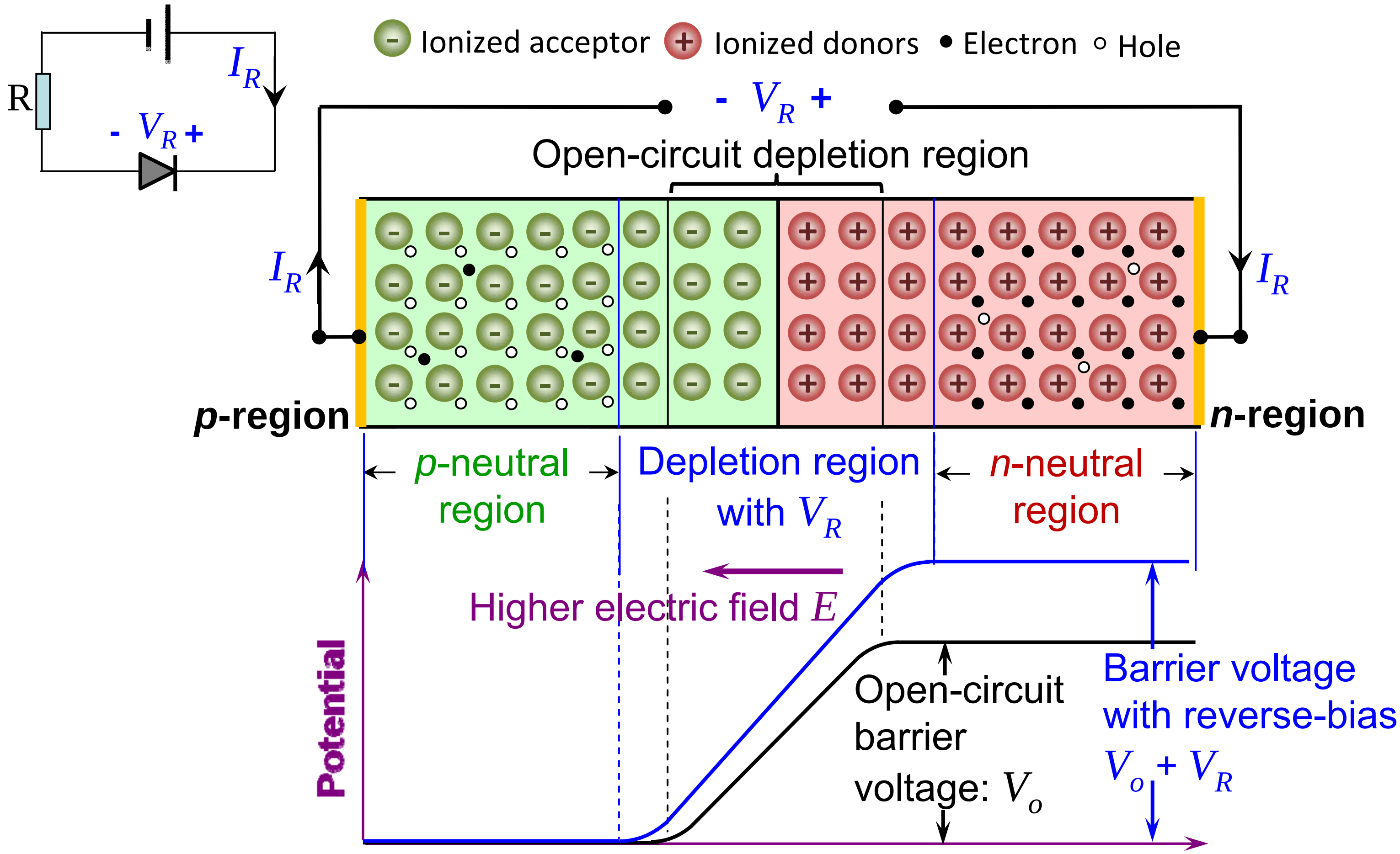
- Electrons in the (neutral) *n*-region will be attracted by the positive voltage of V_R to leave the *n*-region and flow through the external circuit.
- Above causes the uncovered positive bound charge (ionized donors) to increase.

pn Junction – Reverse-Bias Conditions



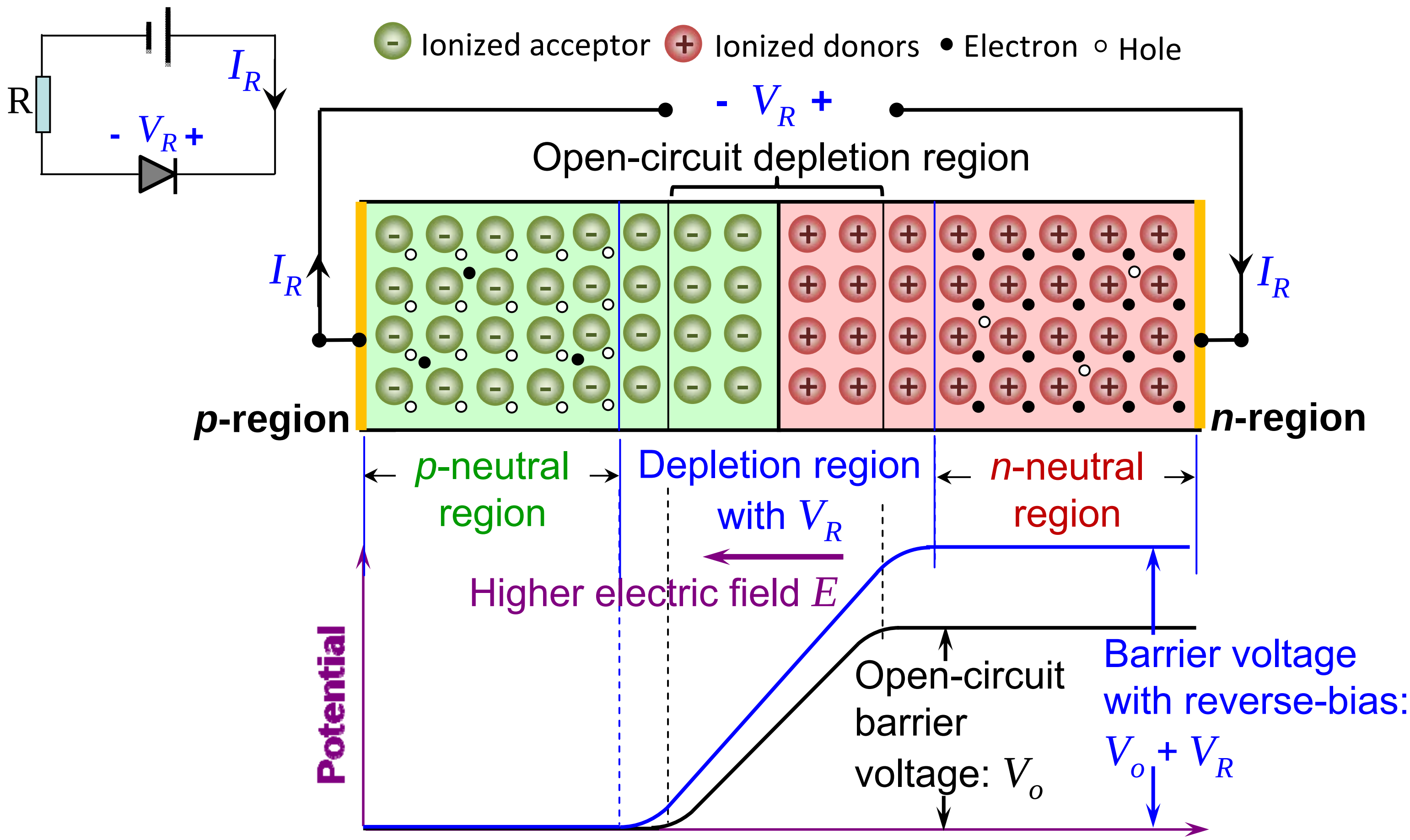
- A current flows from the positive terminal of V_R, through the *pn* junction (from *n*-region to *p*-region), to the negative terminal of V_R.
- As a result of increased bound charge, depletion region widens (with respect to that under open-circuit conditions)
  - Higher electric field and higher (barrier) voltage across the wider depletion region
  - Barrier voltage of the wider depletion region is given by $V_o + V_R$

pn Junction – Reverse-Bias Conditions



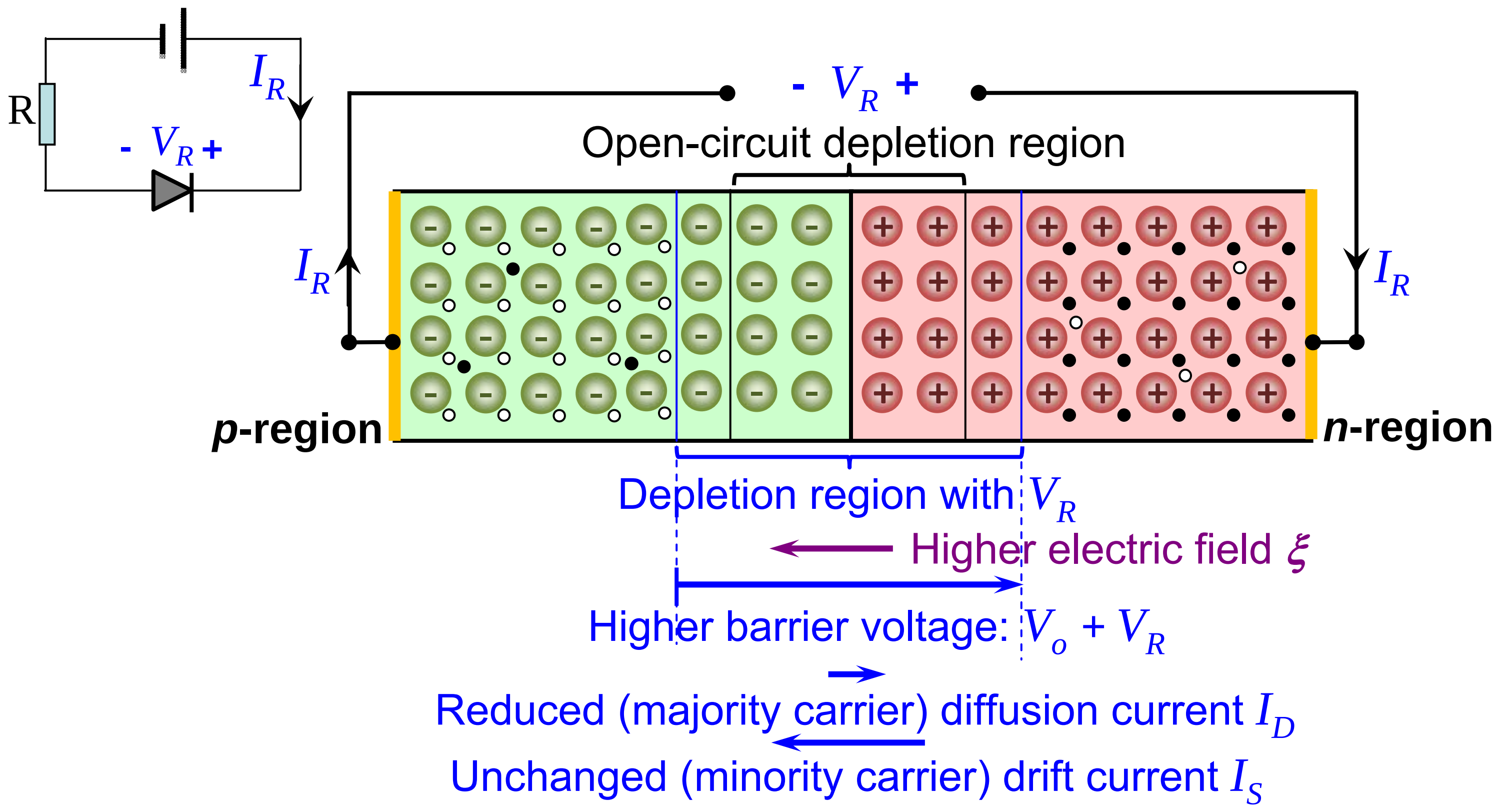
- Higher barrier voltage ($V_o + V_R$) and higher electric field opposing electron/hole diffusion leads to a lower (majority carrier) diffusion current I_D, which becomes negligible small with sufficient large magnitude of V_R.

pn Junction – Reverse-Bias Conditions



- No change in the (minority carrier) drift current I_S, since it is independent on barrier voltage across the depletion region.

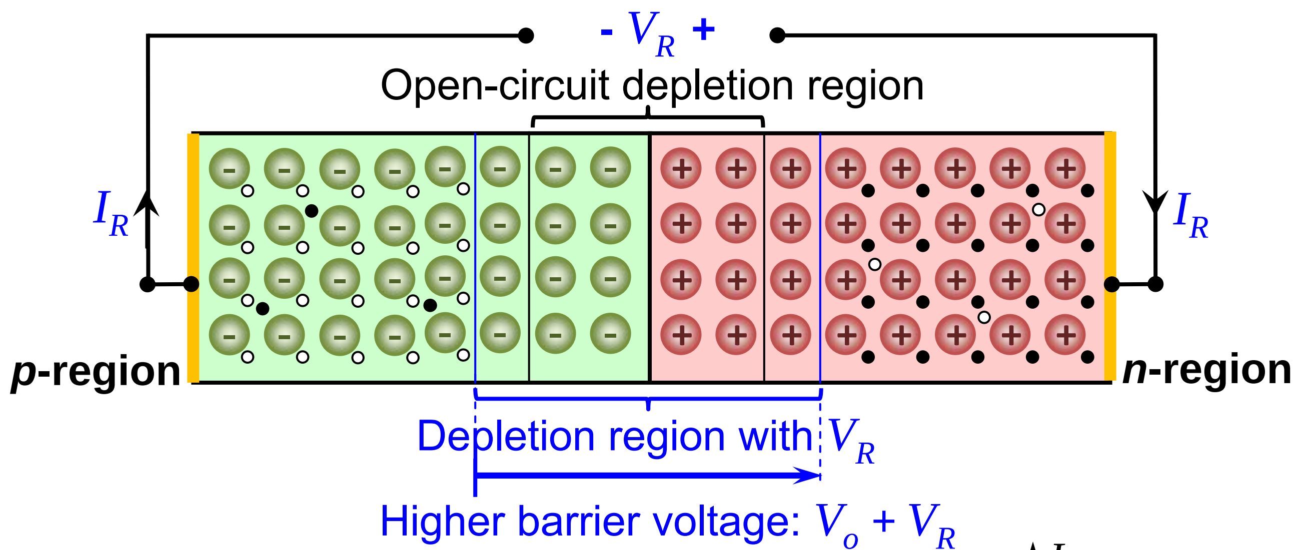
pn Junction – Reverse-Bias Conditions

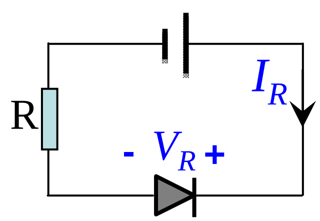


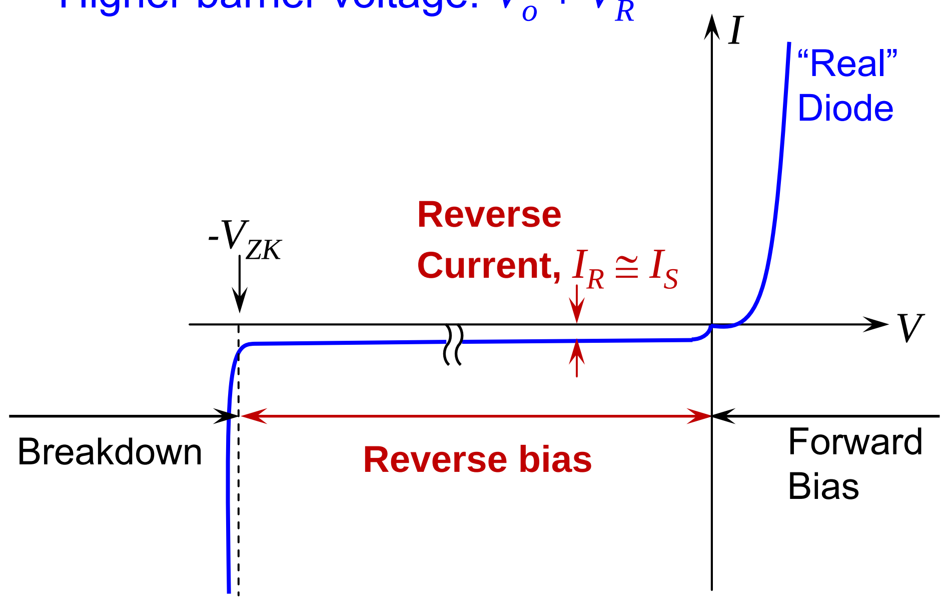
- (Net) current flow through a reverse-bias *pn* junction: $I_R = I_S - I_D \approx I_S$, a small current since I_S is due to drift of minority carriers.

- $I_R \approx I_S$ is also independent on V_R since I_S does not depend on the barrier voltage across the depletion region.

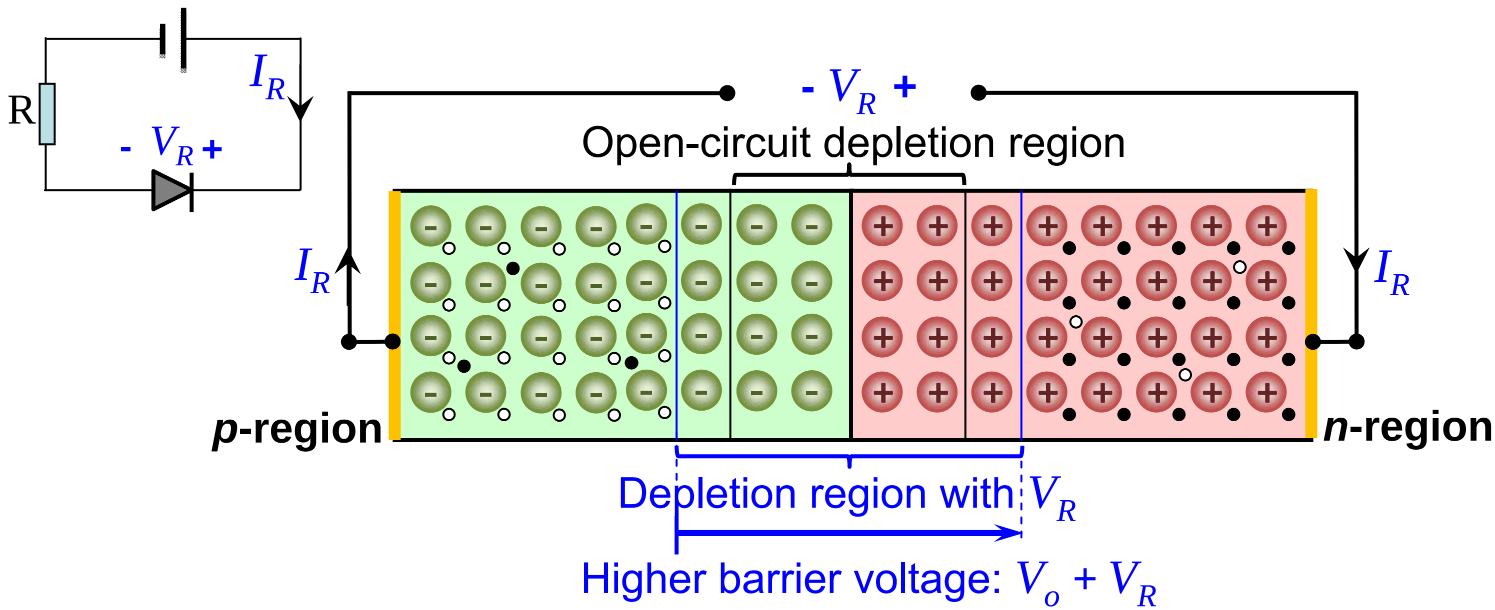
pn Junction – Reverse-Bias Conditions







pn Junction – Reverse-Bias Conditions



- (Total) width of the depletion region under reverse-bias is given by equation (2.3) by replacing V_o, the barrier voltage across the depletion region under open-circuit conditions, by (V_o + V_R) –

$$W_{dep} = x_p + x_n = \sqrt{\frac{2\varepsilon_s}{q}\left[\frac{1}{N_A} + \frac{1}{N_D}\right](V_o + V_R)} \qquad (2.4)$$

- Equation (2.2) that relates x_n and x_p is still valid.

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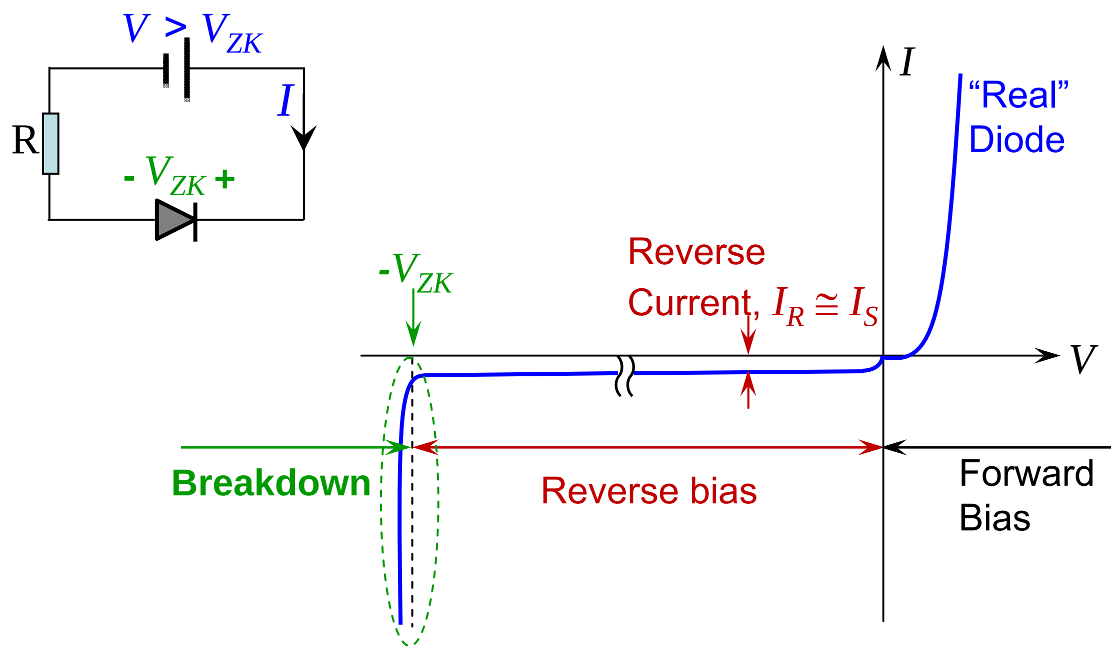
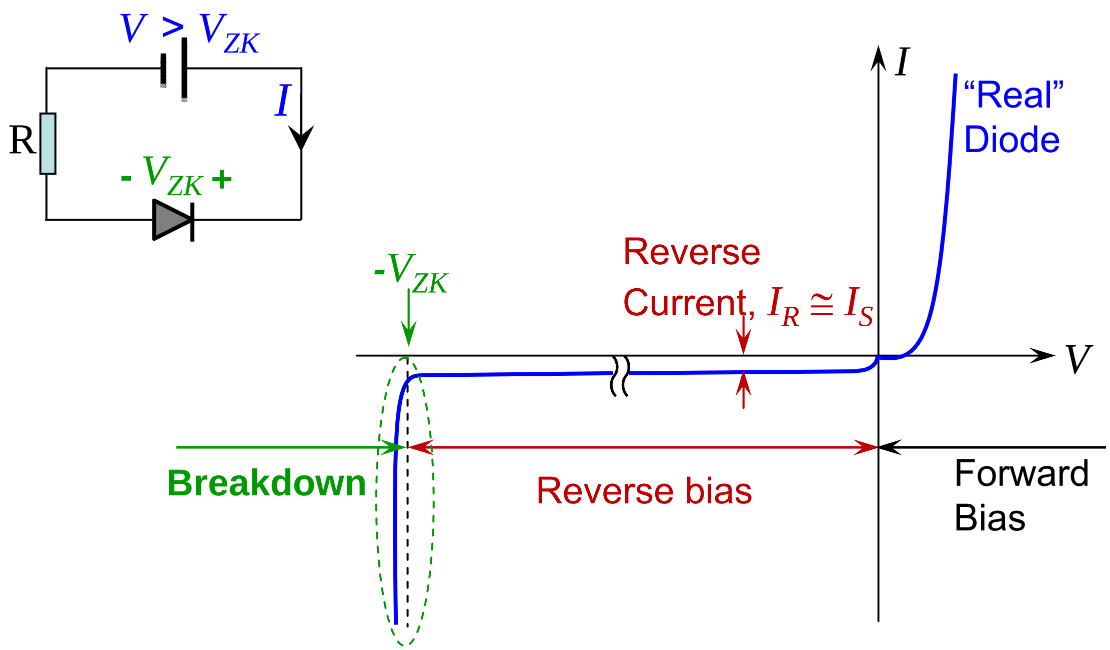
pn Junction – Breakdown Region



- When an external voltage supply in reverse bias $V > V_{ZK}$ (breakdown voltage) is applied across the *pn* junction, the (reverse) current increases rapidly with very small increase in the *pn* junction voltage. This condition is known as breakdown.

- Breakdown does not destroy the junction provided the current is kept below a certain level, to keep the power dissipation ($V \times I$) below what the device can handle. Current can be limited by connecting a resistor of suitable value in series with the *pn* junction.

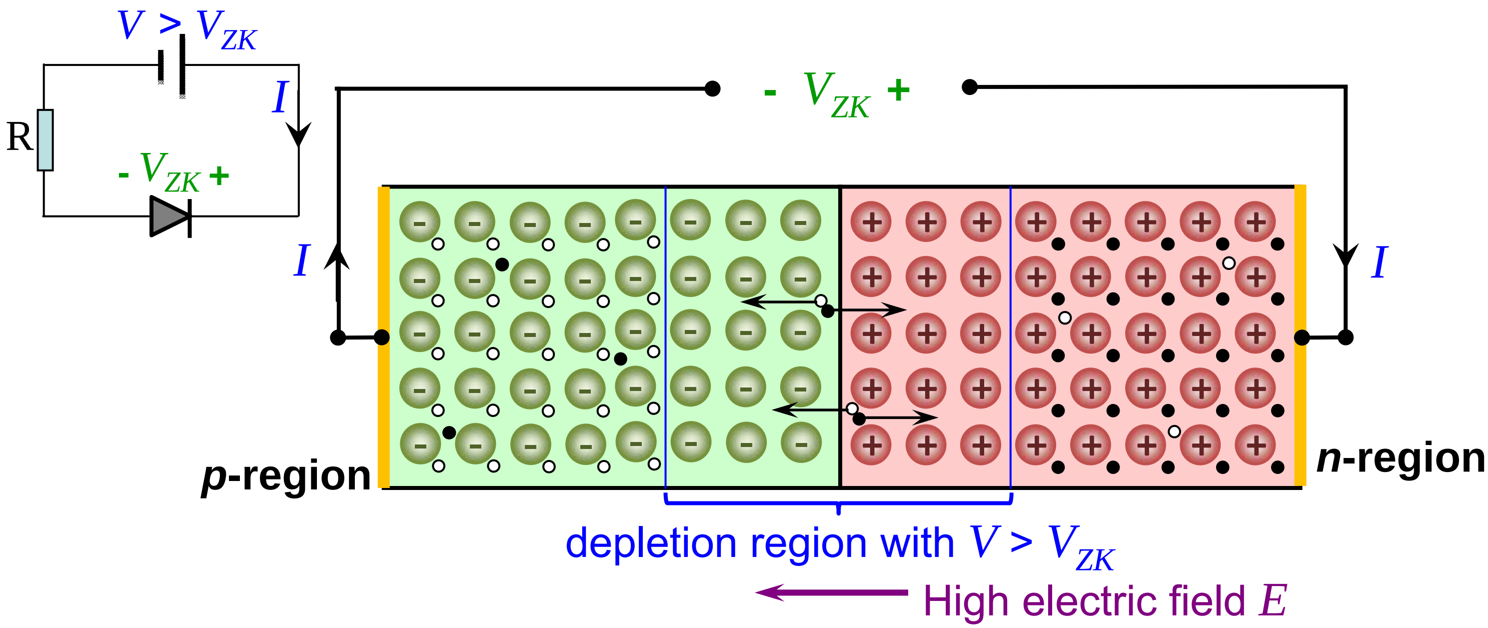
pn Junction – Breakdown Region



Breakdown mechanisms

- There are 2 possible breakdown mechanisms –
  - Zener breakdown - V_{ZK} is typically less than ~5 V
  - Avalanche breakdown - V_{ZK} is greater than approximately ~7 V
- For 5 V < V_{ZK} < 7 V, the breakdown mechanism can be one of the above two mechanisms or a combination of the two.

pn Junction – Breakdown Region

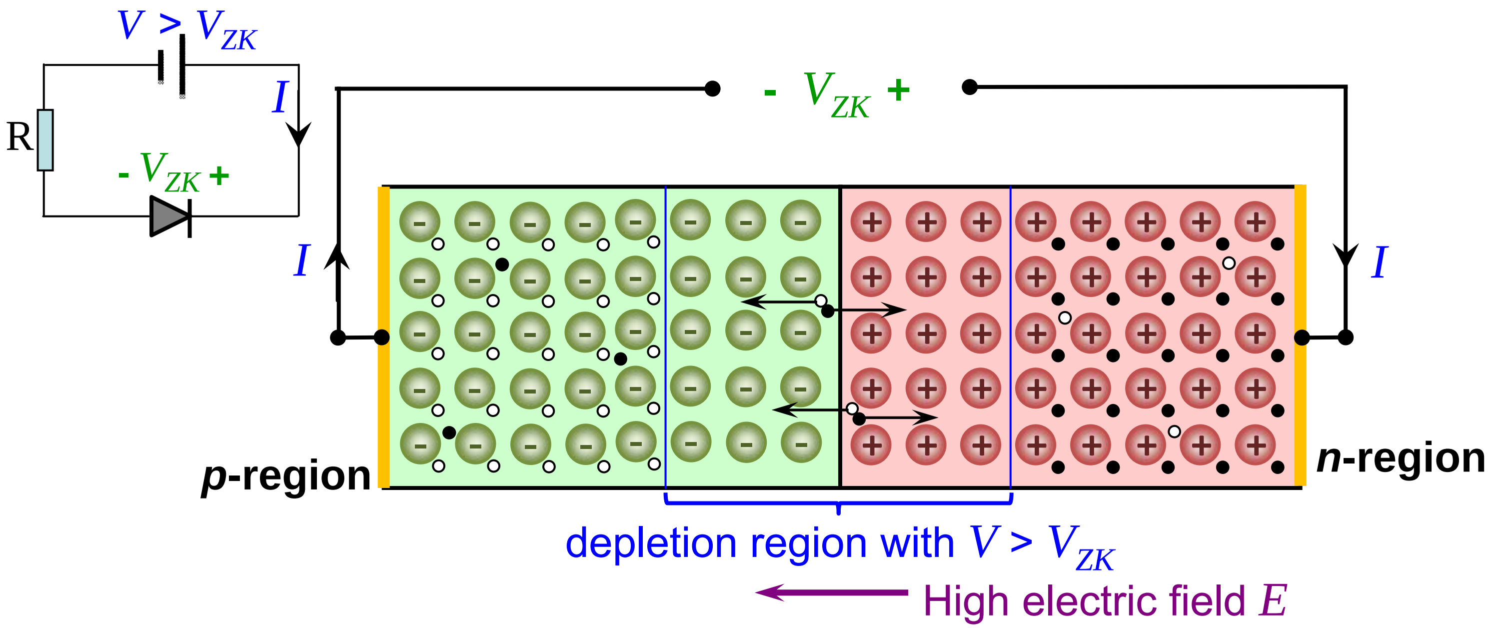


Zener breakdown

- Zener breakdown occurs when the electric field E in the depletion region has increased to a magnitude that it can break the covalent bonds and generate electron-hole pairs (EHPs).

- Electrons generated will be swept by the electric field E into the *n*-side and holes generated will be swept into the *p*-side. These electron and hole flows constitute an additional reverse current component.

pn Junction – Breakdown Region



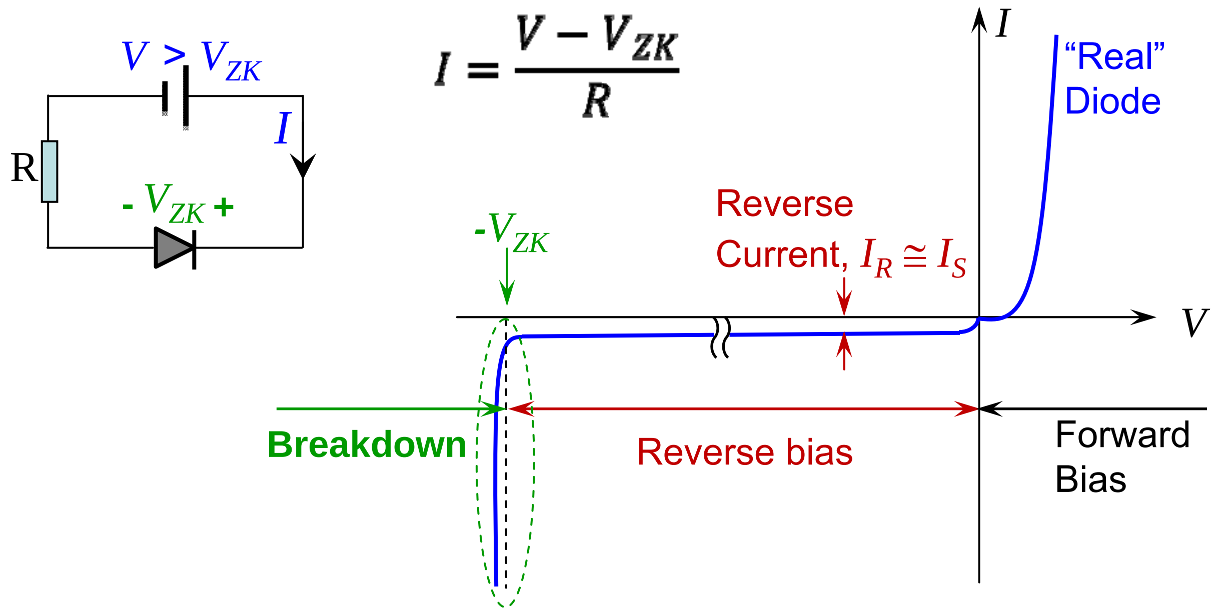
<u>Zener breakdown</u>

- Once Zener breakdown occurs ($V_R > V_{ZK}$), a large number of EHPs can be generated within the depletion region with negligible increase in the *pn* junction voltage. Hence, leading to large reverse current.

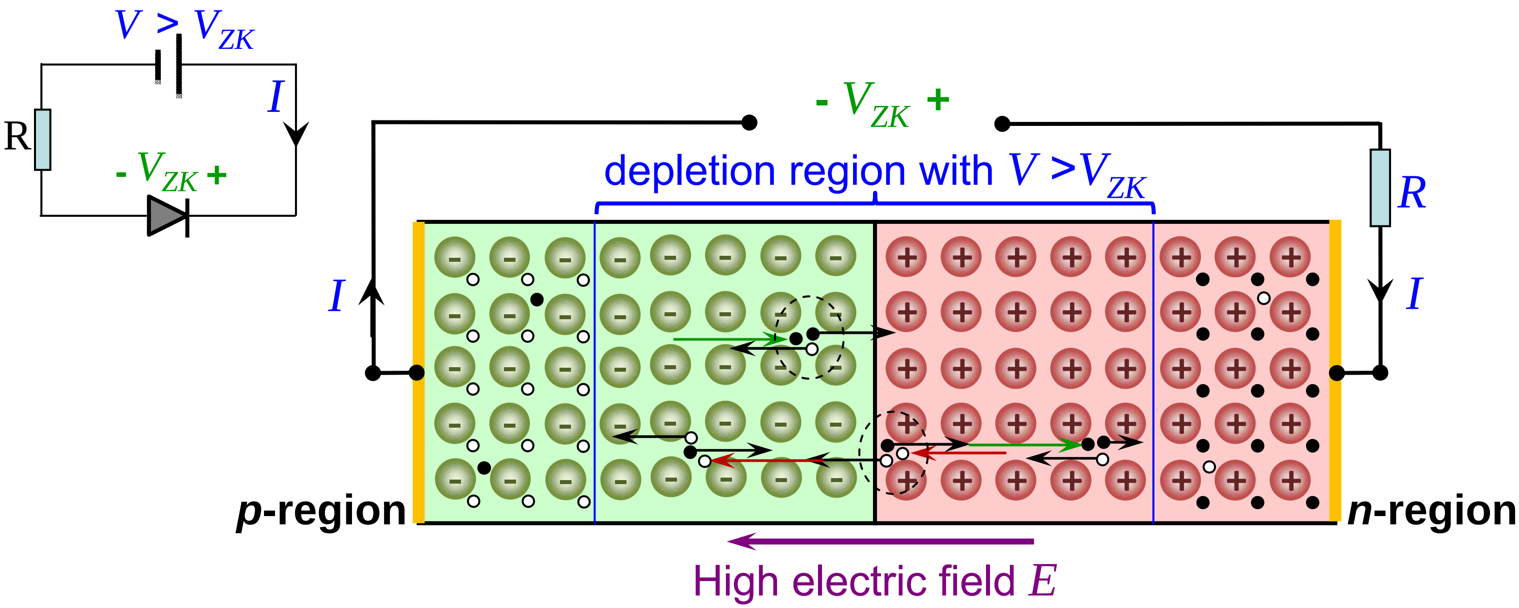
- Reverse current in the breakdown region will be determined by the external circuit, while reverse voltage across the *pn* junction will remain close to V_{ZK}

pn Junction – Breakdown Region

$$I = \frac{V - V_{ZK}}{R}$$



pn Junction – Breakdown Region

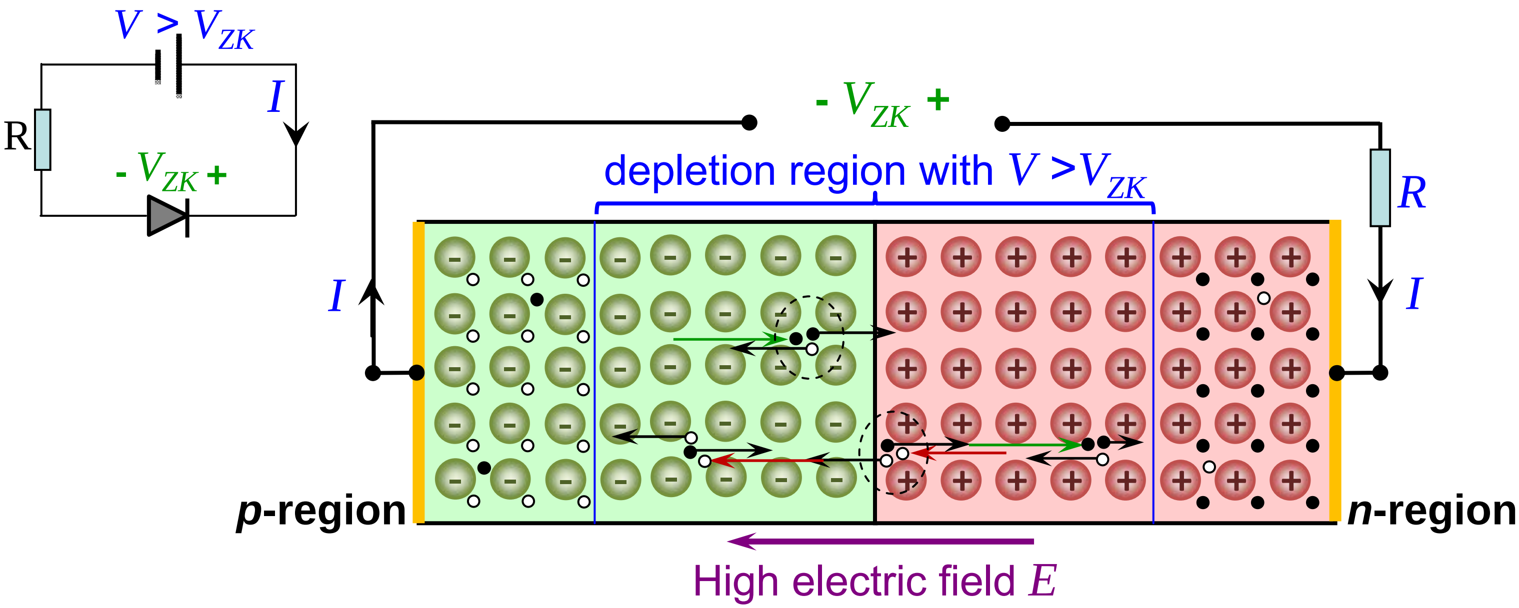


<u>Avalanche breakdown</u>

- Avalanche breakdown occurs when the minority carriers that cross the depletion region under the influence of the electric field (E) gain sufficient kinetic energy to be able to break the covalent bonds of atoms with which they collide. This results in EHPs generation and the process is called impact ionization.

- EHPs generated in turn may gain sufficient kinetic energy to cause additional impact ionizations and more EHPs generated, in an avalanche fashion. Hence, avalanche multiplication.

pn Junction – Breakdown Region

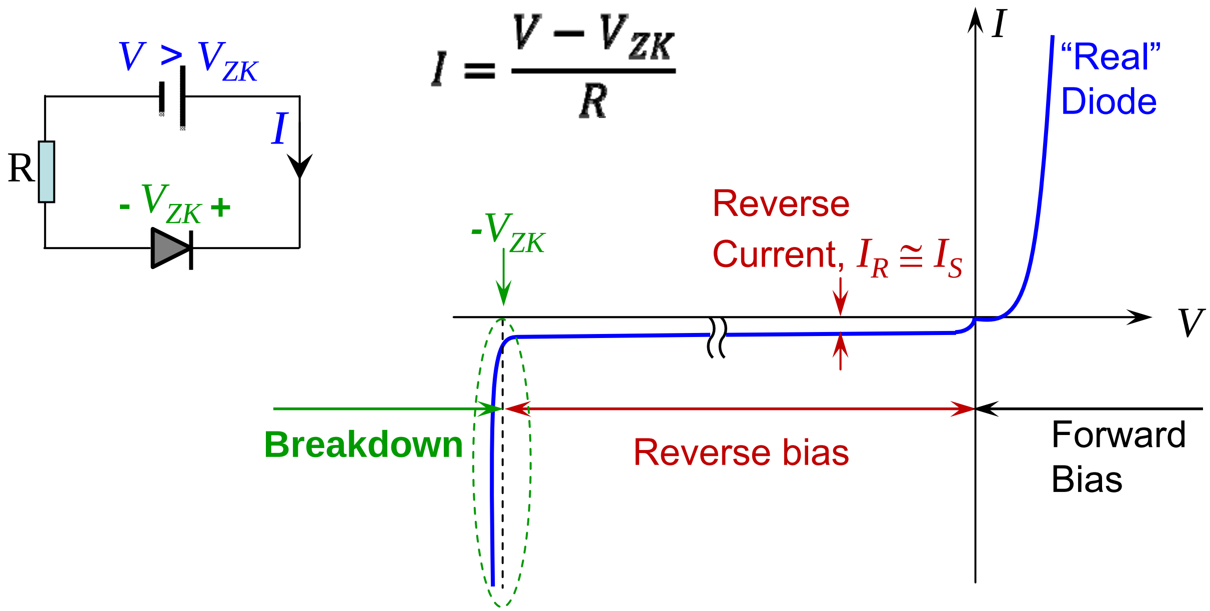


Avalanche breakdown

- Avalanche multiplication results in many EHPs generated in the depletion region, hence contributing to a large reverse current.

- The reverse current will be determined by the external circuit, with negligible increase in the *pn* junction voltage that remains close to V_{ZK}

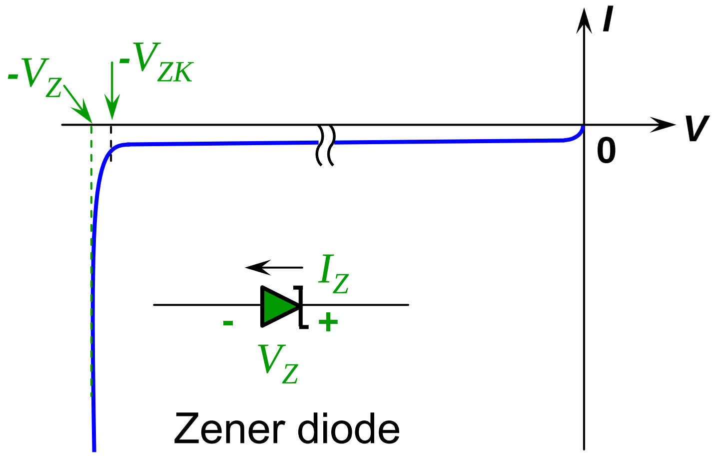
pn Junction – Breakdown Region

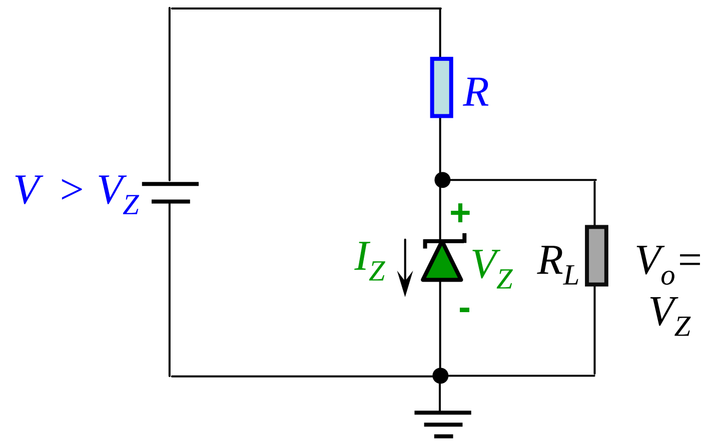


<u>Avalanche versus Zener breakdown</u>

- Avalanche breakdown requires high electric field **<u>and</u>** wide enough depletion region to allow sufficient travel distance for carriers to be accelerated to adequately high kinetic energy for impact ionization and multiplication.
- In contrast, Zener breakdown occurs in sufficiently narrow depletion region with high electric field.

pn Junction – Breakdown Region





<u>Zener diode as a voltage reference</u>

- Zener diodes are special diodes designed to operate in the breakdown region and they can be used in the design of voltage regulator (a circuit that provides a constant dc voltage between its terminals). Zener diodes are specified with V_Z, the breakdown voltage.

- In the above circuit, as long as $V > V_Z$ (meaning Zener diode operates in the breakdown region), the voltage across the load R_L is kept constant (or regulated) at $V_o = V_Z$ by the Zener diode.

- Virtually replaced by specially designed ICs that perform voltage regulation much more effectively and greater flexibility.

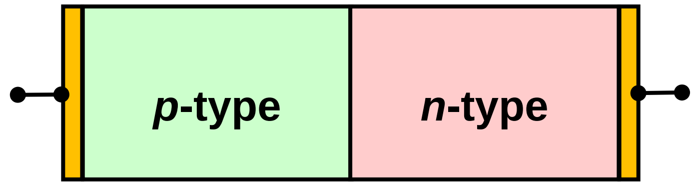
Appendix
***Has full equivalent explanations on both p and n side of pn* Junction**

These slides also contain corresponding slide numbers in the above notes.

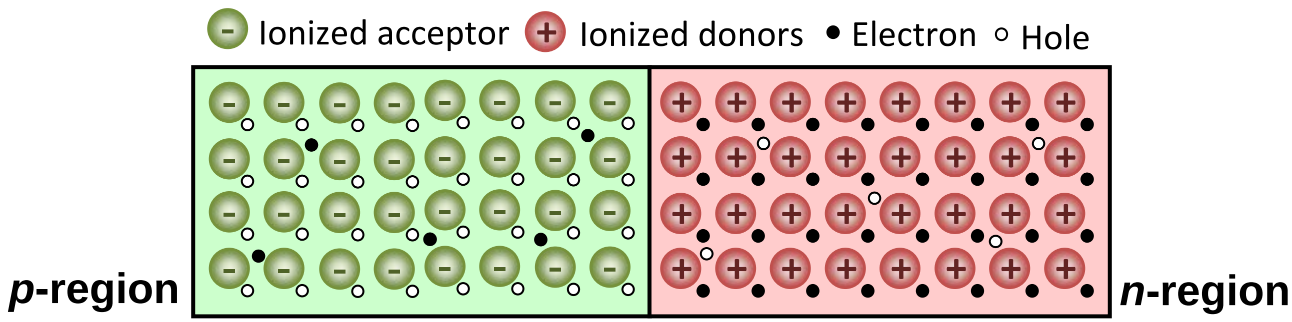
This table contains consolidated information on all slides in the appendix.

Appendix slide	Corresponding slide/s in the notes above
pn-1.45	pn-1.7
pn-1.46	pn-1.8
pn-1.47	pn-1.9
pn-1.48	pn-1.9,10
pn-1.49	pn-1.14

pn Junction – Open-Circuit Conditions



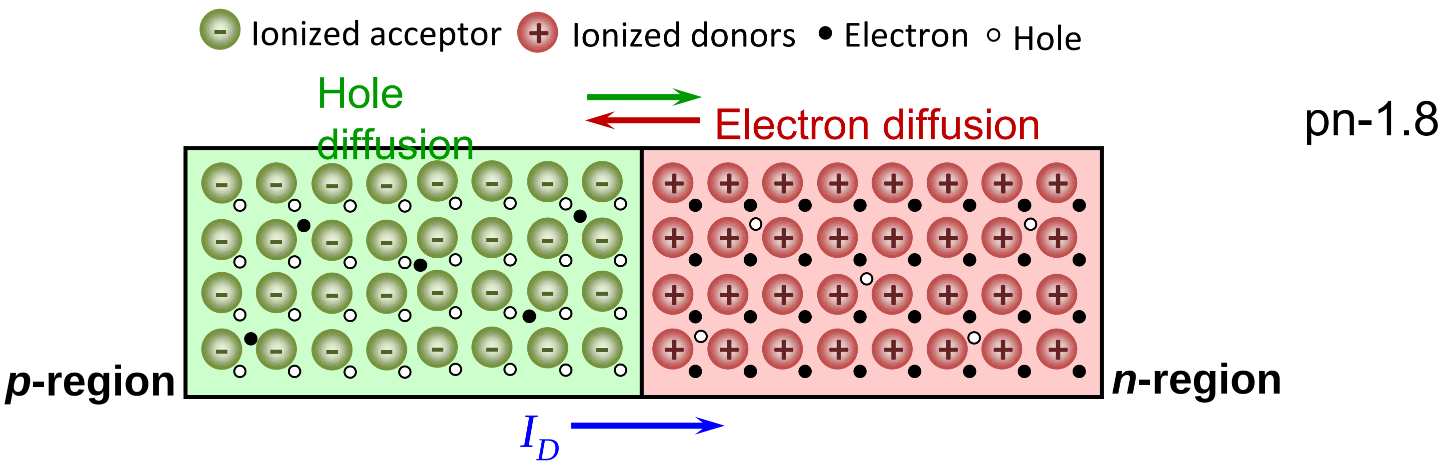
pn-1.7



- The *p*-region has
  - N_A negative bound ionized acceptors
  - $p_{p0} \approx N_A$ positive holes (many - majority carriers)
  - $n_{p0} \approx n_i^2/N_A$ negative electrons (few - minority carriers)
- Hence, electrically neutral

- The *n*-region has
  - N_D positive bound ionized donors
  - $n_{n0} \approx N_D$ negative electrons (many - majority carriers)
  - $p_{n0} \approx n_i^2/N_D$ positive holes (few - minority carriers)
- Hence, electrically neutral

pn Junction – Open-Circuit Conditions

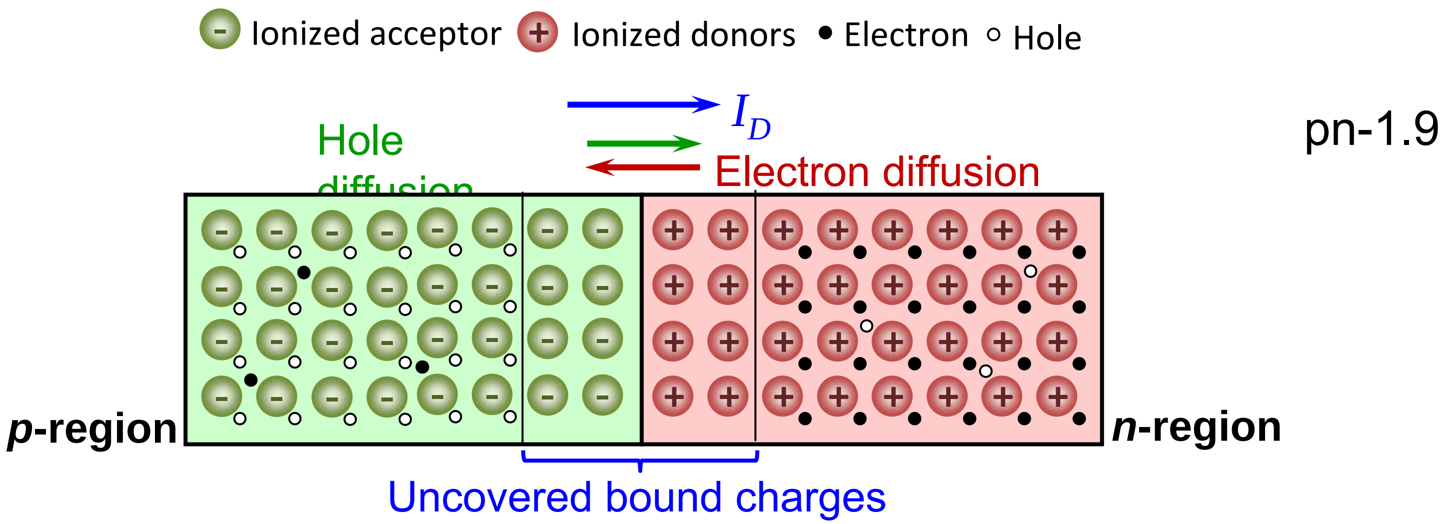


- The *p*-region has many more holes than the *n*-region (hole concentration gradient exists across the metallurgical junction).
- Hence holes diffuse from the *p*-region to the *n*-region

- The *n*-region has many more electrons than the *p*-region (electron concentration gradient exists across the metallurgical junction).
- Hence electrons diffuse from the *n*-region to the *p*-region

- The hole and electron diffusions add to form the diffusion current I_D (from the *p*-region to *n*-region). Note that I_D is due to majority carriers.

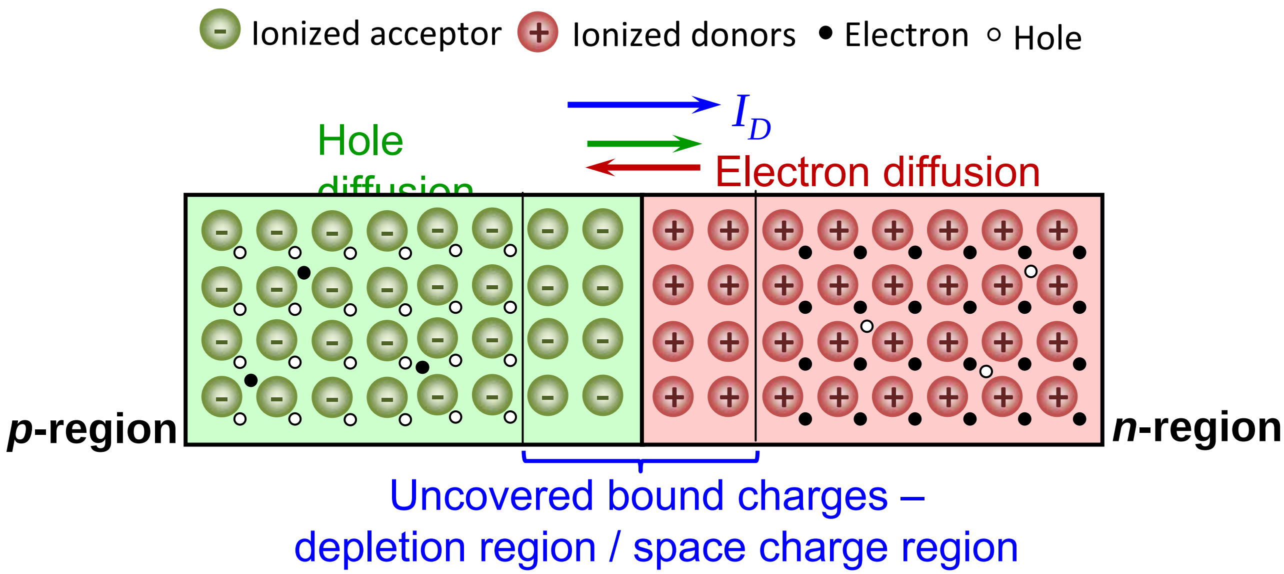
pn Junction – Open-Circuit Conditions



- Electrons that diffuse across the junction into the *p*-region recombine with some of the majority holes there
- Hence, some holes in the *p*-region near the junction disappear, resulting in the bound negative ionized acceptors being no longer neutralized by holes (i.e., uncovered)

- Holes that diffuse across the junction into the *n*-region recombine with some of the majority electrons there
- Hence, some electrons in the *n*-region near the junction disappear, resulting in the bound positive ionized donors being no longer neutralized by electrons (i.e., uncovered)

pn Junction – Open-Circuit Conditions

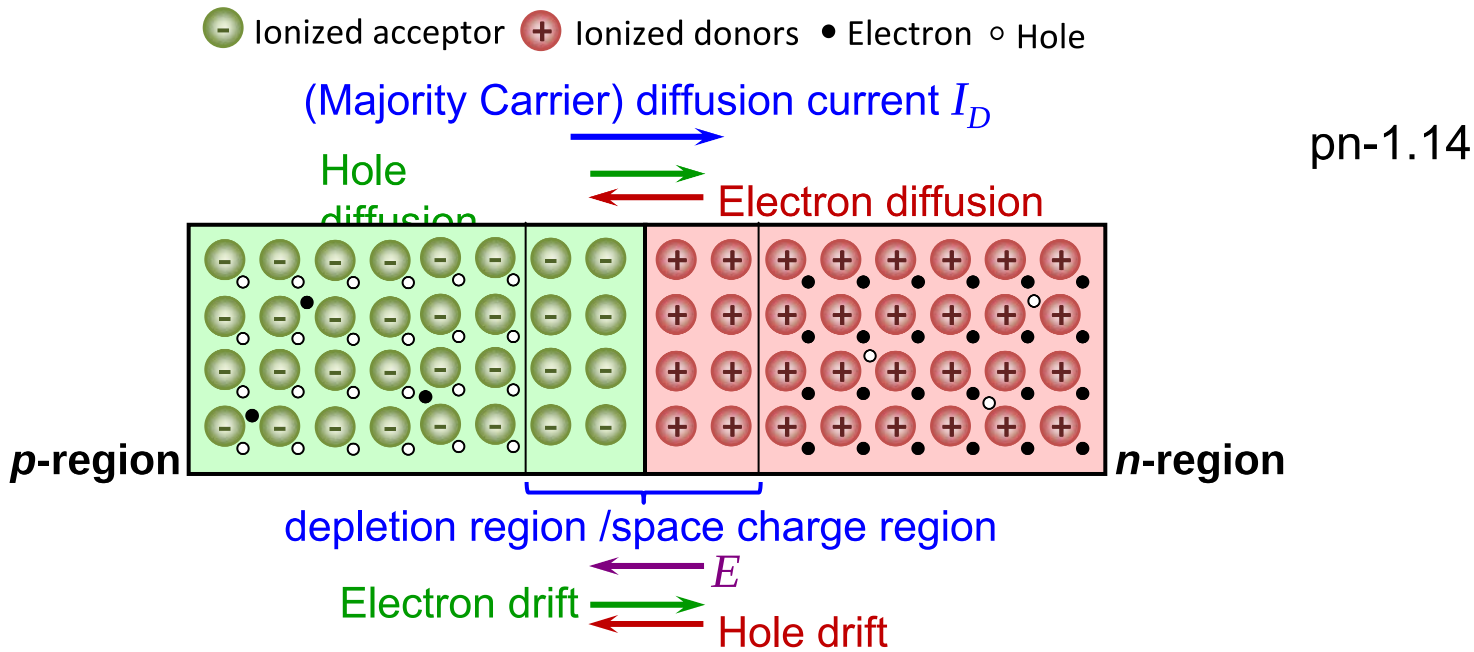


pn-1.9,10

- Region near the junction comprises uncovered bound negative ionized acceptors and is depleted of holes.
- Hence, region is known as the depletion region. It is also called the space charge region as it has negative charges (ionized acceptors).

- Region near the junction comprises uncovered bound positive ionized donors and is depleted of electrons.
- Hence, region is known as the depletion region. It is also called the space charge region as it has positive charges (ionized donors).

pn Junction – Open-Circuit Conditions



- Some thermally generated minority electrons in the *p*-region diffuse through the *p*-region to the edge of the depletion region, where electrons experience the electric field E and are swept across the depletion region into the *n*-region (drift of electrons).

- Some thermally generated minority holes in the *n*-region diffuse through the *n*-region to the edge of the depletion region, where holes experience the electric field E and are swept across the depletion region into the *p*-region (drift of holes).