ELC 1252 — Electronics

Lecture (3)
Semiconductors and PN Junctions

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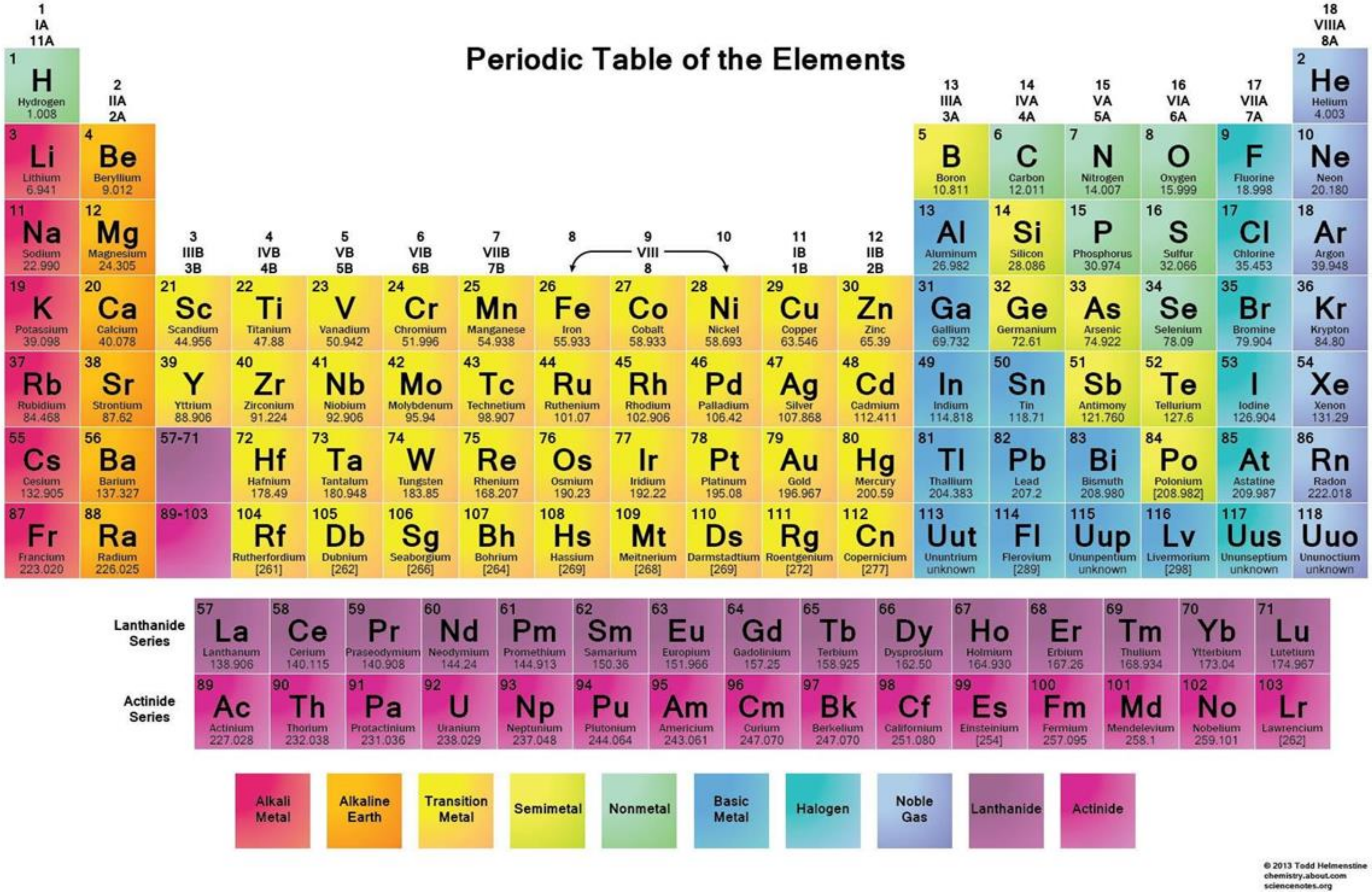
Lecture Outline

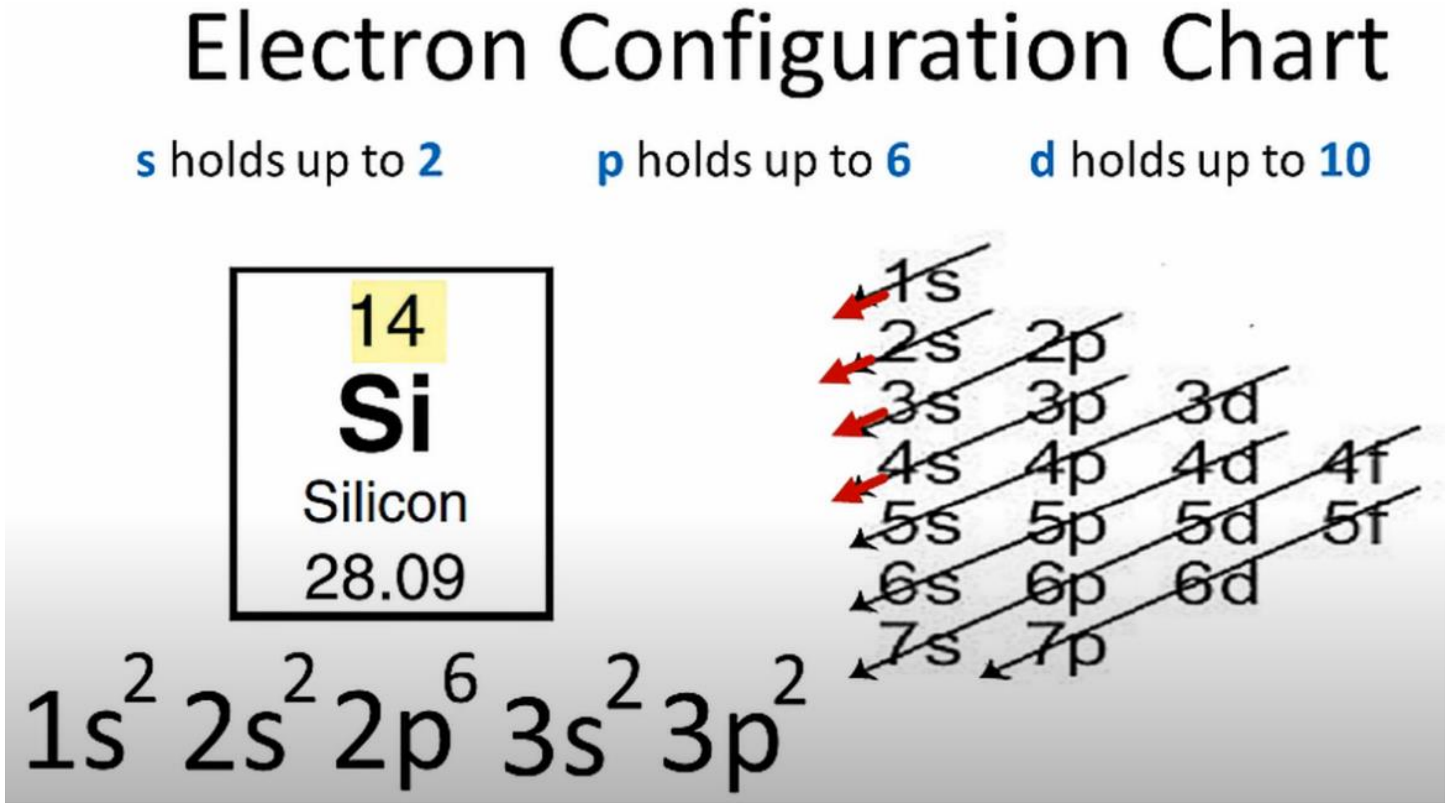
- Introduction to Semiconductor
- PN junction
- Zener diode

- Intrinsic Semiconductors



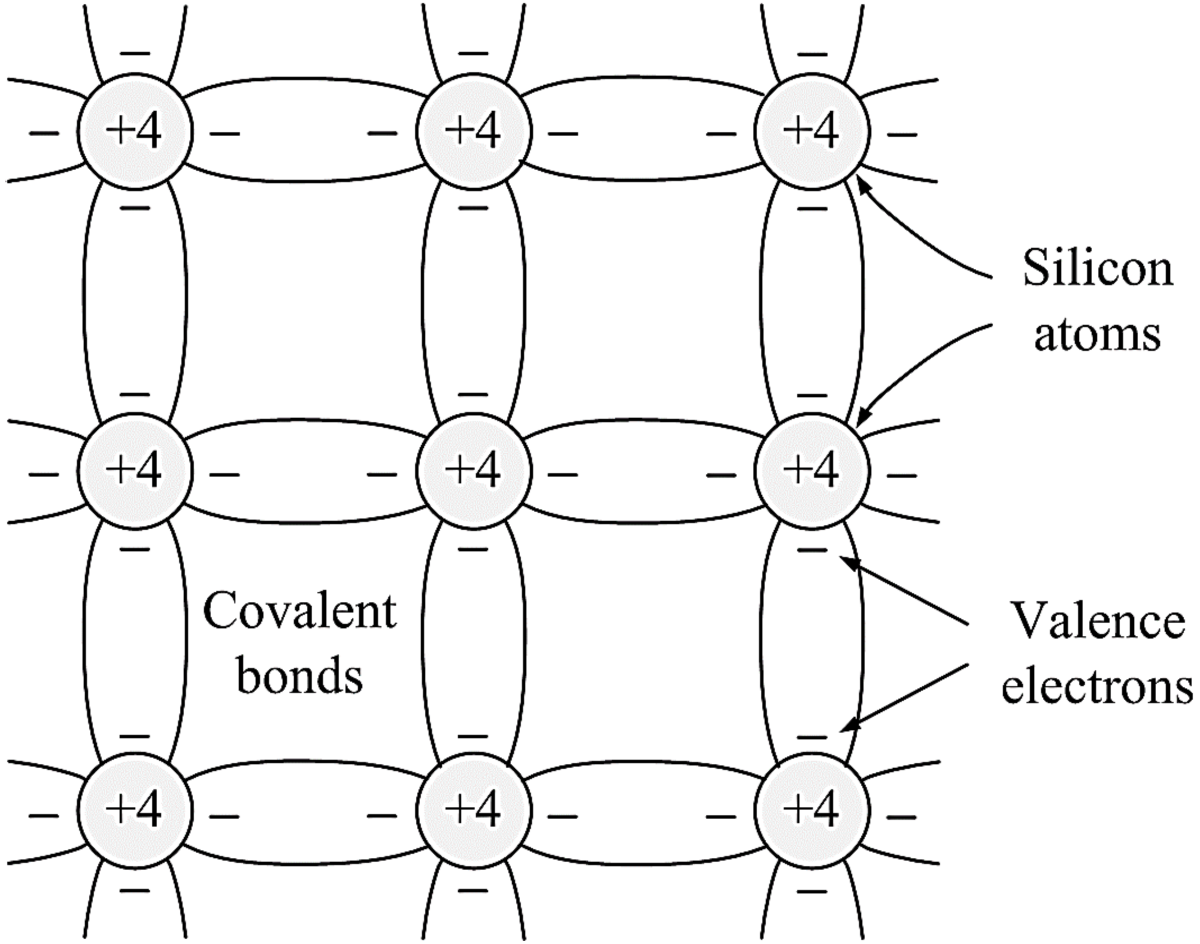
Silicon

- Silicon atomic number is 14 with the shown electron configuration chart
- The outer orbit (3s and 3p) can hold up to 8 electrons, but it only has 4.
- An intrinsic silicon is one which is made of the silicon material in its greatly pure form.



Intrinsic Semiconductors

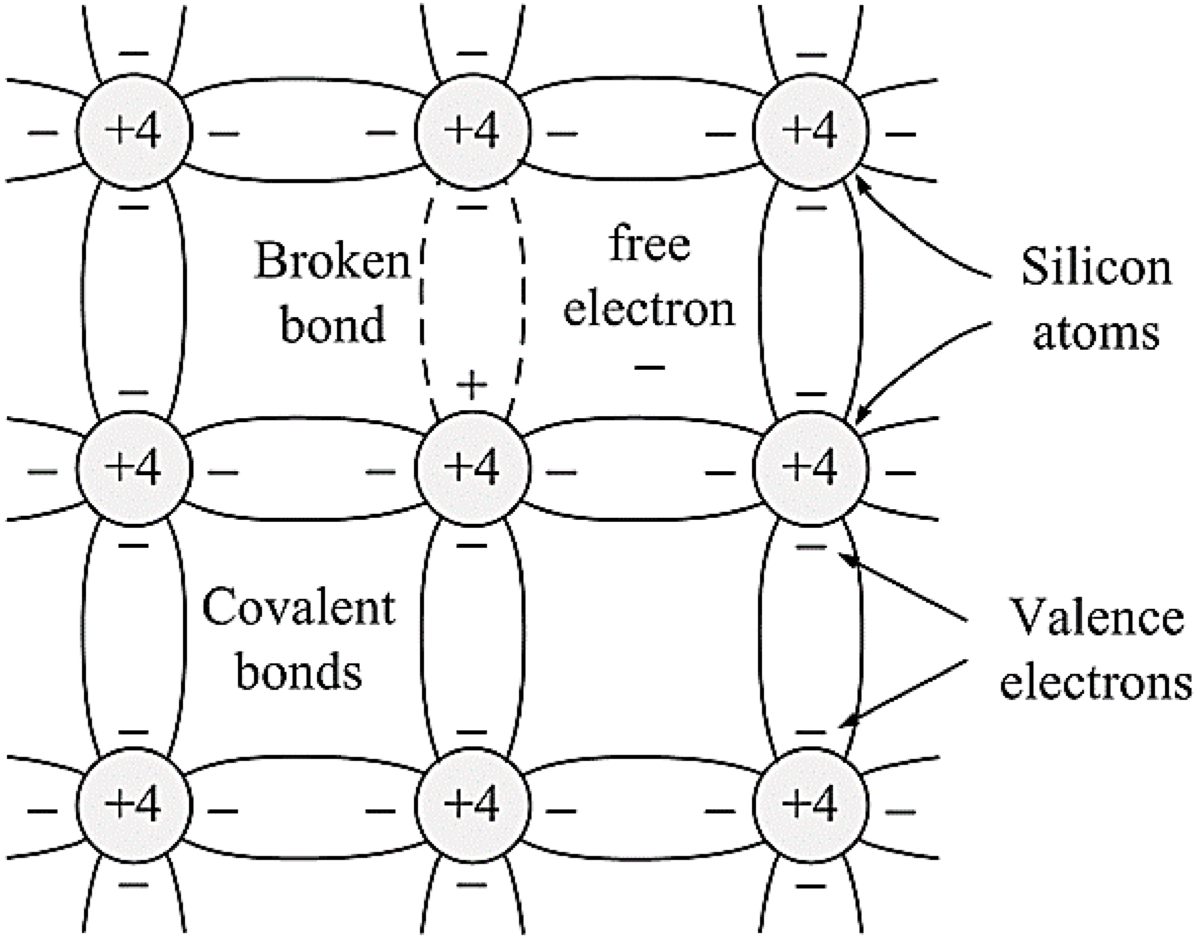
- A silicon atom has four valence electrons.
- To complete its outermost shell, it shares one of its valence electrons with each of its four neighboring atoms.
- Each pair of shared electrons forms a **covalent bond**.



Introduction to Semiconductor

Intrinsic Semiconductors

- At room temperature, sufficient thermal energy exists to break some of the covalent bonds, this process is known as **thermal generation.**

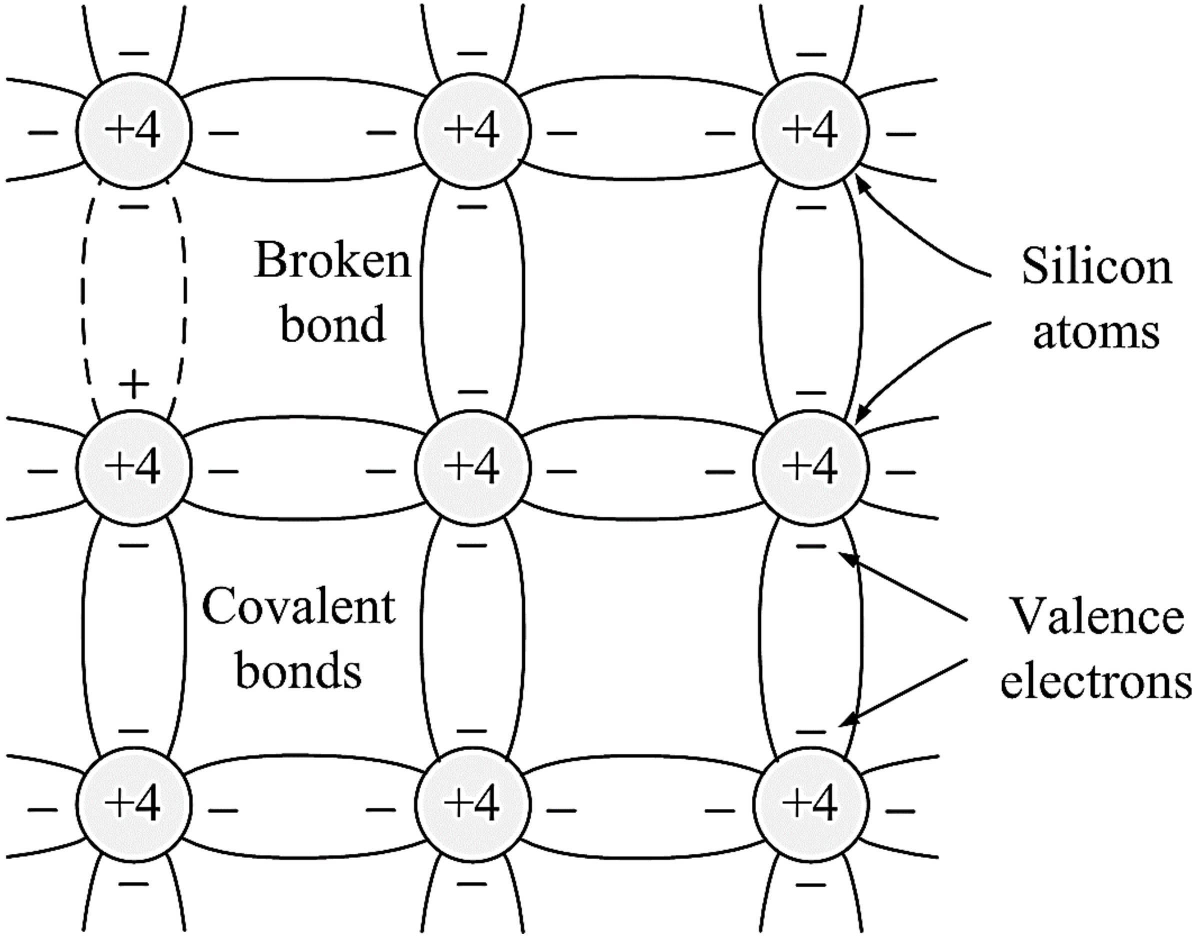


- If an electric field is applied to the crystal, the free electron will move, and a current will follow.

Intrinsic Semiconductors

- The positive charge attracts an electron from a neighboring atom.

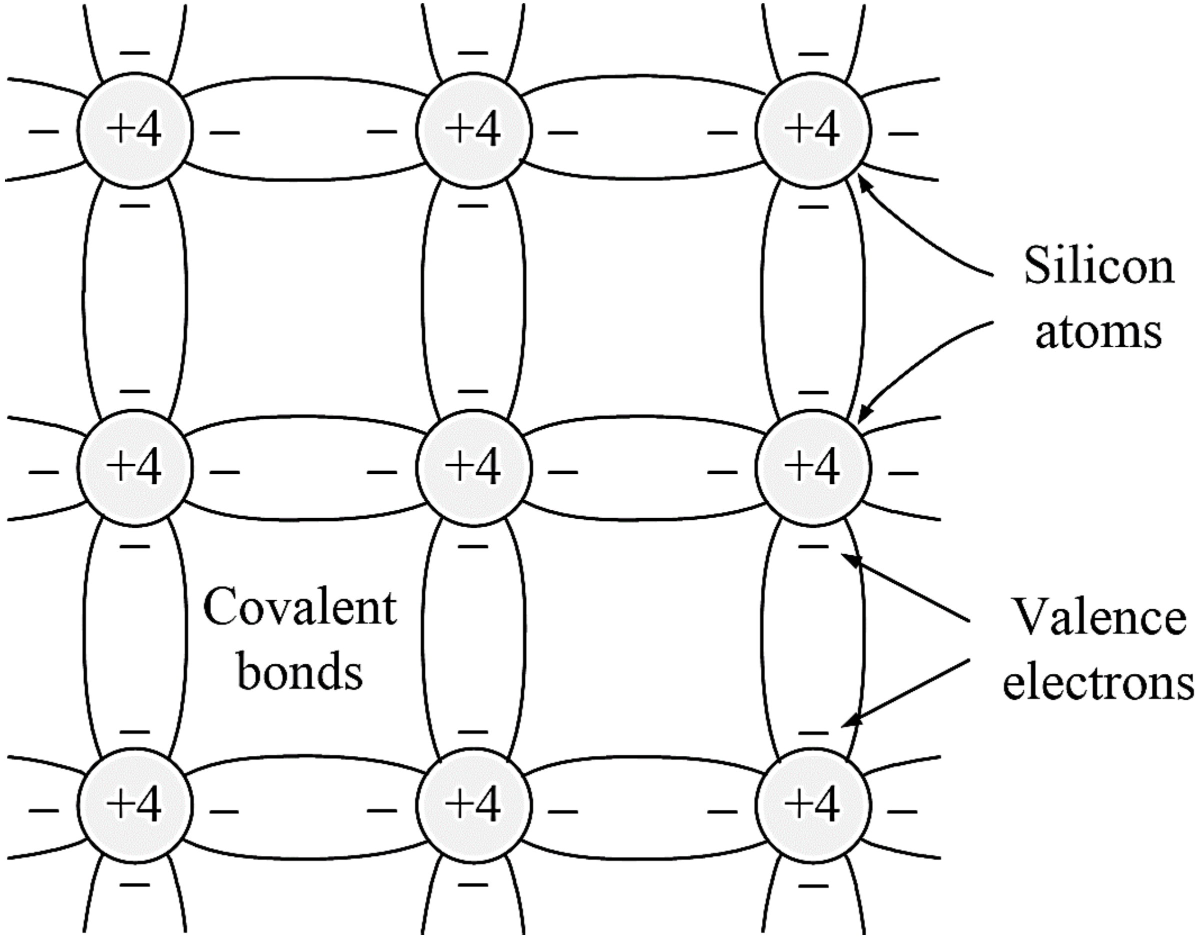
- This process repeats itself, and results in a moving positively charged through the silicon crystal structure.



Intrinsic Semiconductors

- The free electrons and holes move randomly through the silicon crystal structure, and in the process some electrons may fill some of the holes. This process, called **recombination**.

- In thermal equilibrium, the recombination rate is equal to the generation rate.

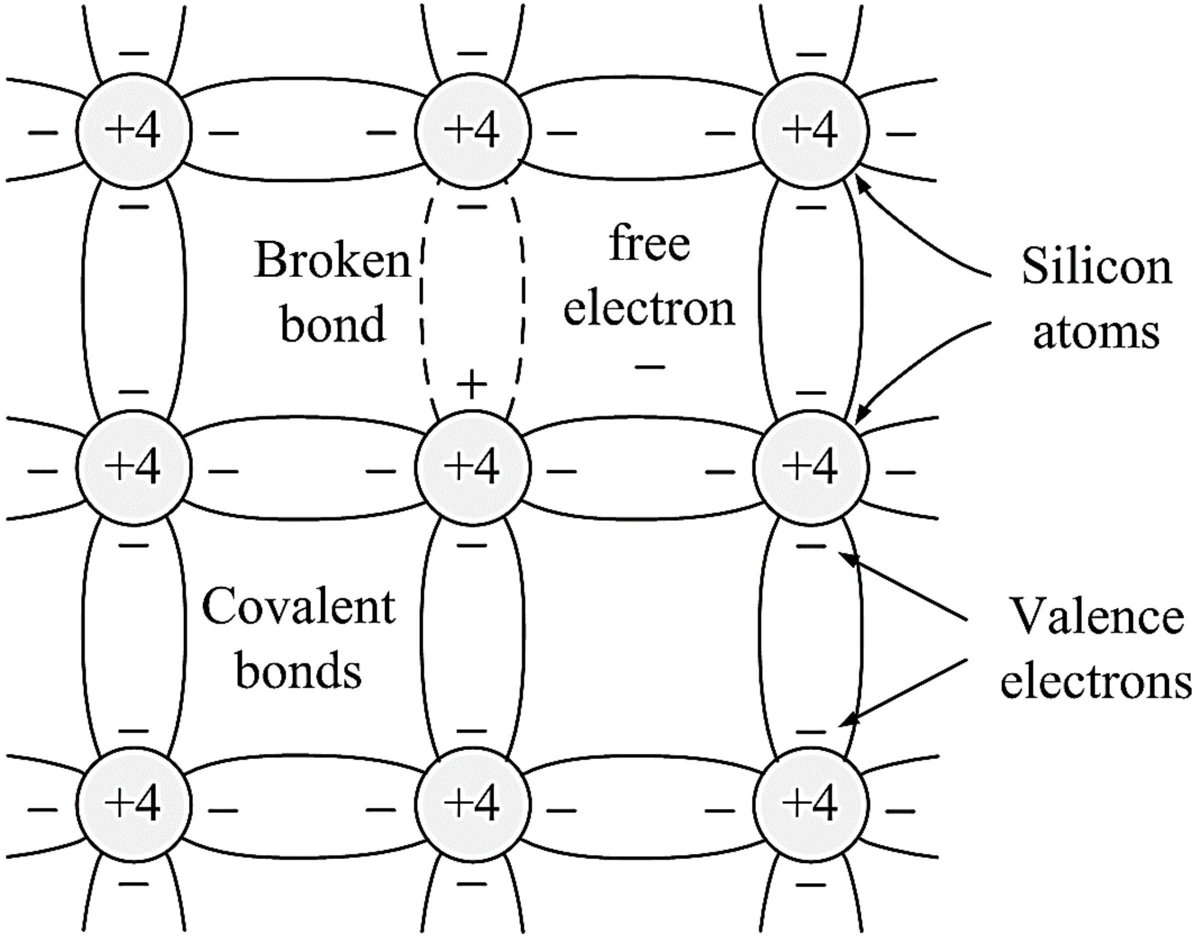


Introduction to Semiconductor

Intrinsic Semiconductors

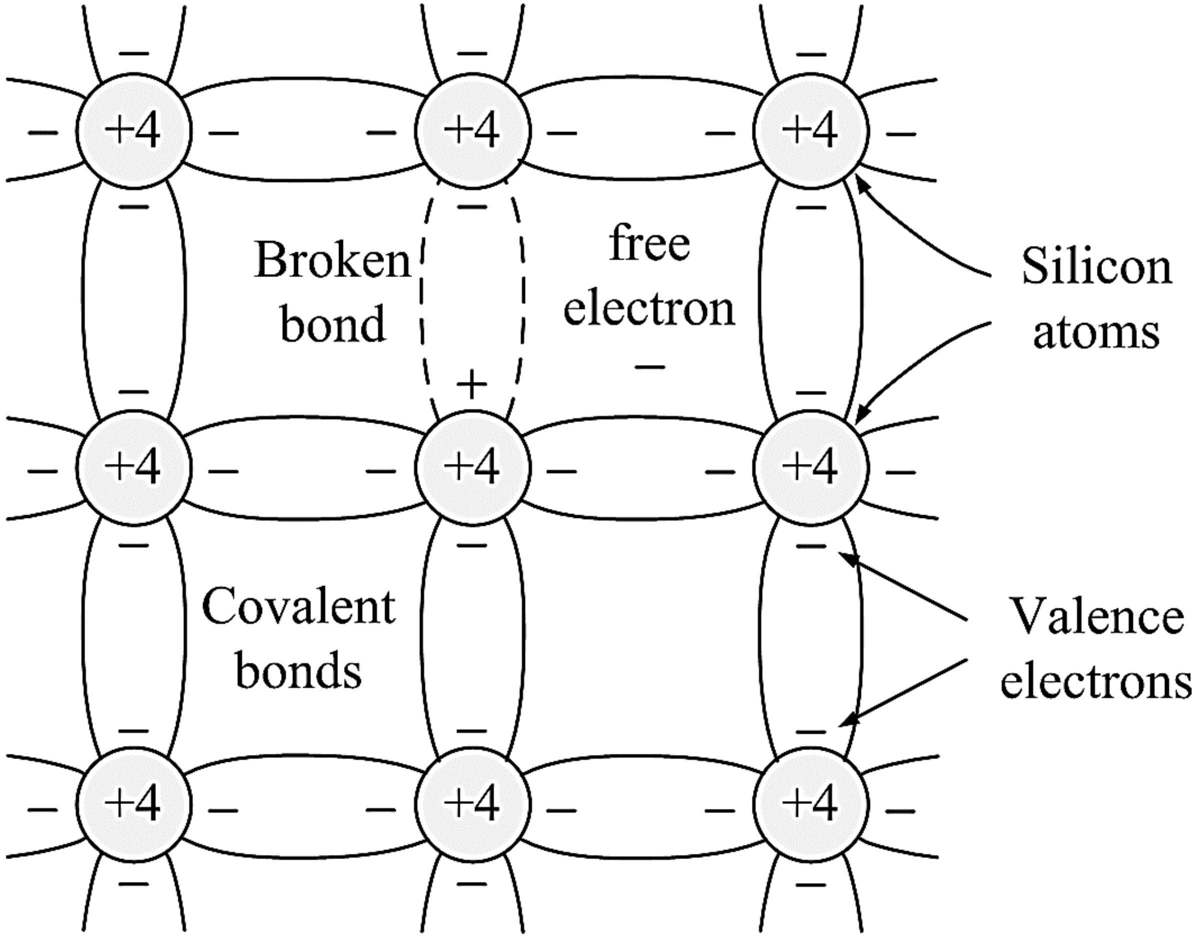
- The concentrations of the free electrons and holes are **far too small** for silicon to conduct appreciable current at room temperature.

- The carrier concentration are strong function of the temperature, this is not a desirable property in an electronic device.



Doped Semiconductors

- Doping means introducing impurity atoms into the silicon crystal in sufficient numbers.
- The goal is to substantially increase the concentration of either free electrons or holes.
- The structure of the crystal needs to be kept the same.

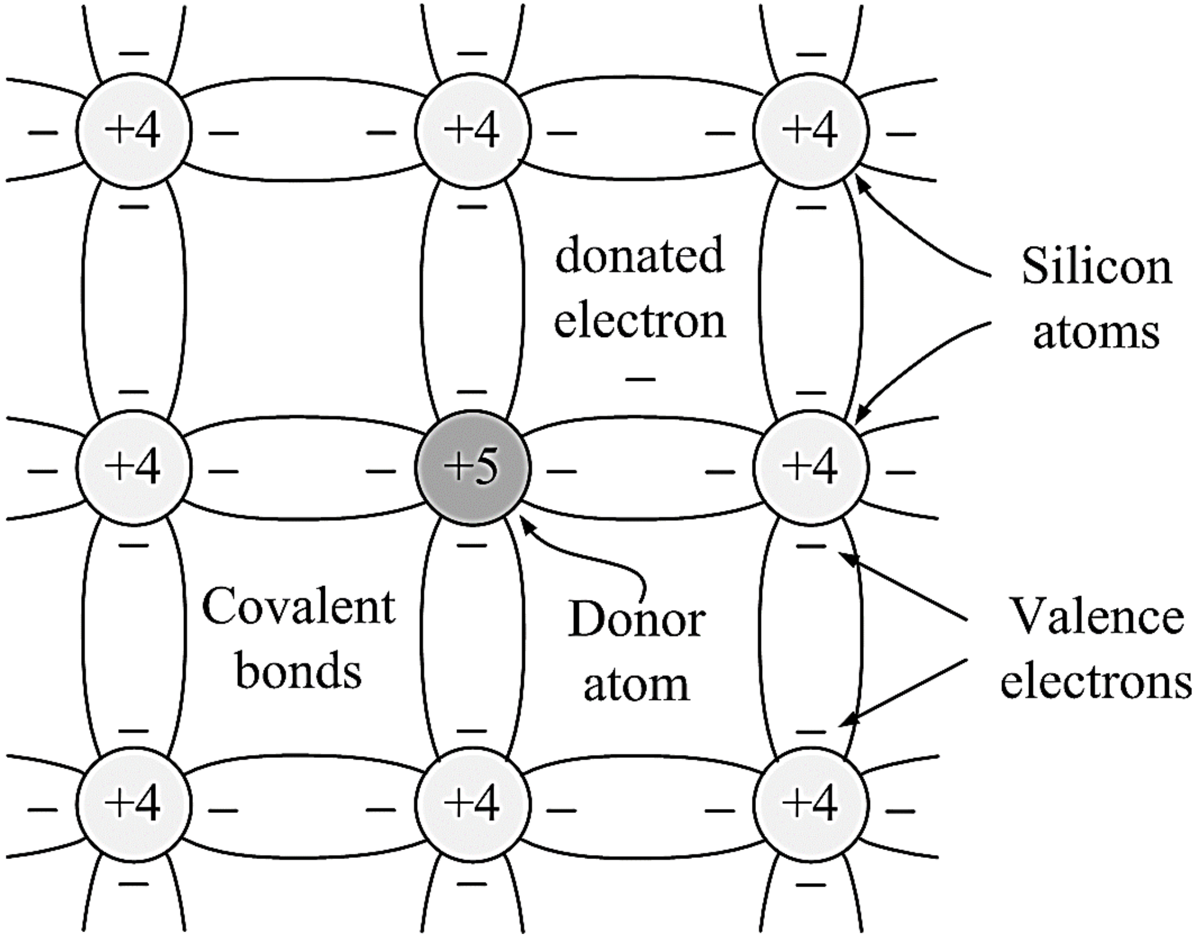


Doped Semiconductors

- The concentration of free electrons silicon is increased by doped the silicon with an element with a **valence of 5**, such as phosphorus.

- The fifth electron becomes a free electron.

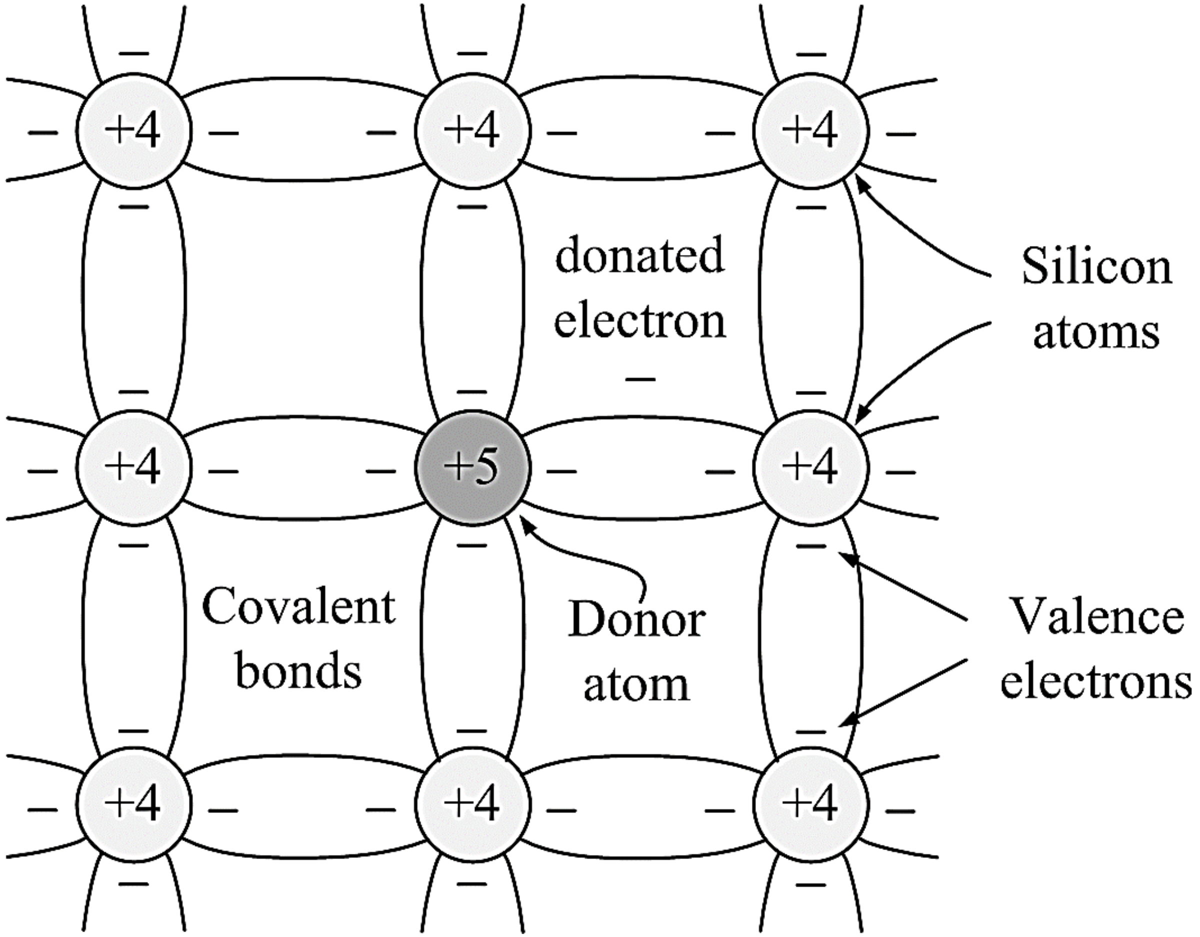
- The resulting doped silicon is then said to be of **n-type**.



Doped Semiconductors

- In n-type silicon, electrons are said to be the **majority carriers** and holes are the **minority carriers**.

- The **n-type** silicon is electrically neutral because the total negative charge is equal to the total positive charge.



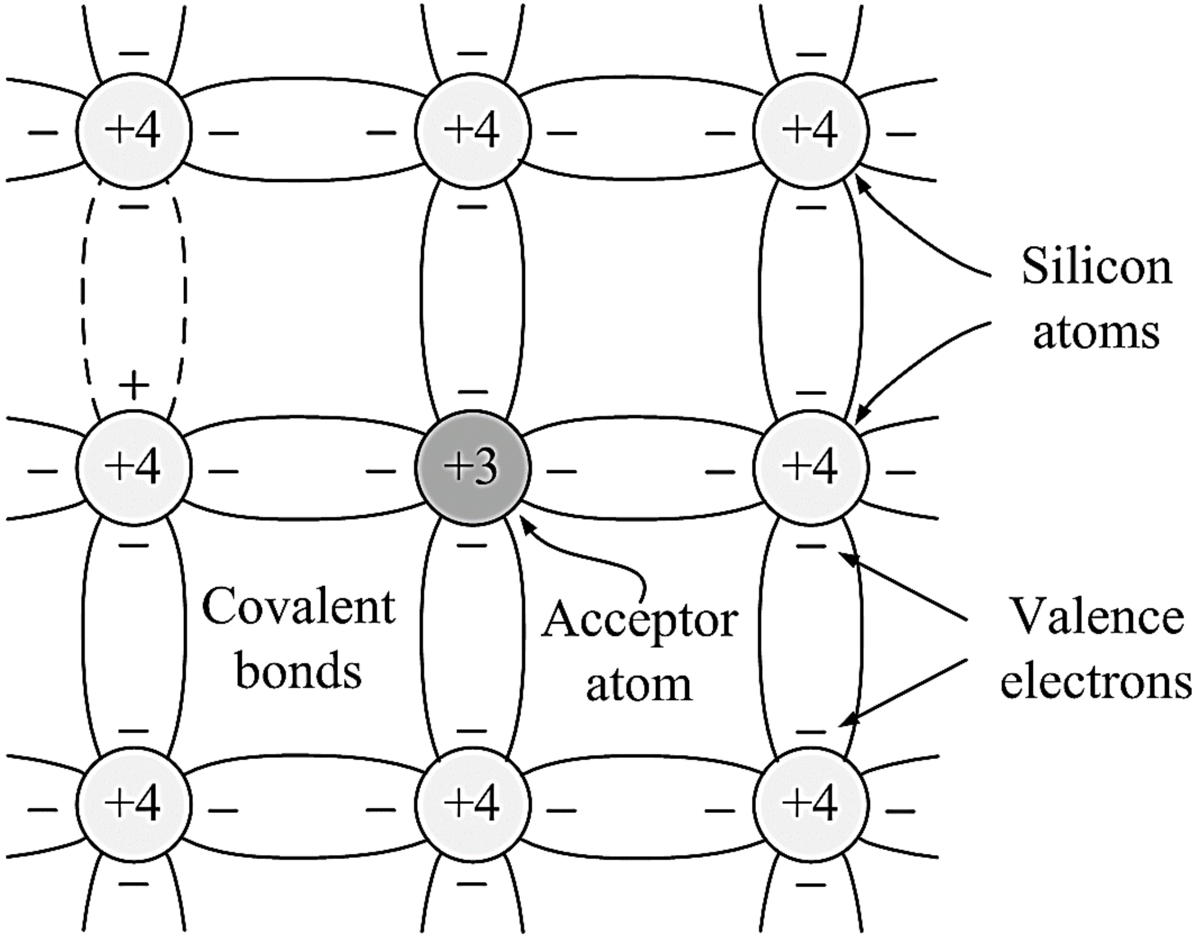
Introduction to Semiconductor

Doped Semiconductors

- The concentration of holes in the silicon is increased by doping the silicon with an element having a **valence of 3**, such as boron.

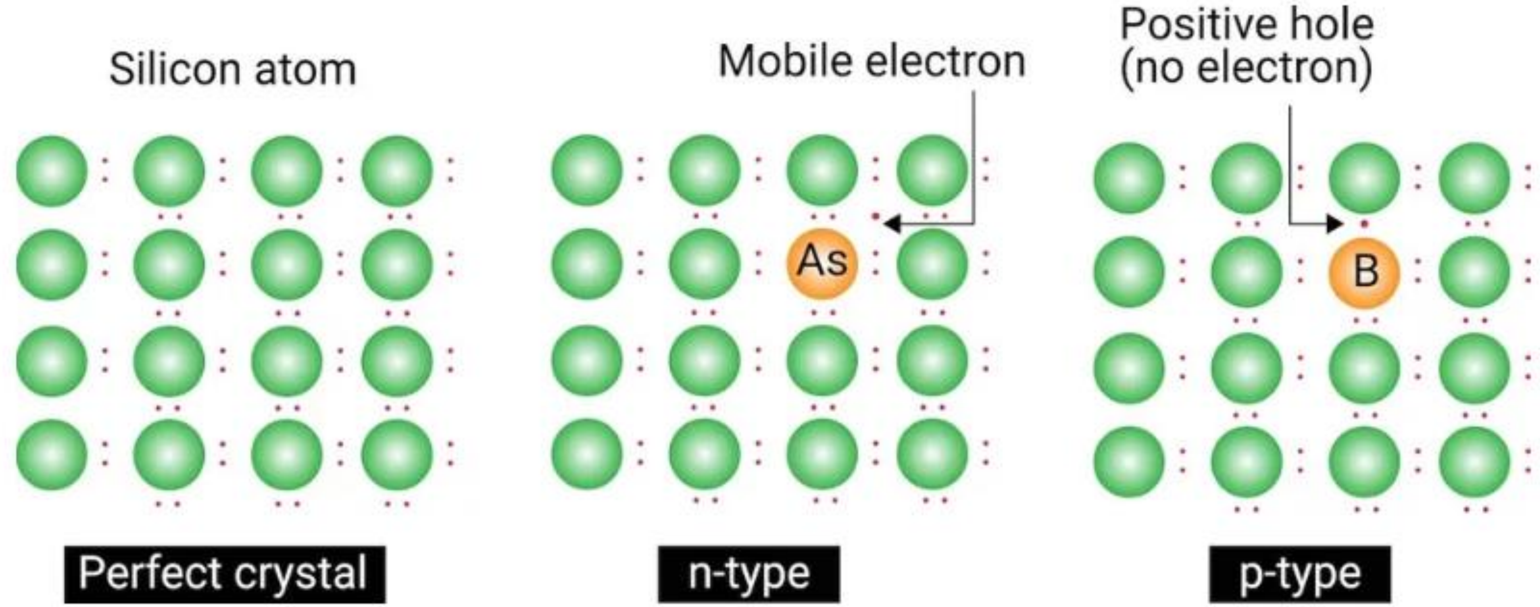
- The resulting doped silicon is said to be of **p-type**.

- In p-type silicon, holes are said to be the majority carriers and electrons are the minority carriers.



P-Type versus N-Type Silicon Substrate

- An extrinsic silicon is doped by a specific impurity which is able to modify its electrical properties.
- **The N-type silicon:** a type of extrinsic silicon doped with a pentavalent (having five valence electrons) impurity element such as Phosphorus, Arsenic and Antimony. The dopant elements are added in the N-type silicon so as to increase the number of free electrons for conduction.
- **The P-type Silicon:** formed when a trivalent (having three valence electrons) impurity such as Gallium and Indium is added to a pure silicon in a small amount, and as a result, a large number of holes are created in it.



4 covalent bonds | N charge carriers | P charge carriers

Illustrative Semiconductor Animation

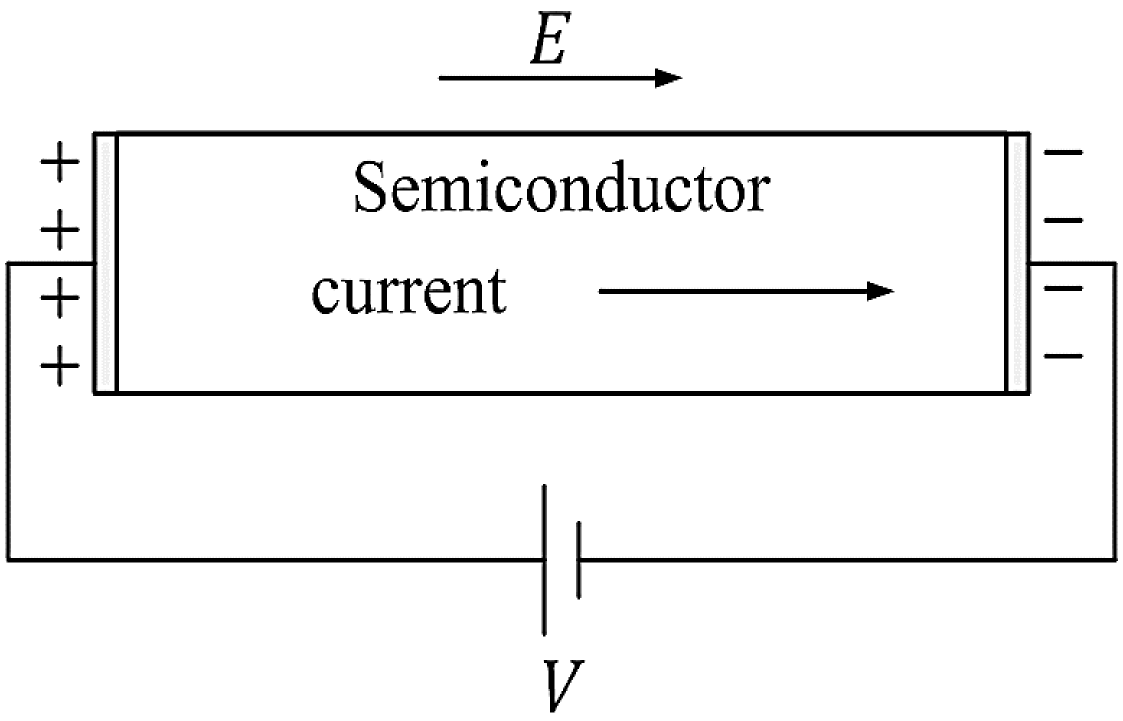
- Intrinsic Semiconductor:
  - YouTube Link:
    https://www.youtube.com/watch?v=gRV-KDy4sHQ&ab_channel=7activestudio

- Extrinsic Semiconductors:
  - YouTube Link:
    https://www.youtube.com/watch?v=s6rQI7t9XM4&ab_channel=7activestudio

Current Flow in Semiconductors

Drift Current

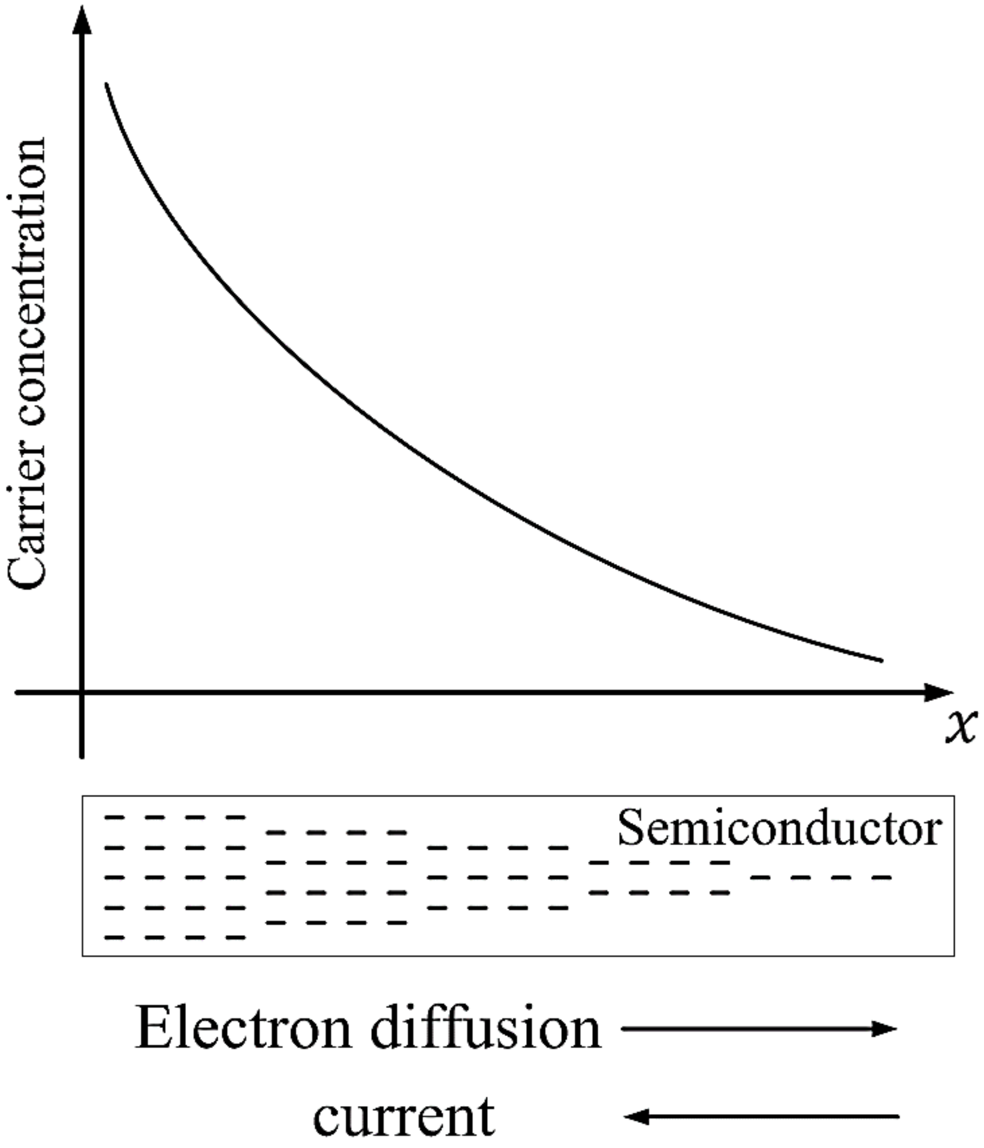
- The mobility represents the degree of ease by which the carrier (electron/hole) moves through the silicon crystal in response to the electrical field E.
- μ_p: the holes mobility
- μ_n: the electrons mobility
- μ_n is found to be $\sim 2.5 \times \mu_p$



Current Flow in Semiconductors

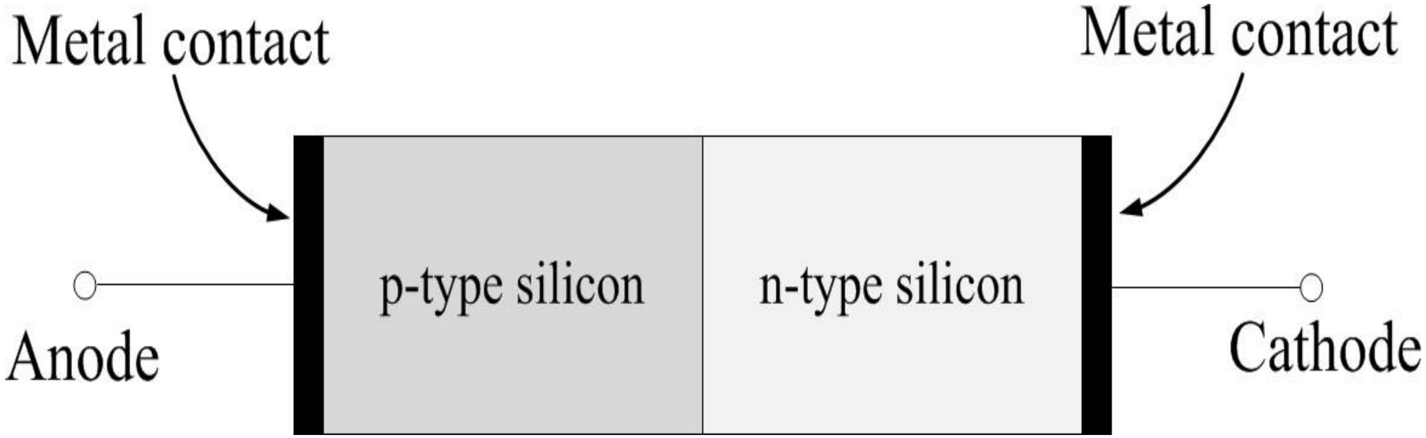
Diffusion Current

- When the density of charge carriers in a piece of semiconductor is not uniform, carrier diffusion occurs.
- The magnitude of the current at any point is proportional to the slope of the concentration curve at that point.



The PN Junction

Physical Structure

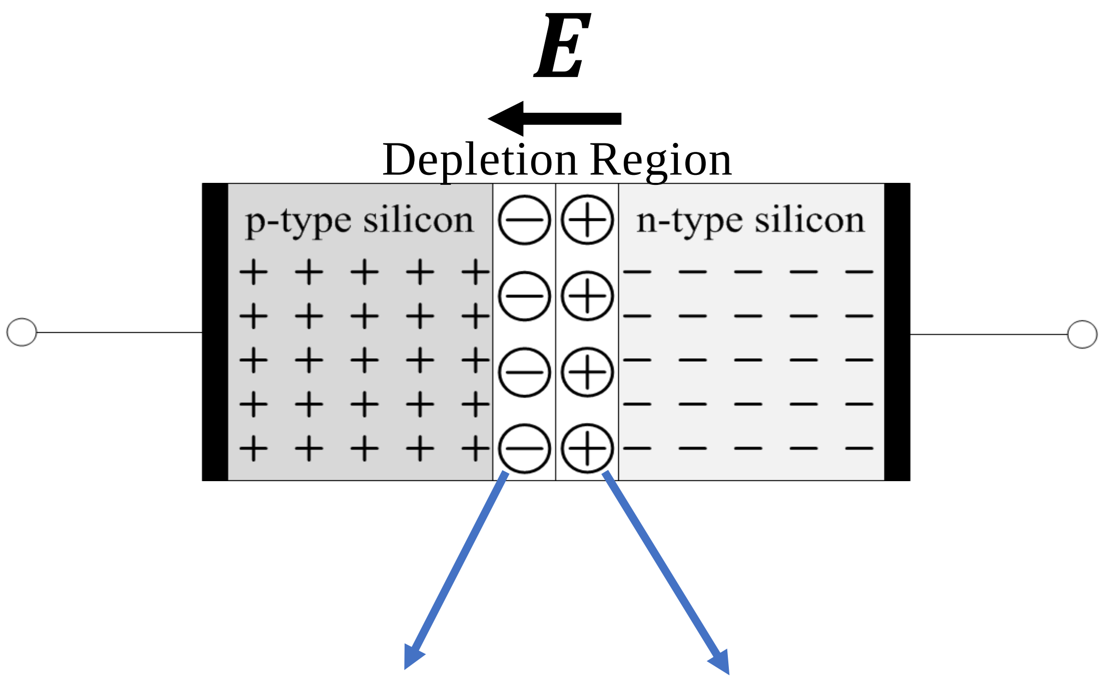


- The $\boldsymbol{pn}$ junction consists of a $\boldsymbol{p-type}$ semiconductor brought into close contact with an $\boldsymbol{n-type}$ semiconductor.
- In actual practice, the $\boldsymbol{pn}$ junction is formed within a single silicon crystal by creating regions of different doping.

The PN Junction

Operation with Open-Circuit Terminals

- <u>The Diffusion of Carriers</u>
- In the ***n*** region, the concentration of electrons is higher than that in the ***p*** region.
- Thus, the electrons diffuse from the ***n*** region to the ***p*** region.
- Similarly, the holes diffuse from the ***p*** region to the ***n*** region.



-ve Ions

Acceptors
Lost
Holes
(received
electrons)

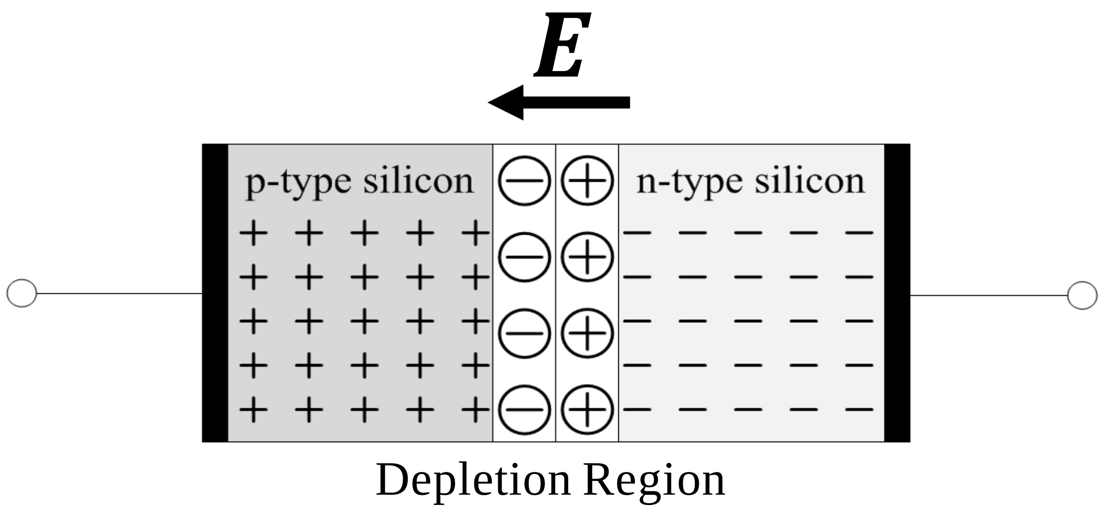
+ve Ions

Donors
Lost
Electrons
(received
holes)

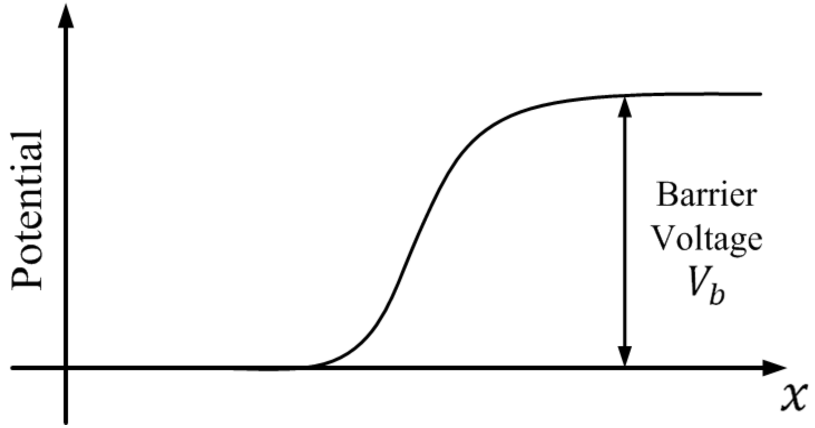
The PN Junction

Operation with Open-Circuit Terminals

- <u>The Diffusion of Carriers</u>
- The resulting electric field opposes the diffusion of holes into the ***n*** region and electrons into the ***p*** region.



- The larger the barrier voltage, the lower the magnitude of the diffusion current.



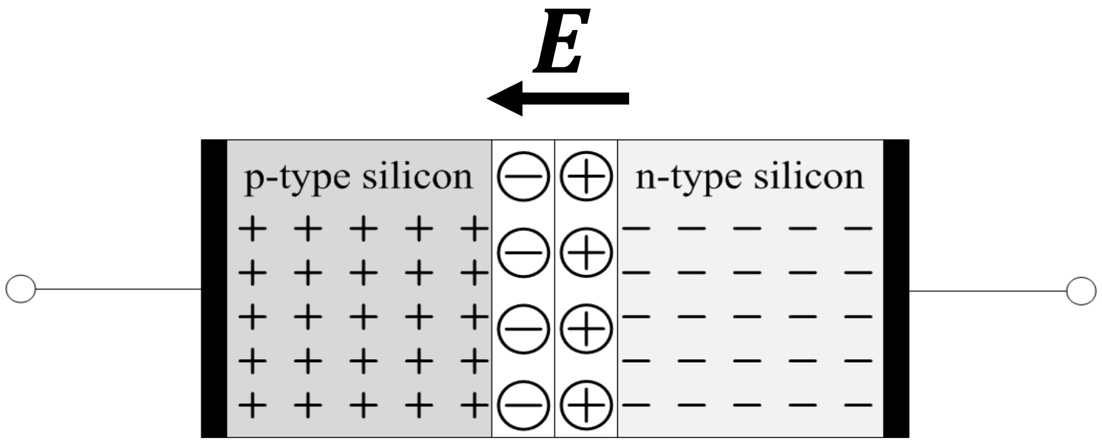
- Typically, $V_b = 0.7V$

The PN Junction

Operation with Open-Circuit Terminals

- <u>In Equilibrium:</u>

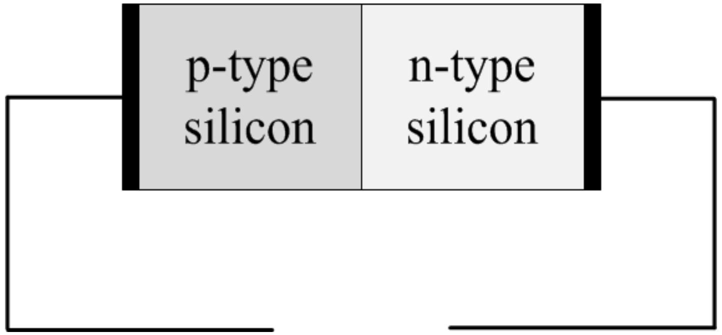
The diffusion current I_D resulting from the diffusion of majority carriers is equal to the drift current I_S resulting from the drift of the minority carriers across the junction.

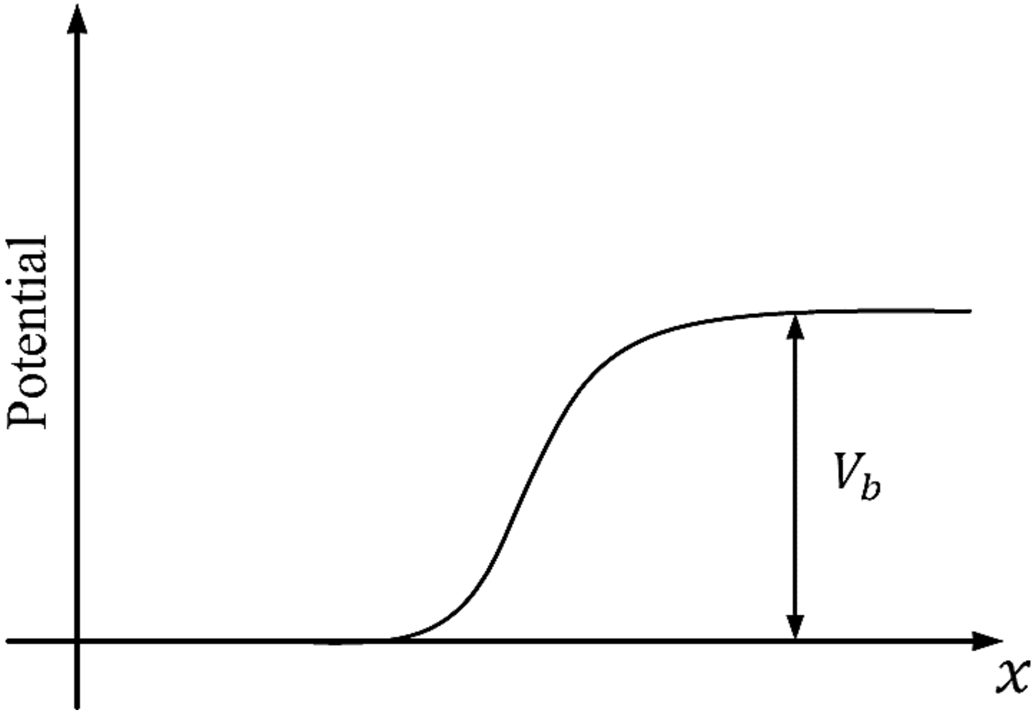


Depletion Region

The PN Junction

Operation with Open-Circuit Terminals

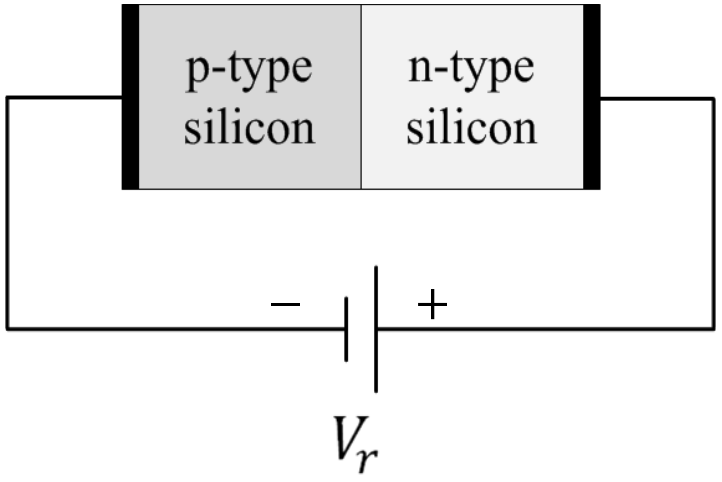


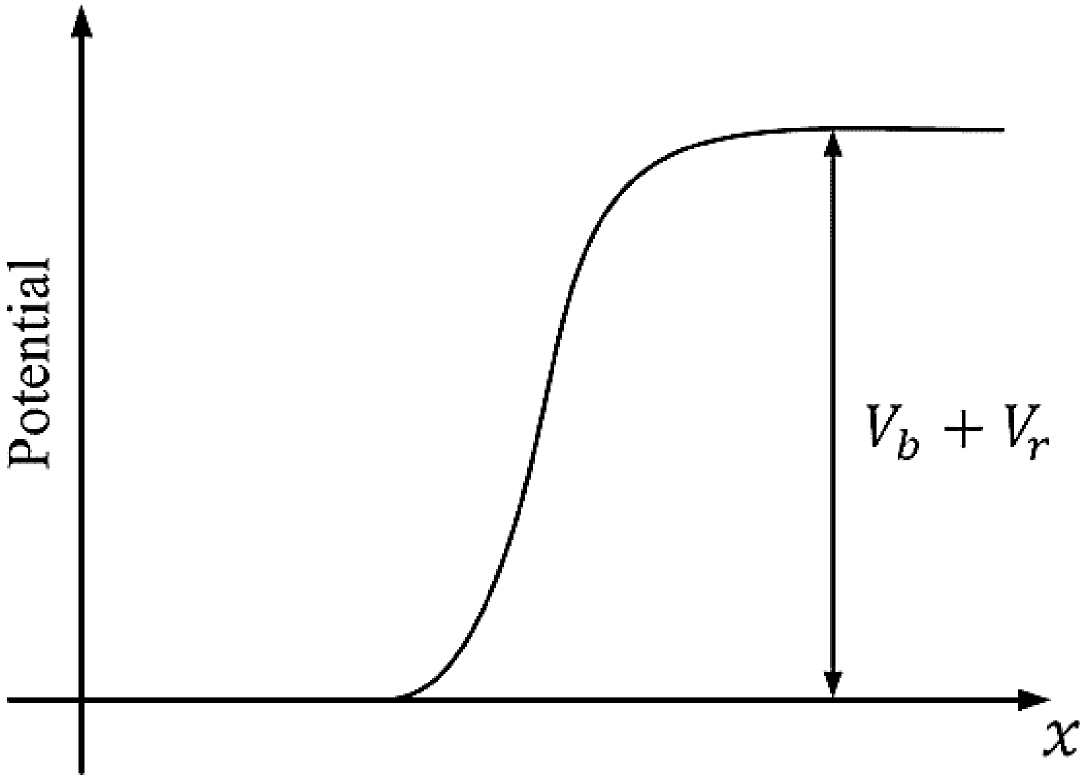


- $\boldsymbol{I_D = I_S}$
- $\boldsymbol{I = 0}$

The PN Junction

The PN Junction with an Applied Voltage



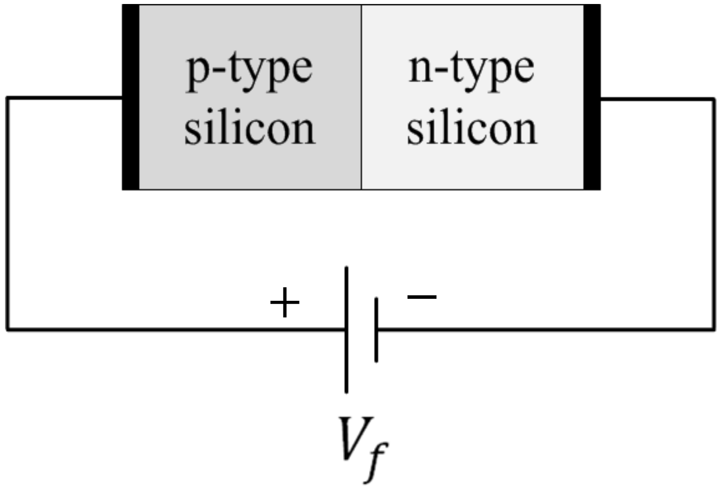


Reverse Biasing:

- $I_D = 0$.
- I_S depends on the minority carriers.
- It is very small and can be neglected.
- Thus $I = 0$.

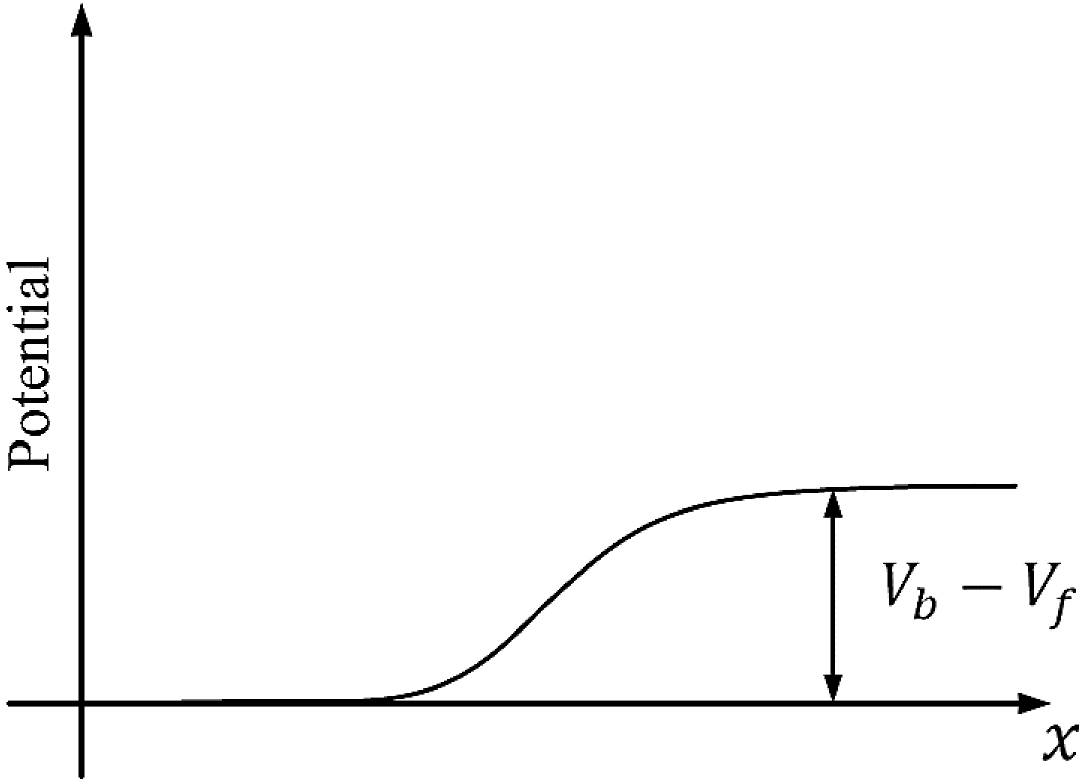
The PN Junction

The PN Junction with an Applied Voltage



Forward Biasing:

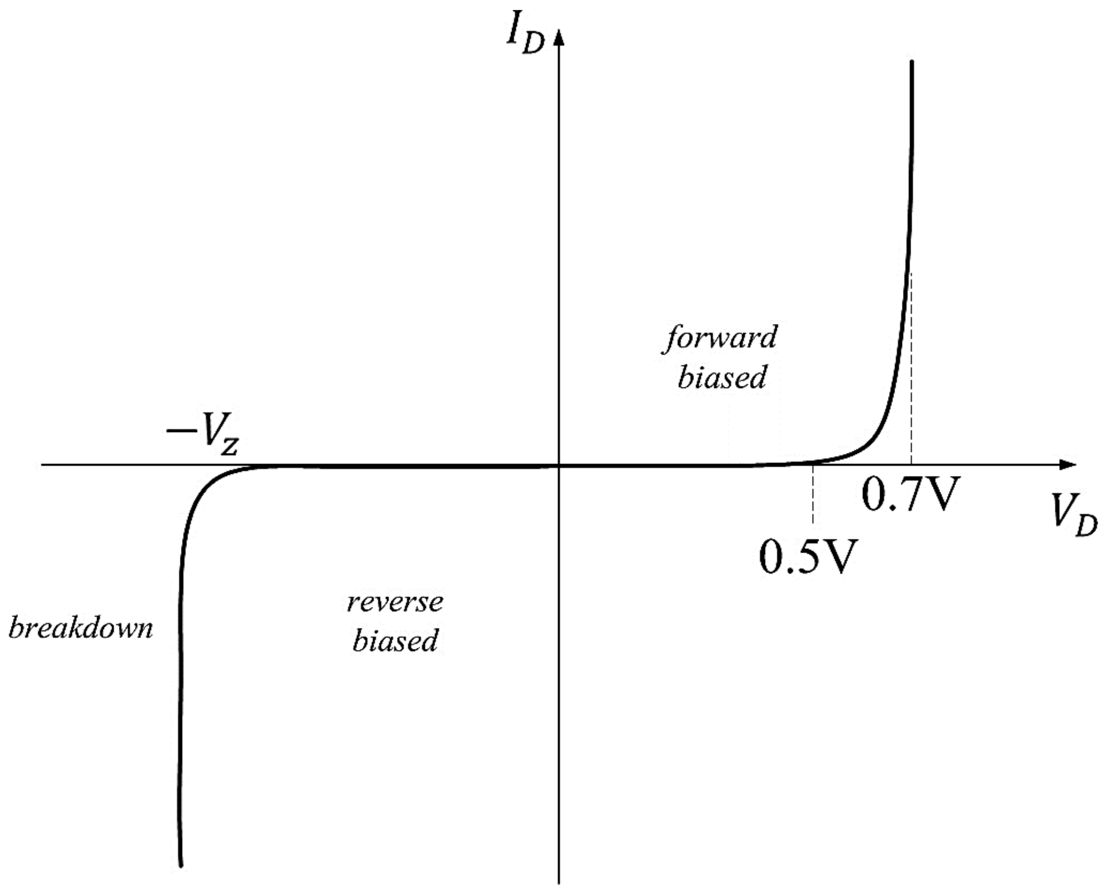
- I_D increases as V_f increases.
- Thus $I = I_D$. (neglecting I_S)



The PN Junction

Diode DC Large Signal Model

- $I_D = I_S\left(e^{V_D/V_T} - 1\right)$
  - $V_T = \frac{KT}{q} = 25mV$
  - $K = 1.38 \times 10^{-23}\, JK$
    - Boltzmann constant
  - $T = 300^o\ K$
    - Absolute room temperature
  - $q = 1.6 \times 10^{-19} C$
    - Electron charge

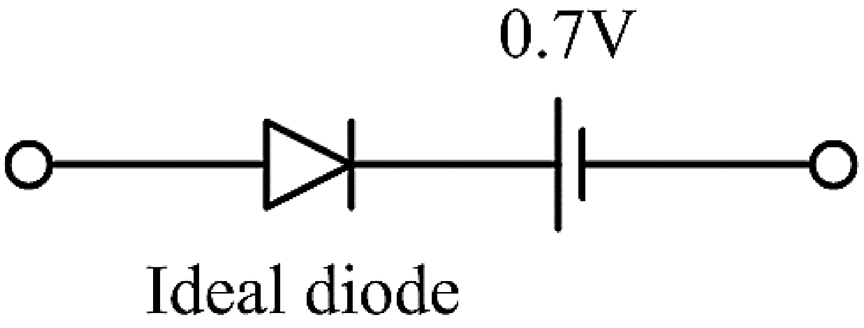


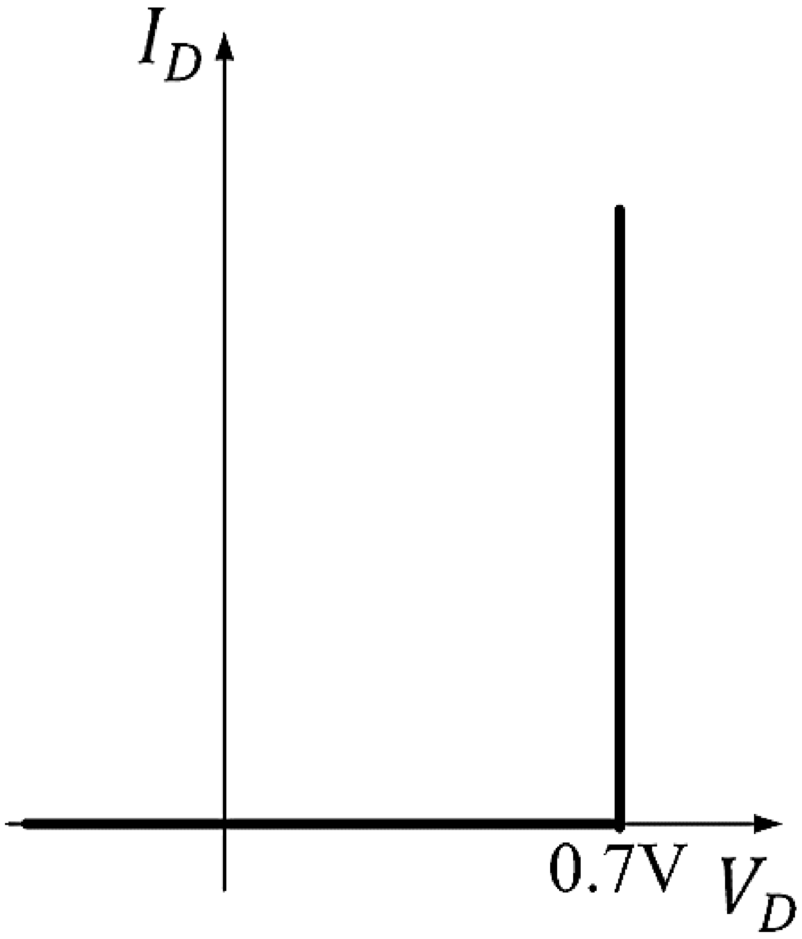
- Forward Bias:
  - $I_D \approx I_S\, e^{V_D/V_T}$
- Reverse Bias:
  - $I_D \approx -I_S$

Note: The thermal voltage of a diode is a key parameter that characterizes the voltage across a diode related to its temperature. It's defined as the voltage required to increase the current flowing through the diode by a factor of “e” (the base of natural logarithms, approximately equal to 2.71828) under constant temperature and is directly proportional to the absolute temperature of the diode.

The Constant-Voltage-Drop (Linear) Model

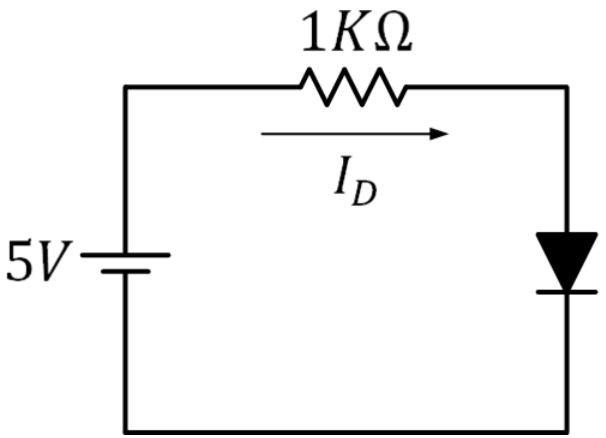
- This model is based on the observation that a forward conducting diode has a voltage drop that varies in a relatively narrow range between $0.6 - 0.8V$
- The model assumes this voltage to be constant at a value of $0.7V$.

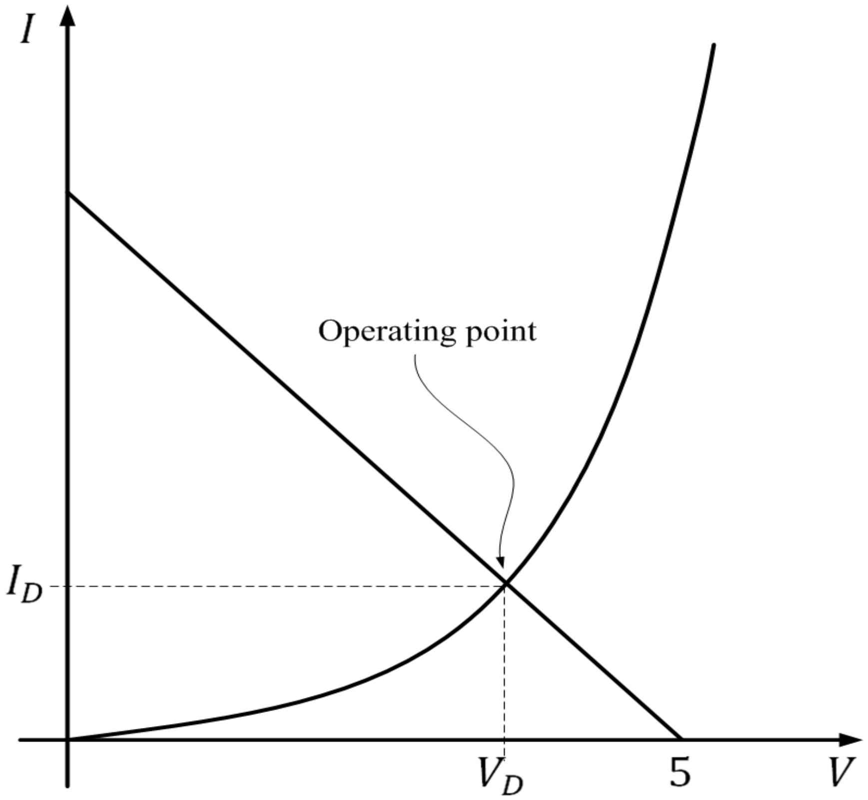




The Constant-Voltage-Drop (Linear) Model

- Example: Determine the current I_D for the shown circuit.



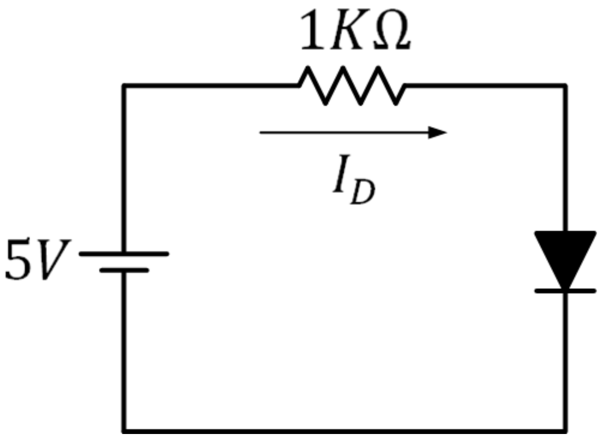


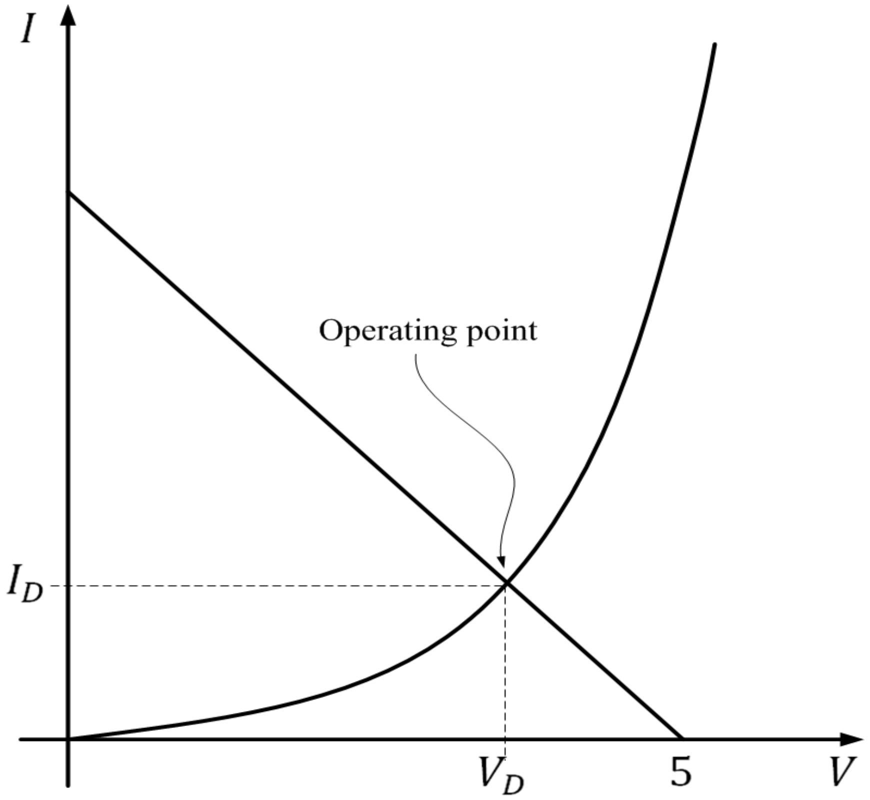
$$\boldsymbol{I_D = 4.262mA}$$

The PN Junction

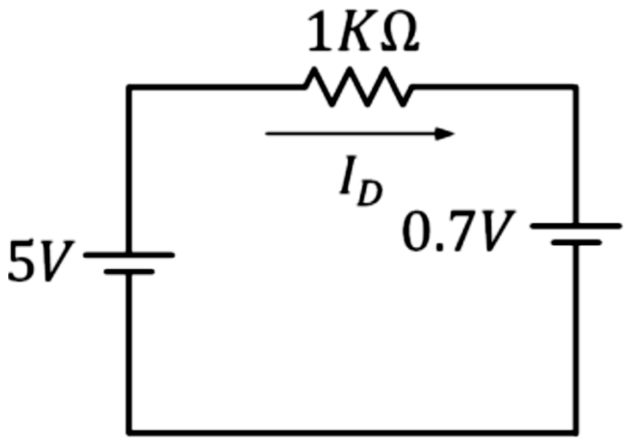
The Constant-Voltage-Drop (Linear) Model

- Example: Determine the current I_D for the shown circuit.





$$I_D = 4.262mA$$



$$I_D = \frac{5-0.7}{1000} = 4.3mA$$

The PN Junction

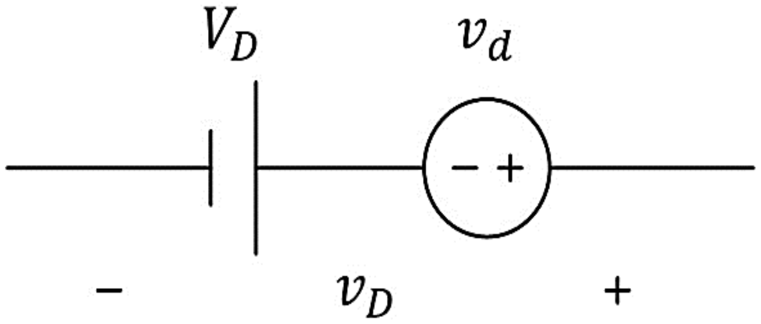
The Small-Signal Model

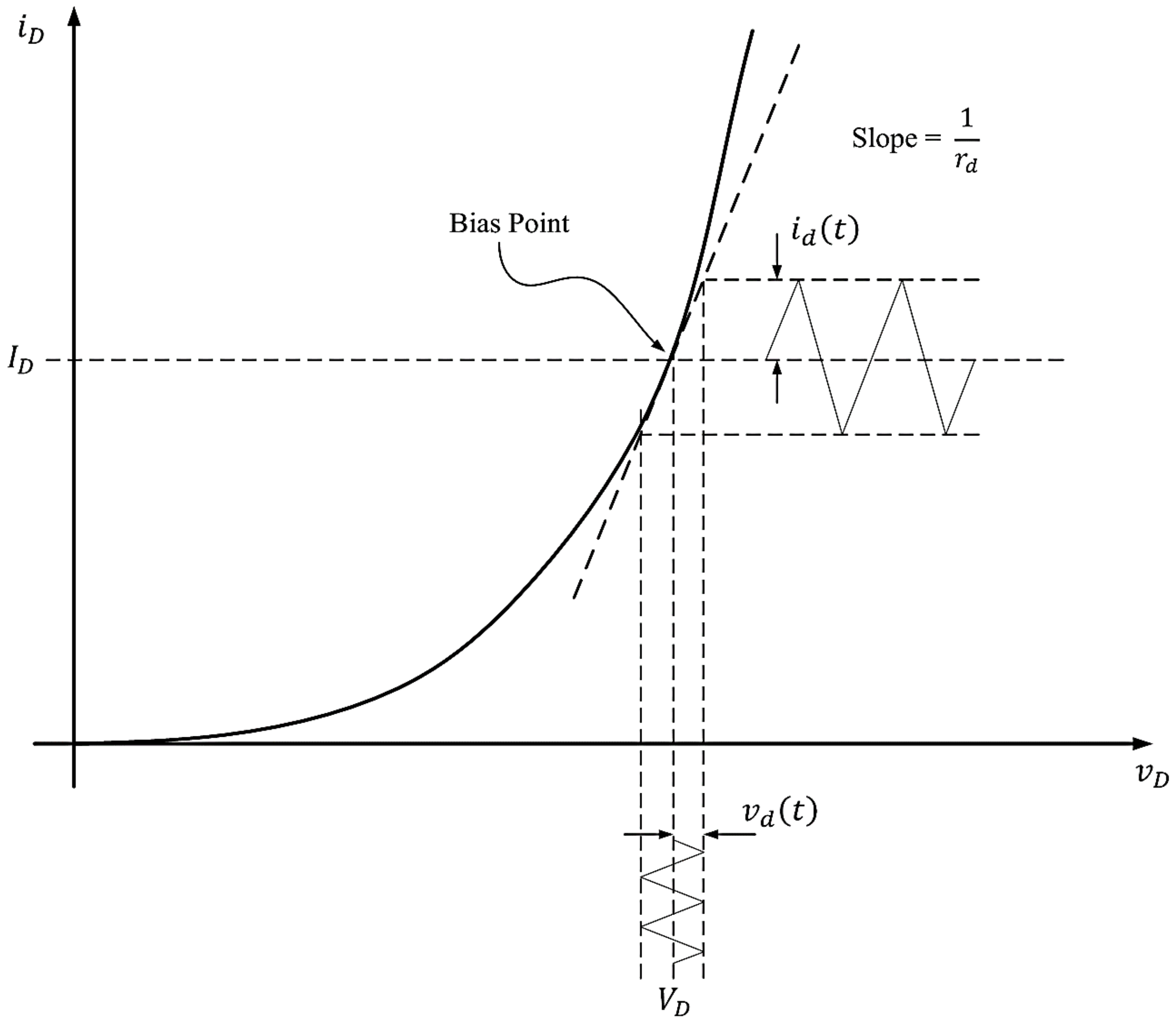
$$V_D \equiv DC\ Voltage$$

$$v_d \equiv AC\ Voltage$$

$$v_D \equiv Total\ Voltage$$

$$v_D = V_D + v_d$$





The PN Junction

The Small-Signal Model

$$i_D = I_S e^{v_D/V_T}$$

$$v_D = V_D + v_d$$

$$i_D = I_S e^{(V_D + vd)/V_T}$$

$$i_D = I_S e^{V_D/V_T} \times e^{v_d/V_T}$$

$$i_D = I_D \times e^{v_d/V_T}$$

$$i_D = I_D \left(1 + \frac{v_d}{V_T}\right)$$

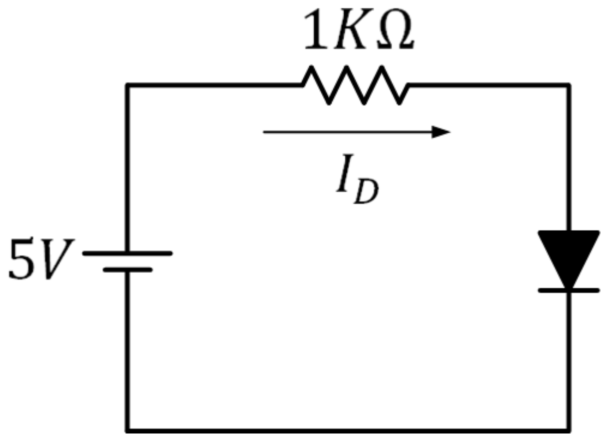
$$i_D = I_D + I_D \frac{v_d}{V_T} = I_D + i_d$$

$$i_d = I_D \frac{v_d}{V_T} = \frac{v_d}{r_d}$$

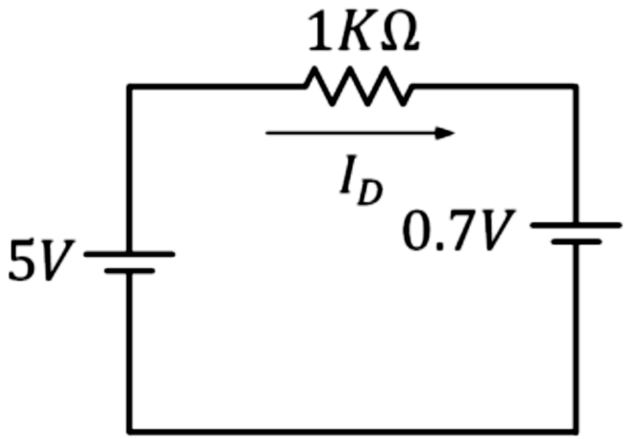
$$r_d = \frac{V_T}{I_D}$$

The Small-Signal Model

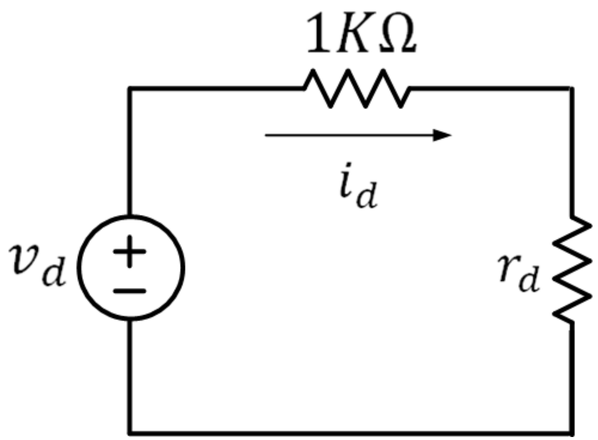
- Example: determine the AC small signal resistance (r_d) of the following circuit.



DC / Large Signal Model



AC / Small Signal Model



$$I_D = \frac{5 - 0.7}{1000} = 4.3mA$$

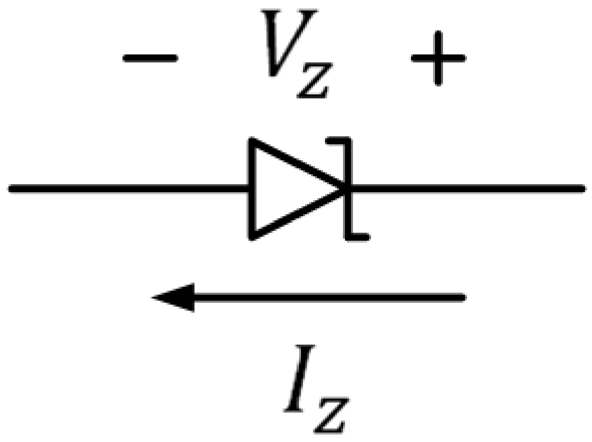
$$r_d = \frac{V_T}{I_D} = \frac{25mV}{4.3mA} = 5.81\Omega$$

Zener Diode

Reverse Breakdown Region (Zener Diodes)

- Zener diodes are manufactured to operate specifically in the breakdown region. Sometimes, we call it breakdown diodes.

- In normal applications of Zener diodes, current flows into the cathode, and the cathode is positive with respect to the anode.

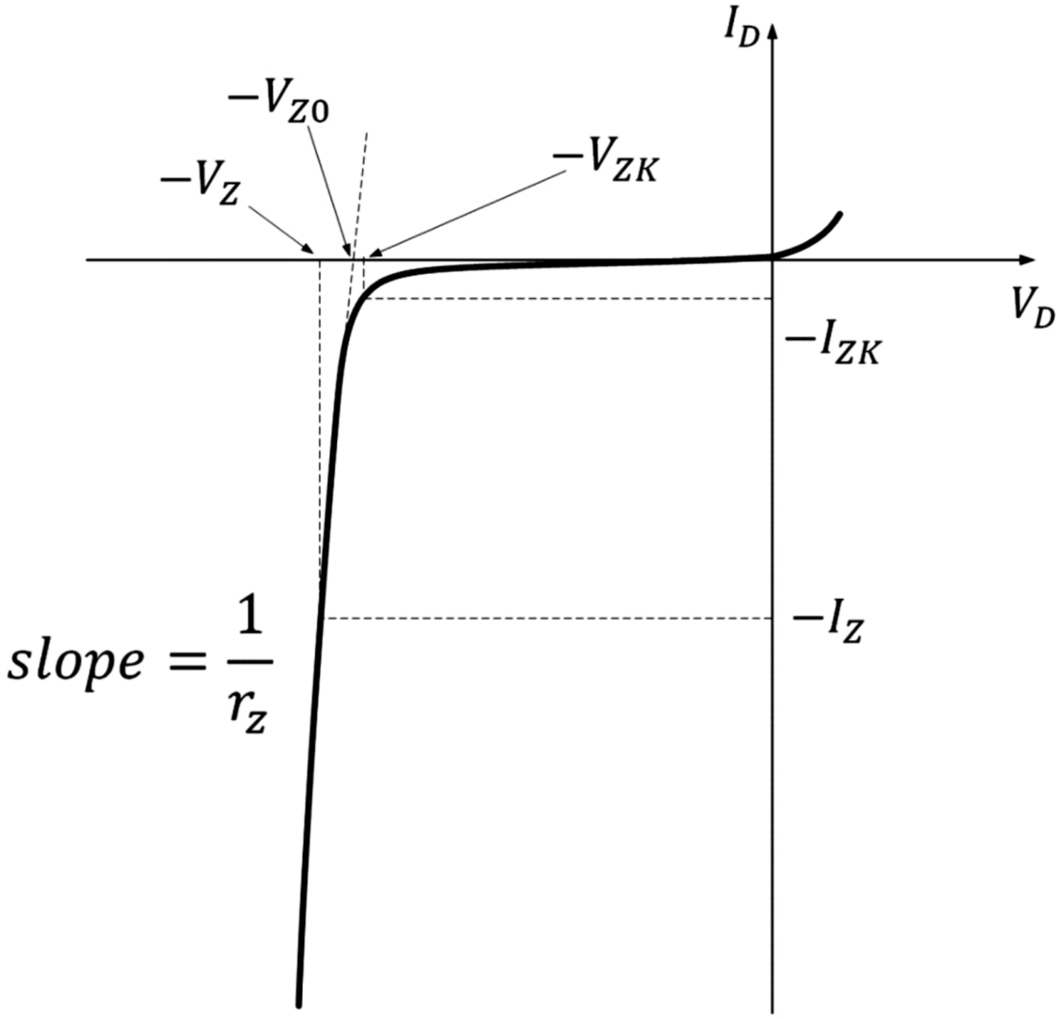


Zener Diode

Reverse Breakdown Region (Zener Diodes)

- For current greater than the **knee current** (I_{ZK}), the I/V characteristic is almost a straight line.

- r_Z is the **incremental resistance** of the Zener diode. It is also known as the **dynamic resistance** of the Zener diode.

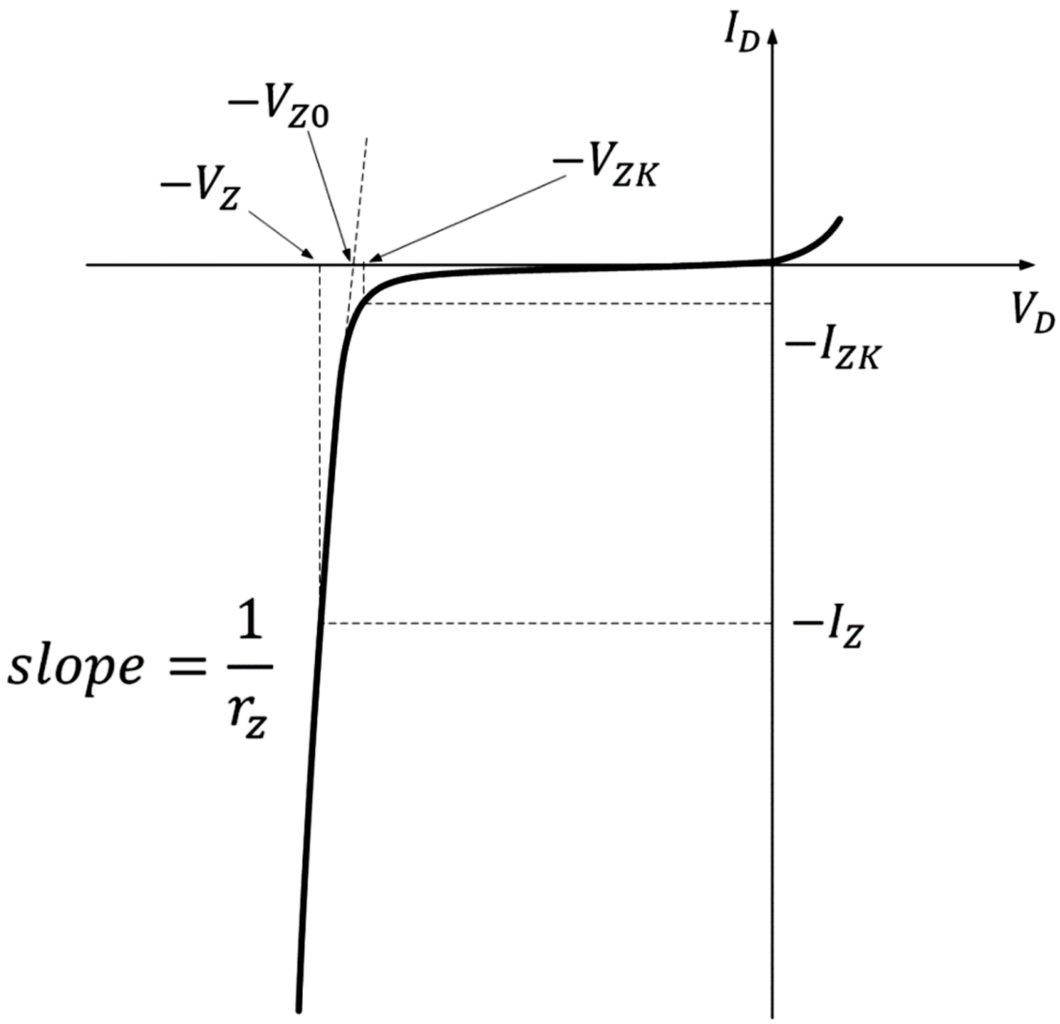


Zener Diode

Reverse Breakdown Region (Zener Diodes)

- ***r_Z* is typically small**, this means that as the current through the Zener diode deviates from I_{ZK}, the voltage across it will change **slightly**.

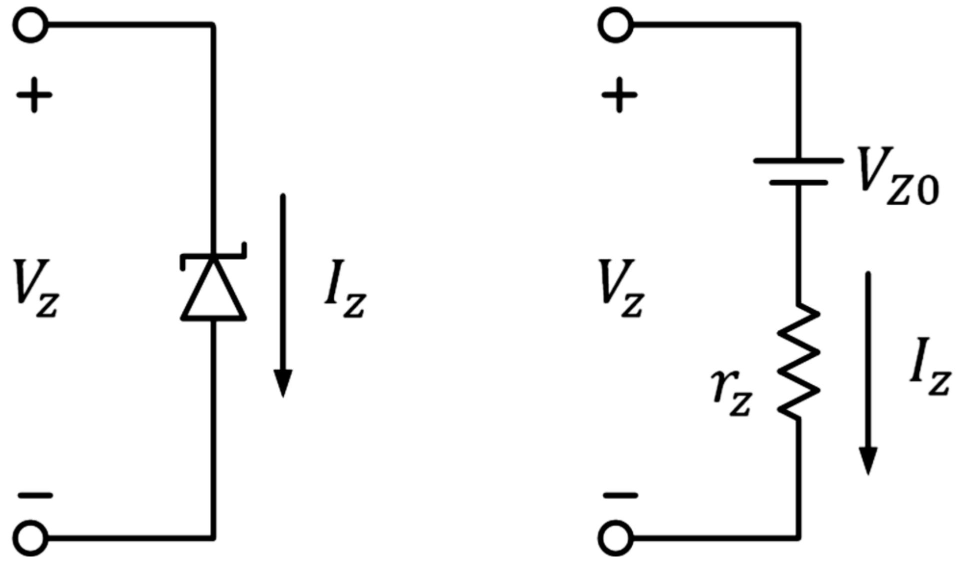
- The **lower** the value of r_Z is, the more **constant** the Zener voltage remains as the current varies, and thus the more ideal its performance becomes in the design of **voltage regulators**.

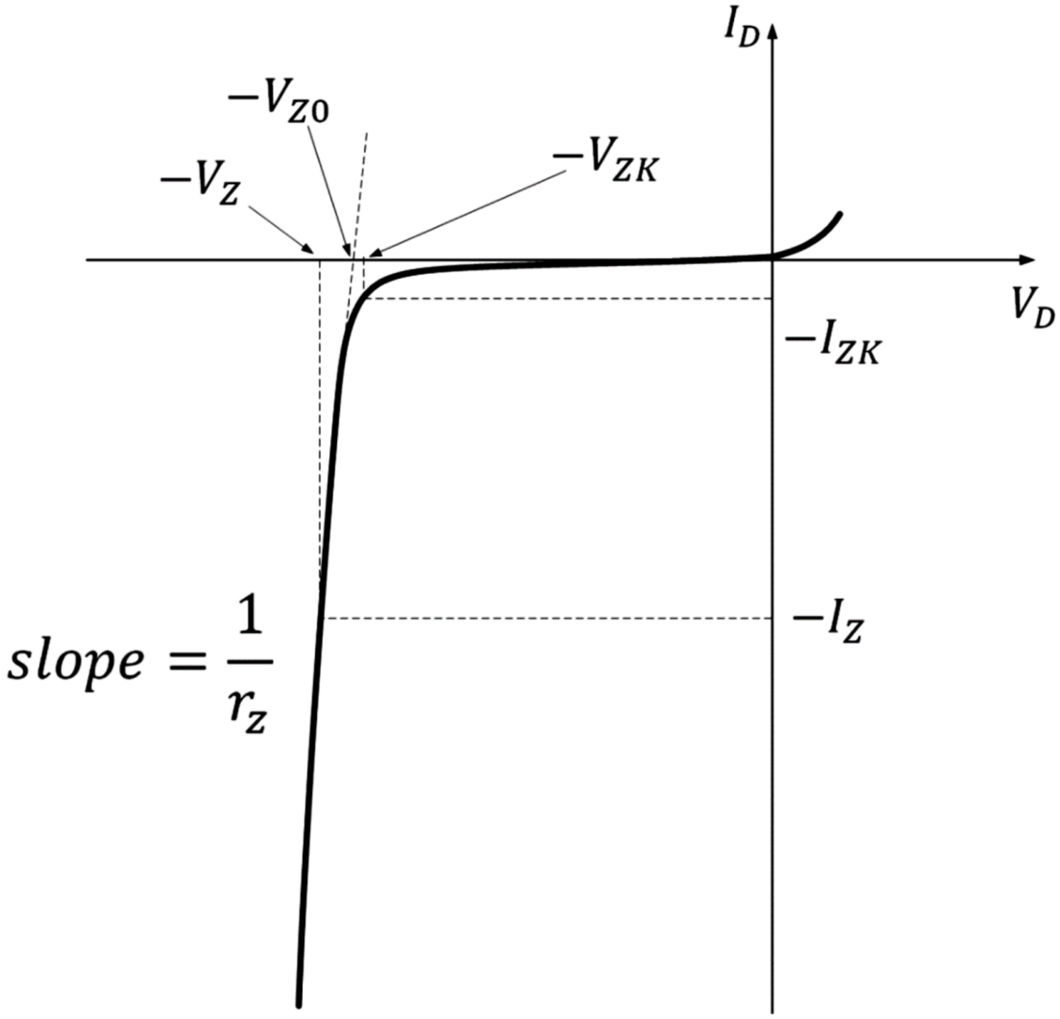


Zener Diode

Reverse Breakdown Region (Zener Diodes)

- V_{Z0} denotes the point at which the straight line of slope intersects the voltage (x) axis.
- $V_Z = V_{Z0} + r_z I_Z$



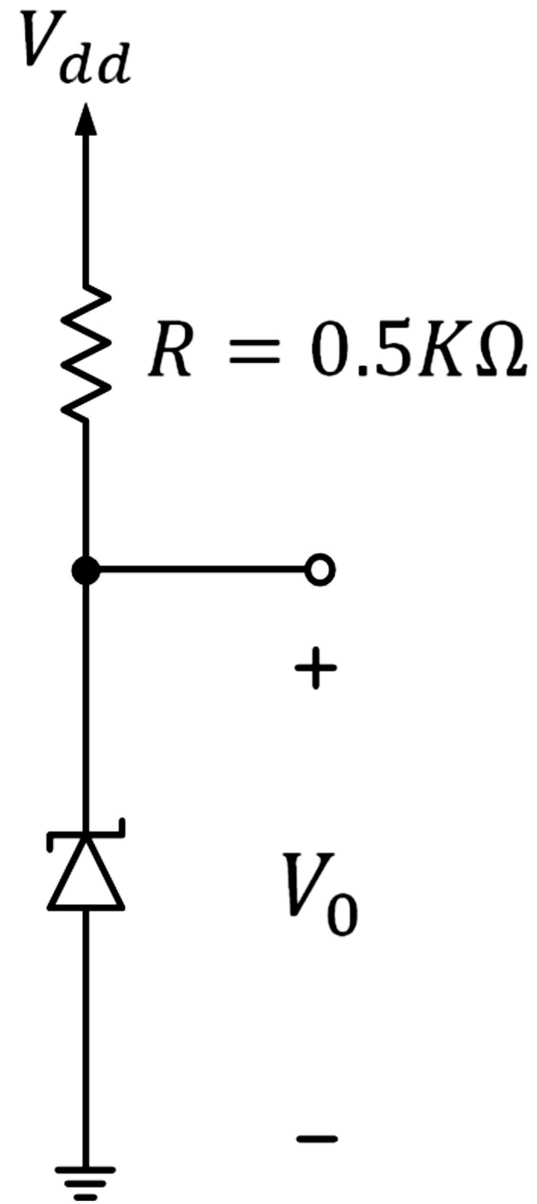


Zener Diode

Zener-Diode as a Voltage Regulator

- Example:

A 6.8-V Zener Diode is used in the shown circuit. The specs of the Zener diode is $V_Z = 6.8V$ at $I_Z = 5mA$, $\mathrm{r_z} = 20\Omega$, and $I_{ZK} = 0.2mA$. The supply voltage V_{dd} is nominally $10V$ but can vary by $\pm 1V$.



Find the value of Vo corresponding to V_{dd}.

Zener Diode

Zener-Diode as a Voltage Regulator

- Solution:
  - $V_Z = V_{Z0} + r_z I_z$
  - $6.8 = V_{Z0} + 20 \times 5m \rightarrow V_{Z0} = 6.7V$
  - $I_Z = I = \frac{V_{dd} - V_{Z0}}{R + r_Z} = \frac{10-6.7}{500+20} = 6.35mA$
  - $V_o = V_{Z0} + r_z I_z = 6.7 + 20 \times 6.35m = 6.83V$

  For a change $\pm 1V\ in\ V_{dd}$
  - $V_o = V_{Z0} + r_z I_z = V_{Z0} + r_z \frac{V_{dd} - V_{Z0}}{R + r_Z}$
  - $\Delta V_o = \Delta V_{dd} \frac{r_z}{R + r_Z} = \pm 1 \times \frac{20}{500+20} = \pm 38.5mV$
  - This indicates that $\pm 10\%$ change in V_{dd} → $\pm$ 0.56% change in V_o.