EEE-2103:
ELECTRONIC DEVICES AND CIRCUITS

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Course Objectives

Introduce electronic components such as semiconductor Diodes, Bipolar Junction Transistors (BJTs) and Field Effect Transistors (FETs) and their applications in switching and amplification

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Course Learning Outcomes

- Describe diode operation, and the use of diode in various electronic circuits.
- Understand the principle of operation of BJT in CE, CB, and CC configuration and analyze transistor hybrid model.
- Bias the transistors and analyze the low frequency response of BJT amplifiers
- Study and analyze the behavior of FET and MOSFET.
- Analyze FET amplifiers in CS,CG,CD modes using small signal model, and
- Familiar with the behaviour of special purpose diodes.

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Atomic Structure

Atom

1. Atom is the **smallest particle** of an element that retains the characteristics of that element.
2. An atom consists of the **protons** and **neutrons** that make up the **nucleus (core)** at the center and **electrons** that orbit about the nucleus.
   - The **nucleus carries almost the total mass** of the atom.

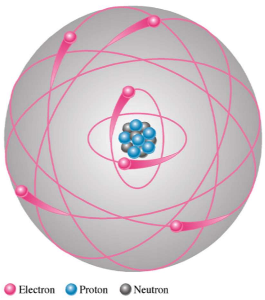

Figure 1:
The Bohr model of an atom

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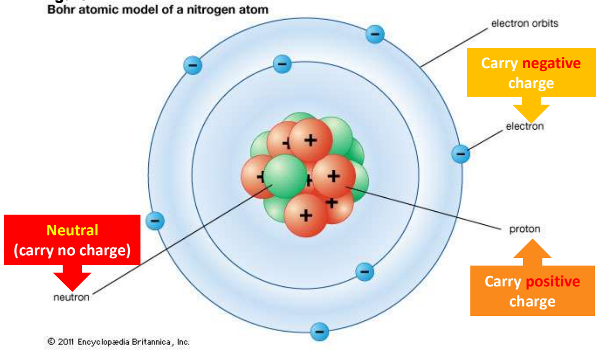
Atomic Structure

Figure 2:
Bohr atomic model of a nitrogen atom



Atomic Structure

Num. of protons = Num. of electrons ➡ Electrically balanced (neutral) atom

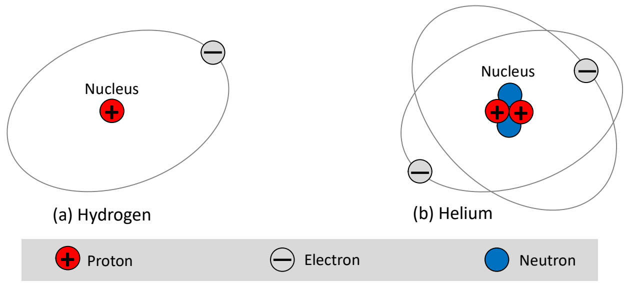


Figure 2: Bohr model of hydrogen and helium

Atomic Structure

Electrons and Shells

1. **Electrons near the nucleus have less energy** than those in more distant orbits.
2. Each distance (orbit) from the nucleus corresponds to a certain energy level.
3. In an atom, the orbits are grouped into **energy levels = shells**.
4. A given atom has a fixed number of shells and each shell has a fixed maximum number of electrons.

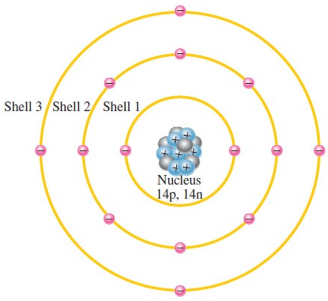


Figure 3: Bohr model of the silicon atom

Atomic Structure

Valence Electron

1. *Valence shell* is the **outermost shell** in an atom that determines the conductivity of an atom.
2. The **electrons in valence shell** are called *valence electrons*.
3. Valence electrons **have higher energy** and are **less tightly bound to the atom**.

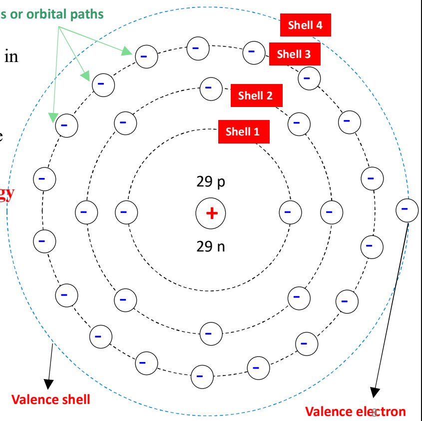


Figure 4: Bohr model of copper atom (Cu)

Atomic Structure

The Maximum Number of Electrons in Each Shell

1. The maximum number of electrons (N_e) in each shell is calculated using formula below:

$$N_e = 2n^2$$

where n = number of shell.

2. Example for the copper atom (Cu) shell :

Atomic number = 29 = 29 electrons

1^{st} shell : $2n^2 = 2(1)^2 = 2\ electrons$

2^{nd} shell : $2n^2 = 2(2)^2 = 8\ electrons$

3^{rd} shell : $2n^2 = 2(3)^2 = 18\ electrons$

$2 + 8 + 18 = 28$

4^{th} shell : $29 - 28 = 1\ electron$

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Atomic Structure

Ionization

1. When atom absorb energy (e.g, from heat source) the energies of the electron are raised.
2. Valence electron obtain **more energy** and **more loosely bound** to the atom compared to the inner electron.
3. If a valence electron acquires sufficient energy – escape from the outer shell and the **process of losing valence electron called** ***ionization***.
4. The resulting **positively charged atom** is called a ***positive ion***.
5. The **escape electron is called** ***free electron***.
6. On the other hand, the atom that has **acquired the extra electron** is called a ***negative ion***.
7. This can occur in certain atoms when a **free electron collides with the atom** and **is captured** (e.g. $Cl \rightarrow Cl^-$).

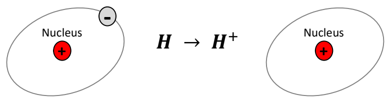

Figure 5: Ionization of hydrogen atom (H)

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Semiconductors, conductors and insulators

In terms of electrical properties

Material

Insulators | Semiconductors | Conductors

All materials are made up of atoms that contribute to its ability to conduct electrical current

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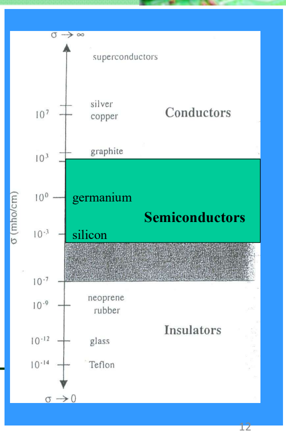
Semiconductor

- Materials that permit flow of electrons are called conductors (e.g., gold, silver, copper, etc.).
- Materials that block flow of electrons are called insulators (e.g., rubber, glass, Teflon, mica, etc.).
- Materials whose conductivity falls between those of conductors and insulators are called semiconductors.
- Semiconductors are "part-time" conductors whose conductivity can be controlled.



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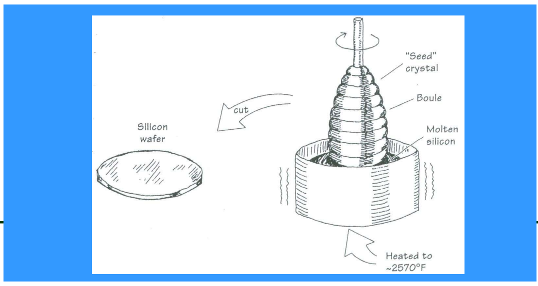
Semiconductor

- Silicon is the most common material used to build semiconductor devices.
- Si is the main ingredient of sand and it is estimated that a cubic mile of seawater contains 15,000 tons of Si.
- Si is spun and grown into a crystalline structure and cut into wafers to make electronic devices.



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Semiconductor Materials

Materials commonly used in the development of semiconductor devices:

- **Silicon (Si)**
- **Germanium (Ge)**
- **Gallium Arsenide (GaAs)**

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Doping

The intrinsic semi-conductive materials are improved by adding materials in a process called doping.

There are just two types of doped semiconductor materials:

***n*-type *p*-type**

- ***n*-type materials contain an excess of conduction band electrons.**
- ***p*-type materials contain an excess of valence band holes.**

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N-Type and P-Type Semiconductors

N-Type Semiconductor

- Is formed by adding **pentavalent** (**5valence $\bar{e}$**) impurity atoms.
- To **increase the number of free electrons**.
- 1 **extra electrons becomes a conduction electrons** because it is **not attached to any atom**.
- Pentavalent atom **gives up (donate) an electron** – call a ***donor atom.***

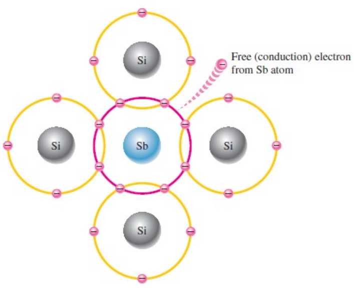

Figure 8: Pentavalent impurity atom in a silicon crystal structure. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

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N-Type and P-Type Semiconductors

N-Type Semiconductor

- No. of conduction electrons can be controlled by the no. of impurity atoms.
- Since **most of the current carriers are electrons**, semiconductor doped with pentavalent atoms is an ***n-type*** semiconductor.
- The **electrons** are called the ***majority carriers***, while the **holes** is ***minority carriers***.

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N-Type and P-Type Semiconductors

P-Type Semiconductor

- Is formed by adding **trivalent** (**3valence $\bar{e}$**) impurity atoms.
- To **increase the number of hole**.
- A**hole is created** when each trivalent atom is added.
- Because the **trivalent atom can take an electron**, it is often referred to as an *acceptor atom*.
- No. of holes can be controlled by the no. of trivalent impurity atoms.
- Since **most of the current carriers are holes**, semiconductor doped with trivalent atoms is an ***p-type***semiconductor.
- The **holes**are called the ***majority carriers***, while the **conduction electrons**is ***minority carriers***.

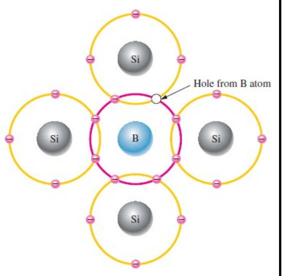

Figure 9: Trivalent impurity atom in a silicon crystal structure. A boron (B) impurity atom is shown in the center.

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Majority and Minority Carriers

Two currents through a diode:

Majority Carriers

- **The majority carriers in *n*-type materials are electrons.**
- **The majority carriers in *p*-type materials are holes.**

Minority Carriers

- **The minority carriers in *n*-type materials are holes.**
- **The minority carriers in *p*-type materials are electrons.**

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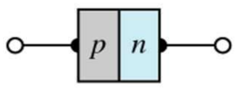
p-n Junctions

One end of an intrinsic semi-conductive materials can be doped as a *p-* type material and the other end as an *n*-type material.

The result is a *p-n* junction.



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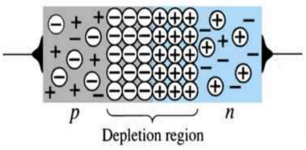
p-n Junctions

At the *p-n* junction, the excess conduction-band electrons on the *n*-type side are attracted to the valence-band holes on the *p*-type side.

The electrons in the *n*-type material migrate across the junction to the *p*-type material (electron flow).

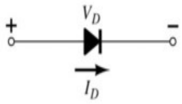
The electron migration results in a negative charge on the p-type side of the junction and a positive charge on the n-type side of the junction.



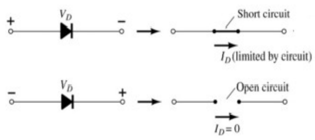
The result is the formation of a depletion region around the junction.

Diodes

The diode is a 2-terminal device.

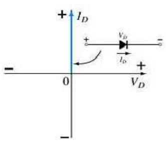


A diode ideally conducts in only one direction.



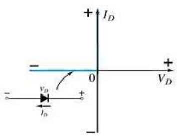
Diode Characteristics

Conduction Region



- The voltage across the diode is 0 V
- The current is infinite
- The forward resistance is defined as $R_F = V_F / I_F$
- The diode acts like a short

Non-Conduction Region



- All of the voltage is across the diode
- The current is 0 A
- The reverse resistance is defined as $R_R = V_R / I_R$
- The diode acts like open

Diode Operating Conditions

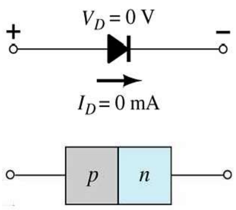
A diode has three operating conditions:

- No bias
- Forward bias
- Reverse bias

Diode Operating Conditions

No Bias

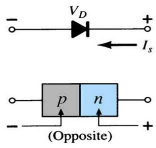
- No external voltage is applied: $V_D = 0\,\text{V}$
- No current is flowing: $I_D = 0\,\text{A}$
- Only a modest depletion region exists

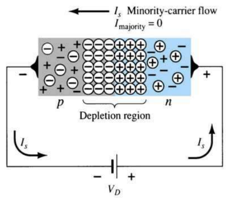


Diode Operating Conditions

Reverse Bias

External voltage is applied across the *p-n* junction in the opposite polarity of the *p-* and *n*-type materials.



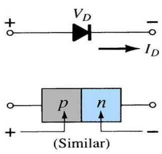


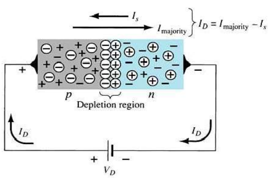
- The reverse voltage causes the depletion region to widen.
- The electrons in the *n*-type material are attracted toward the positive terminal of the voltage source.
- The holes in the *p*-type material are attracted toward the negative terminal of the voltage source.

Diode Operating Conditions

Forward Bias

External voltage is applied across the *p-n* junction in the same polarity as the *p-* and *n*-type materials.



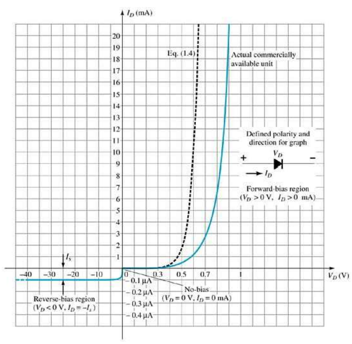


- The forward voltage causes the depletion region to narrow.
- The electrons and holes are pushed toward the *p-n* junction.
- The electrons and holes have sufficient energy to cross the *p-n* junction.

Actual Diode Characteristics

Note the regions for no bias, reverse bias, and forward bias conditions.

Carefully note the scale for each of these conditions.



Forward Bias Voltage

The point at which the diode changes from no-bias condition to forward-bias condition occurs when the electrons and holes are given sufficient energy to cross the *p-n* junction.
This energy comes from the external voltage applied across the diode.

The forward bias voltage required for a:

- **gallium arsenide diode ≅ 1.2 V**
- **silicon diode ≅ 0.7 V**
- **germanium diode ≅ 0.3 V**

Temperature Effects

- As temperature increases it adds energy to the diode.
- It reduces the required forward bias voltage for forward- bias condition.
- It increases the amount of reverse current in the reverse- bias condition.
- It increases maximum reverse bias avalanche voltage.
- Germanium diodes are more sensitive to temperature variations than silicon or gallium arsenide diodes.

Resistance Levels

Semiconductors react differently to DC and AC currents.

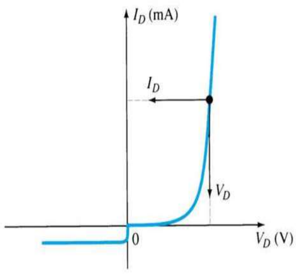
There are three types of resistance:

- **DC (static) resistance**
- **AC (dynamic) resistance**
- **Average AC resistance**

DC (Static) Resistance

For a specific applied DC voltage V_D, the diode has a specific current I_D, and a specific resistance R_D.

$$R_D = \frac{V_D}{I_D}$$



DC (Static) Resistance Example

Determine the dc resistance level when;

i. **ID = 2 mA, VD = 0.5 V**
ii. **ID = 20 mA, VD = 0.8 V**
iii. **ID = - 1 µA , VD = -10 V**

AC (Dynamic) Resistance

In the forward bias region:

$$r_d' = \frac{26\text{mV}}{I_D} + r_B$$

- **The resistance depends on the amount of current (I_D) in the diode.**
- **The voltage across the diode is fairly constant (26 mV for 25°C).**
- **r_B ranges from a typical 0.1 Ω for high power devices to 2 Ω for low power, general purpose diodes. In some cases r_B can be ignored.**

In the reverse bias region:

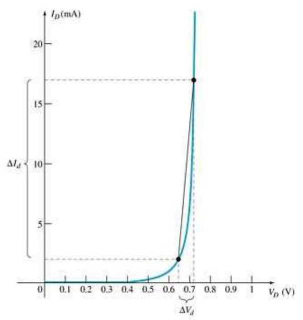
$$r_d = \infty$$

The resistance is effectively infinite. The diode acts like an open.

Average AC Resistance

$$r_{av} = \frac{\Delta V_d}{\Delta I_d}$$

AC resistance can be calculated using the current and voltage values for two points on the diode characteristic curve.



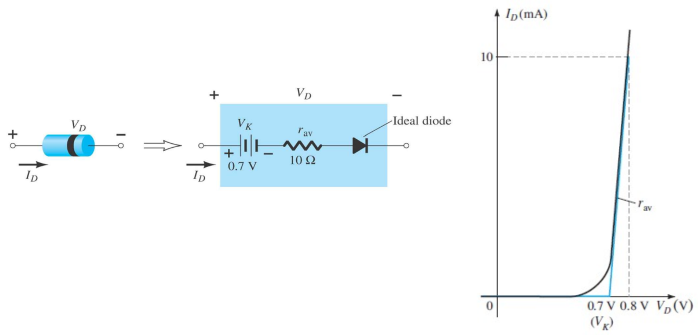
Resistance Level

Type	Equation	Special Characteristics	Graphical Determination
DC or static	$R_D = \frac{V_D}{I_D}$	Defined as a point on the characteristics	
AC or dynamic	$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{26\text{ mV}}{I_D}$	Defined by a tangent line at the Q-point	
Average ac	$r_{av} = \frac{\Delta V_d}{\Delta I_d}\Big\vert_{\text{pt. to pt.}}$	Defined by a straight line between limits of operation	

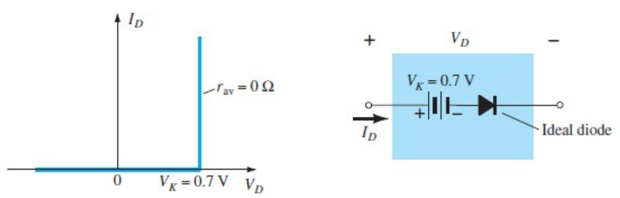
Diode Equivalent Circuit

- Three type of diode equivalent circuit
  - Piecewise linear model
  - Simplified model
  - Ideal model

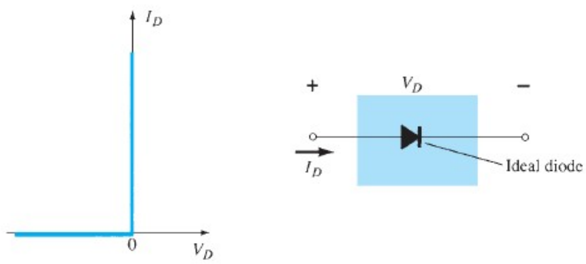
Diode Equivalent Circuit Piecewise-Linear Model



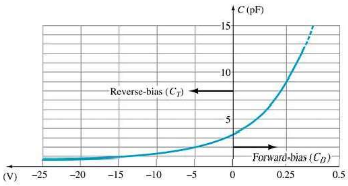
Diode Equivalent Circuit Simplified Model



Diode Equivalent Circuit Ideal Model



Diode Capacitance

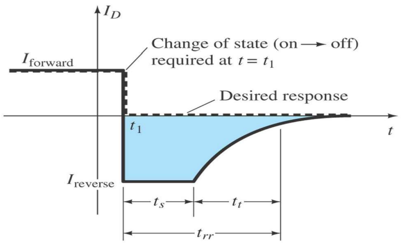


In reverse bias, the depletion layer is very large. The diode's strong positive and negative polarities create capacitance, C_T. The amount of capacitance depends on the reverse voltage applied.

In forward bias storage capacitance or diffusion capacitance (C_D) exists as the diode voltage increases.

Reverse Recovery Time (t_{rr})

Reverse recovery time is the time required for a diode to stop conducting once it is switched from forward bias to reverse bias.

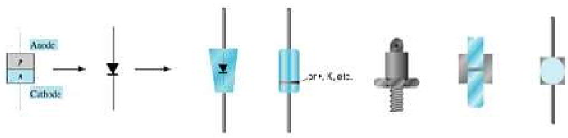


Diode Specification Sheets

Data about a diode is presented uniformly for many different diodes. This makes cross-matching of diodes for replacement or design easier.

1. **Forward Voltage (V_F) at a specified current and temperature**
2. **Maximum forward current (I_F) at a specified temperature**
3. **Reverse saturation current (I_R) at a specified voltage and temperature**
4. **Reverse voltage rating, PIV or PRV or V(BR), at a specified temperature**
5. **Maximum power dissipation at a specified temperature**
6. **Capacitance levels**
7. **Reverse recovery time, t_{rr}**
8. **Operating temperature range**

Diode Symbol and Packaging



The anode is abbreviated A
The cathode is abbreviated K

Diode Testing

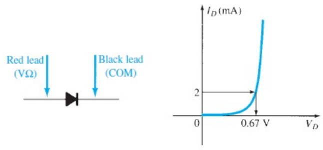
Diode checker
Ohmmeter
Curve tracer

Diode Checker

Many digital multimeters have a diode checking function. The diode should be tested out of circuit.

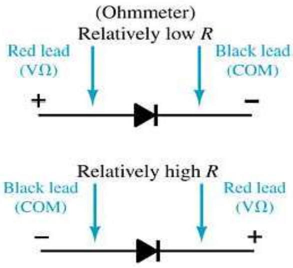
A normal diode exhibits its forward voltage:

- **Gallium arsenide ≅ 1.2 V**
- **Silicon diode ≅ 0.7 V**
- **Germanium diode ≅ 0.3 V**



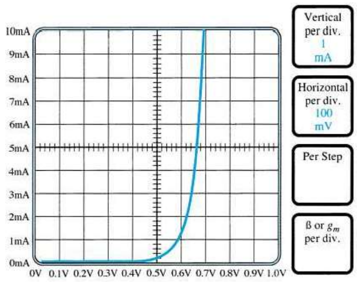
Ohmmeter

An ohmmeter set on a low Ohms scale can be used to test a diode. The diode should be tested out of circuit.



Curve Tracer

A curve tracer displays the characteristic curve of a diode in the test circuit. This curve can be compared to the specifications of the diode from a data sheet.



Other Types of Diodes

Zener diode
Light-emitting diode
Diode arrays