EE-110 Electronic Devices

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Course outcome 1st topic

- To understand the semiconductor materials that are suitable for electronic devices
- To study the properties of materials for electronic devices
- To understand the biasing of diode
- Able to design Diode circuit
- Able to apply some types of diodes

Assessments/Books

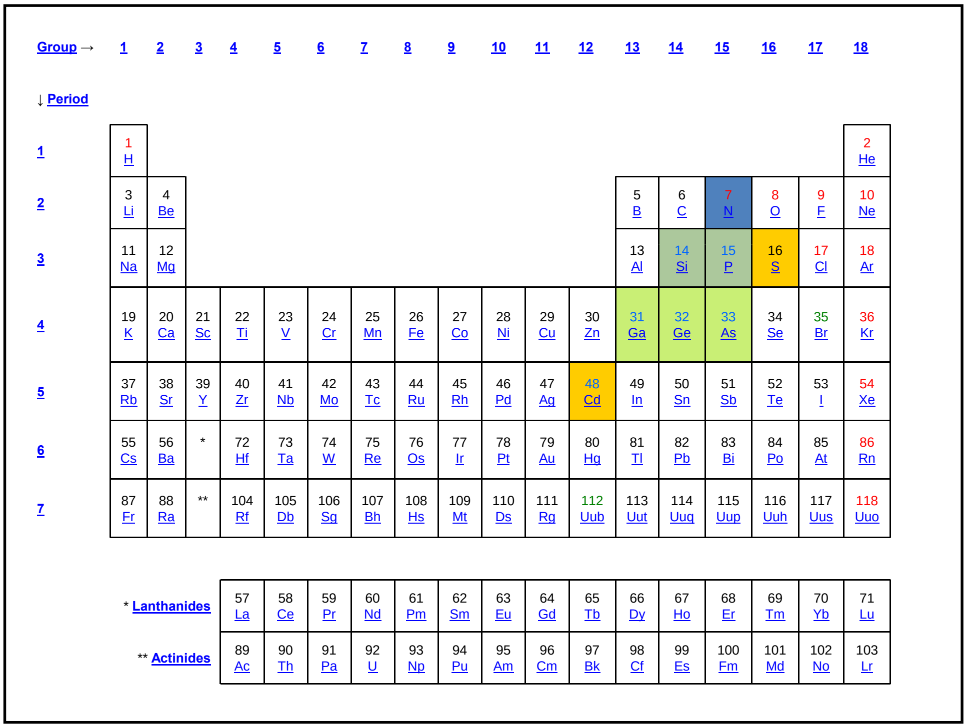
- Tests 2.5%
- Assignment 2.5%
- Mid Term 15%
- Lab 20%
- Examination 60%

Text books: Electronic devices and circuit theory by Robert L. Boylestad and Louis Nashelsky

Semiconductor Material

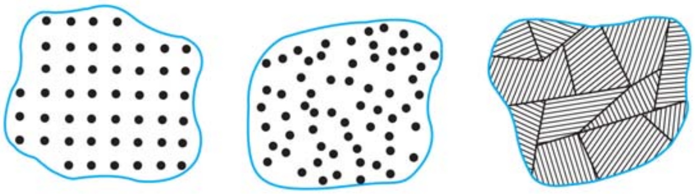
- Semiconductors are a special class of elements having a conductivity between that of a good conductor and that of an insulator.
- They are fall into two classes : single crystal and compound
- Single crystal e.g Ge and Si
- Compound e.g GaAs , CdS, GaN and GaAsP

Ge-germanium; Si-silicon; Ga-gallium ;As –arsenide; Cd-cadmium; S-sulfide; N-nitride; P-phosphide



Group →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
↓ Period																		
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

* **Lanthanides**	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** **Actinides**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



(a) Crystalline (b) Amorphous (c) Polycrystalline

Figure 1.1

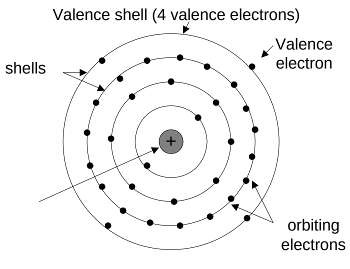
Three types of solids, classified according to atomic arrangement: (a) crystalline and (b) amorphous materials are illustrated by microscopic views of the atoms, whereas (c) polycrystalline structure is illustrated by a more macroscopic view of adjacent single-crystalline regions, such as (a).

From *Solid State Electronic Devices*, Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.
ISBN 0-13-149726-X.

Historical

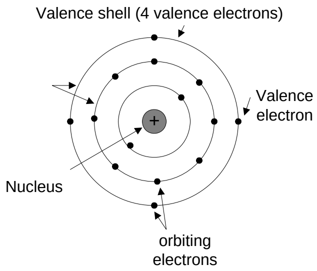
- Diode , in 1939 was using Ge
- Transistor, in 1947 was using Ge
- In1954 Si was used in Transistor because Si is less temperature sensitive and abundantly available.
- High speed transistor was using GaAs in 1970 (which is 5 times faster compared to Si)
- Si, Ge and GaAs are the semiconductor of choice

Atomic structure



Germanium

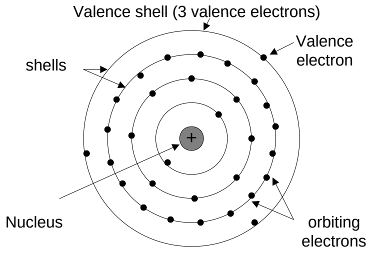
32 orbiting electrons
(tetravalent)



Silicon

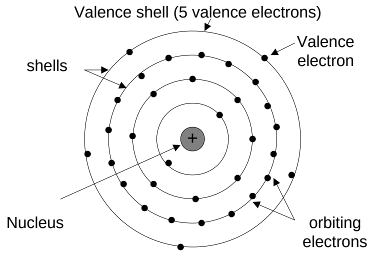
14 orbiting electrons
(Tetravalent)

Atomic structure



Gallium

31 orbiting electrons
(trivalent)



Arsenic

33 orbiting electrons
(pentavalent)

ENERGY LEVELS

- Each and every isolated electron has a specific energy level associated with shell and orbiting electron.
- The farther an electron from the nucleus, the higher is the energy state.
- Electron left its parent atom has a higher energy state than any electron in the atomic structure.

Band Theory

- Analogy to atoms
  - –From chemistry, we are familiar with the idea of "electron clouds" orbiting the nucleus.
  - –The energy of the different clouds, or levels, is discrete. Adding energy can cause an electron to "jump" into a higher level. In the same way, an electron can lose energy and emit a specific wavelength of light when falling to a lower energy level. (Atomic spectra)
  - –Pauli Exclusion Principle: no two electrons can occupy the same exact state at the same time. This is why electrons fill the energy levels in the way they do.
  - –Valence electrons are the electrons bound farthest from the nucleus

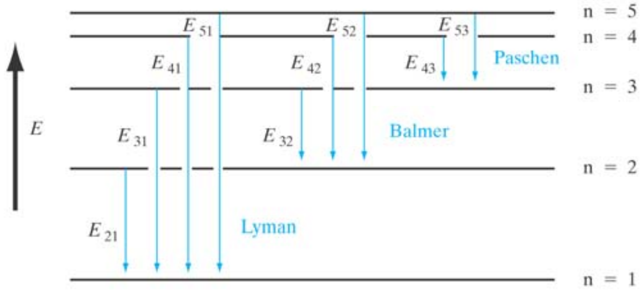


Figure 2.3

Relationships among photon energies in the hydrogen spectrum.

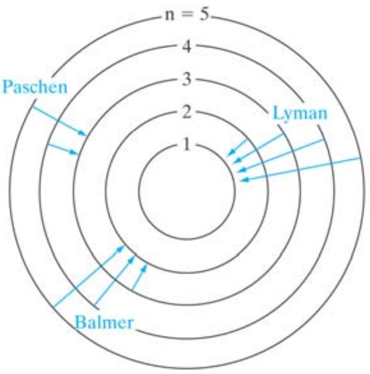
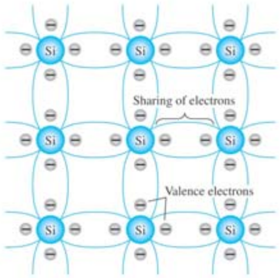


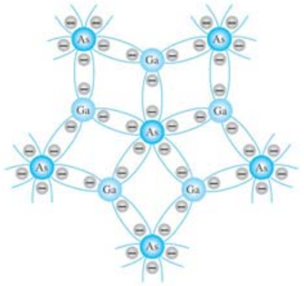
Figure 2.4

Electron orbits and transitions in the Bohr model of the hydrogen atom. Orbit spacing is not drawn to scale.

Covalent bonding



Covalent bonding of Si crystal



Covalent bonding of GaAs crystal

This bonding of atoms, strengthened by the sharing of electrons, is called covalent bonding

Exercise 1

- Name the materials that suitable for electronic devices
- What are the advantages and disadvantages of each materials?
- What is a covalent bonding? Describe it.

Free state

- Energy from external natural cause the valence electrons to absorb sufficient kinetic energy and break the covalent bond. This is assume to be free state.
- Electron that has separated from the fixed lattice structure is called free carriers.
- At room temperature, approximately 1.5X 10^{10} free carriers in 1 cm^3 of intrinsic silicon material

*intrinsic means material has been refined to a very low level of impurities.

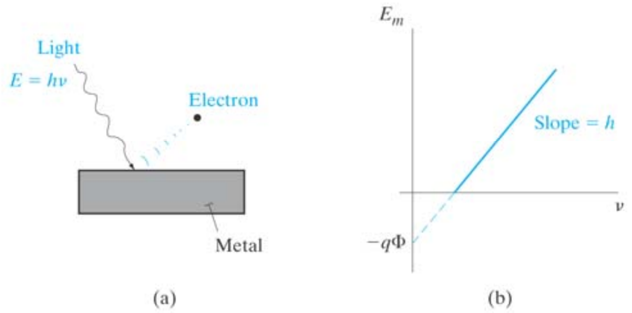


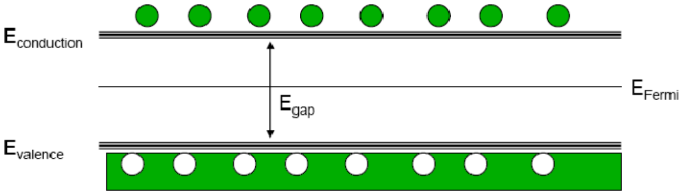
Figure 2.1

The photoelectric effect: (a) electrons are ejected from the surface of a metal when exposed to light of frequency ν in a vacuum; (b) plot of the maximum kinetic energy of ejected electrons vs. frequency of the incoming light.

Effect on temperature

- Conductor – increase resistance with increase in heat (number of carrier do not increase)- is said to have a positive temperature coefficient.
- Semiconductor- increase conductivity with increase in heat (number of carrier increase)- is said to have a negative temperature coefficient.

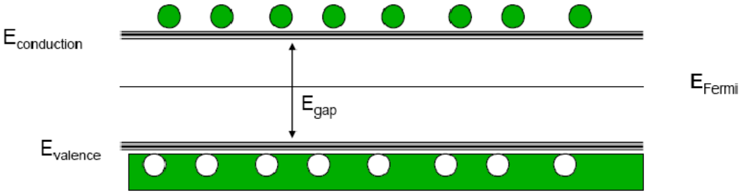
Transport in Semiconductors



Electrons that get excited into the conduction band carry current.

- The space left behind in the valence band is called a hole.
- Holes also conduct current. In reality, it's the movement of all the other electrons. The hole allows this motion. (Bubbles)
- Holes can easily travel "up" in energy.
- Holes have positive charge.
- Current flows in the same direction as the holes move.
- Holes have different mass (effective mass) and mobility compared to electrons.

Intrinsic Semiconductor



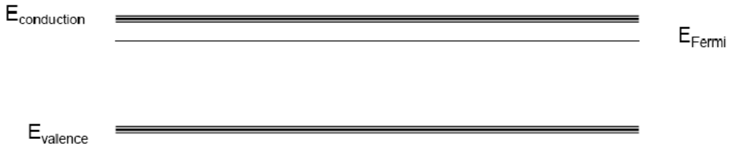
Fermi Level: All solids are characterized by an energy that describes the highest energy electron at 0K, the level which has1/2 probability of being occupied at finite temperature.

- Semiconductors: A solid with its Fermi level exactly between bands, with a band gap small enough to be overcome at room temperature.
- Both electrons and holes carry current.

Extrinsic materials

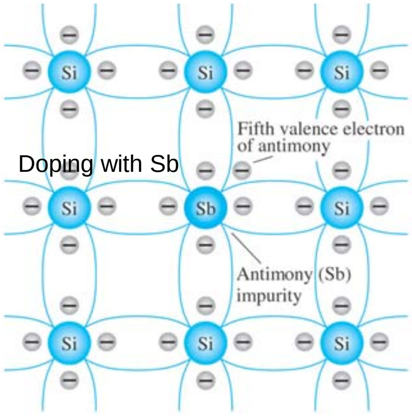
- A semiconductor material that has been subjected to the doping process is called an extrinsic material.
- Type of materials
  - n-type
  - p-type

Phosphorus Doping (n-type)



- Phosphorus has 5 valence electrons.
  - P atoms will sit in the location of a Si atom in the lattice, to avoid breaking symmetry, but each will have an extra electron that does not bond in the same way.
  - These electrons form their own band. Exactly where depends on the amounts of the two materials.
  - This new band is located closer to the conduction band, because these extra electrons are easier to excite (and can move around more easily)

Eg. Of n-type material doping

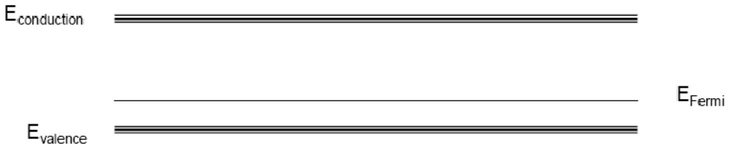


Doping with Sb

One electron loosely bound and freely to move in the crystal structure. The atoms (in this case is antimony (Sb)) with five valence electrons are called the donor atoms. Similarly with Phosphorus (P) which also a donor.

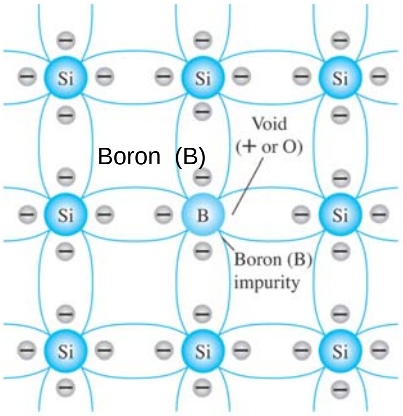
Sb - antimony

Boron Doping (p-type)



- Boron has 3 valence electrons.
  - B will sit at a lattice site, but the adjacent Si atoms lack an electron to fill its shell. This creates a hole.
  - These holes form their own energy band.
  - This band is located closer to the valence band, because these extra holes are easy to “excite down” into the valence band.

Eg of p-type material

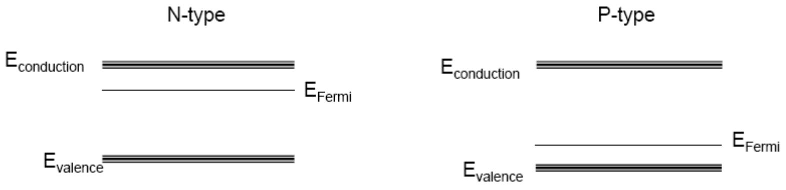


•In this case, an insufficient number of electrons to complete the covalent bonds.

•The impurities with three valence electrons are called acceptor atoms. E.g of materials are Gallium (Ga), Indium (In)

•Void is called hole

Doping

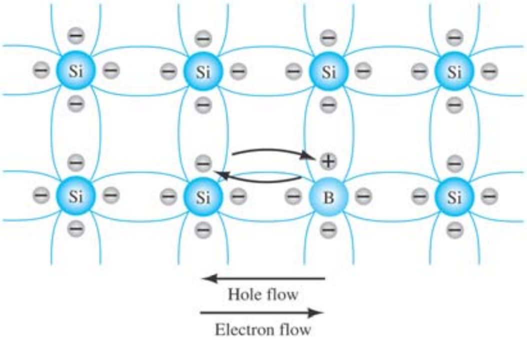


- Doping involves in adding dopant atoms to an intrinsic semiconductor.
- n-type materials: Doping Si with a Group V element, providing extra electrons (n for negative) and moving the Fermi level up.
- p-type materials: Doping Si with a Group III element, providing extra holes (p for positive) and moving the Fermi level down.

Dopant

- Group V (n-type) –usually antimony(Sb), arsenic(A), phosphorus(P)
- Group III (p-type)-usually Boron(B) , Gallium (Ga) and Indium (In)

Electron versus hole flow

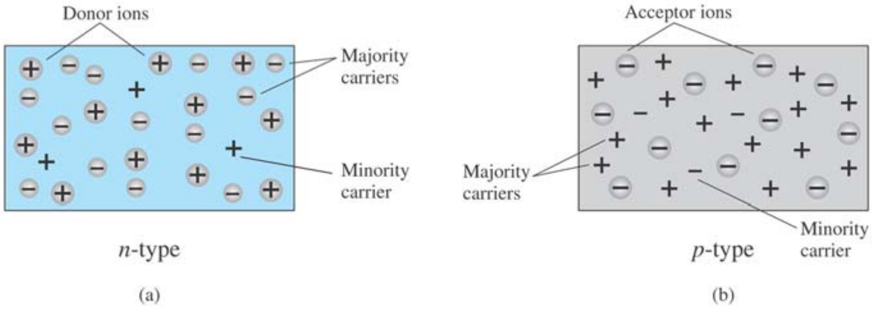


•The valence electron acquires sufficient kinetic energy to break its covalent bond and fills the void created by hole

•When the electron move to fill the hole therefore a transfer of holes to the left and electrons to the right

•This flow is known as conventional flow.

Majority and Minority Carriers



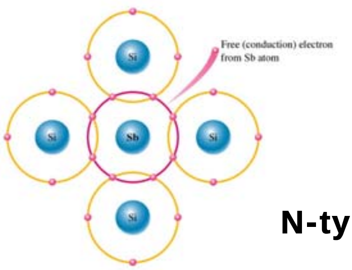
- N-type material, the electron is called majority carrier and hole the minority carrier
- P-type material, the hole is called majority carrier and electron the minority carrier.

N-type and P-type Semiconductors

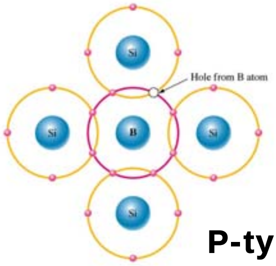
The process of creating N and P type materials is called doping.

Other atoms with 5 electrons such as Antimony are added to Silicon to increase the free electrons.

Other atoms with 3 electrons such as Boron are added to Silicon to create a deficiency of



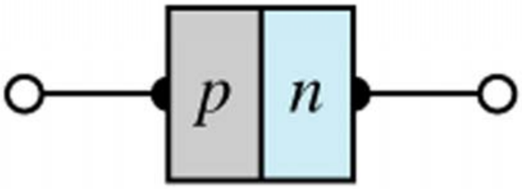
N-type



P-type

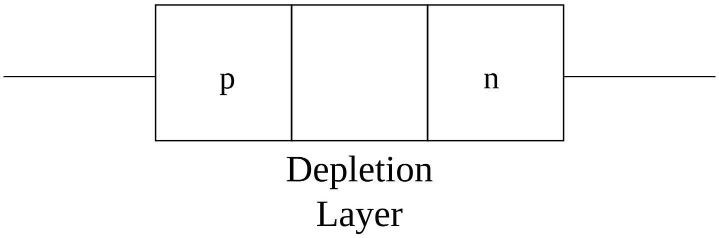
n-type versus p-type

- n-type materials make the Silicon (or Germanium) atoms more negative.
- p-type materials make the Silicon (or Germanium) atoms more positive.
- Join n-type and p-type doped Silicon (or Germanium) to form a p-n junction.



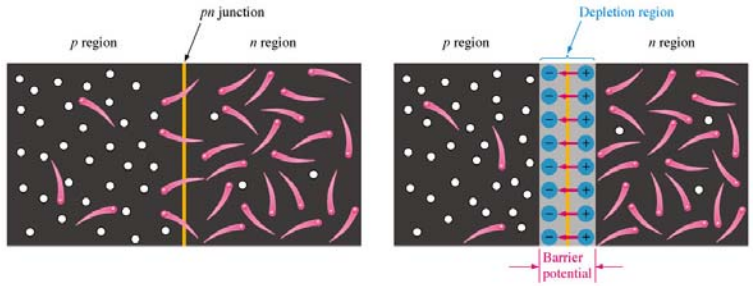
p-n junction

- When the materials are joined, the negatively charged atoms of the n-type doped side are attracted to the positively charged atoms of the p-type doped side.
- The electrons in the n-type material migrate across the junction to the p-type material (electron flow).
  Or you could say the 'holes' in the p-type material migrate across the junction to the n-type material (conventional current flow).
- The result is the formation of a depletion layer around the junction.



The Depletion Region

p region n region p region n region



With the formation of the p and n materials combination of electrons and holes at the junction takes place.

This creates the depletion region and has a barrier potential. This potential cannot be measured with a voltmeter but it will cause a small voltage drop.

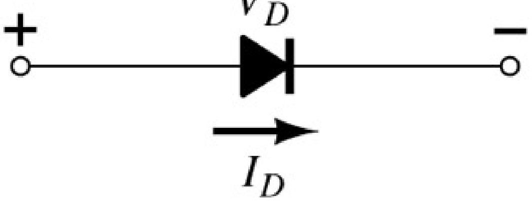
Barrier Potential

- Potential difference of the electric field in the depletion region
- The amount of energy required to move electron through the depletion region
- Silicon diode approximately 0.7 V
- Germanium diode approximately 0.3V

Operating Conditions

- No Bias
- Forward Bias
- Reverse Bias

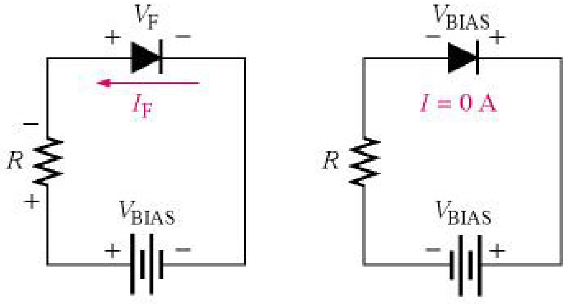
Diodes Simplest Semiconductor Device



(a)

Introduction

The basic function of a diode is to restrict current flow to one direction.



(a) Forward bias (b) Reverse bias

Forward bias

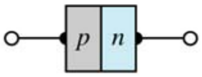
Current flows

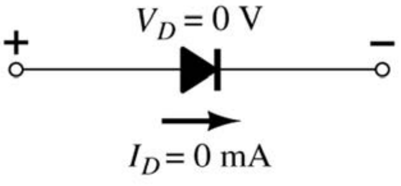
Reverse Bias

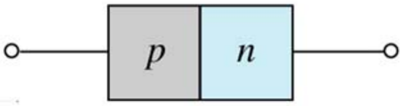
No current flow

No Bias Condition

No external voltage is applied: VD = 0V and no current is flowing ID = 0A.

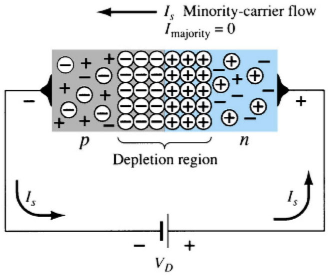




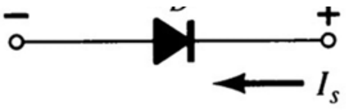


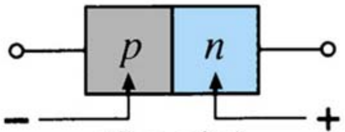
Only a modest depletion layer exists.

Reverse Bias Condition



- External voltage is applied across the p-n junction in the opposite polarity of the p- and n-type materials.
- This causes the depletion layer to widen.
- The electrons in the n-type material are attracted towards the positive terminal and the 'holes' in the p-type material are attracted towards the negative terminal.

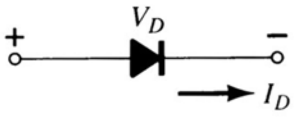


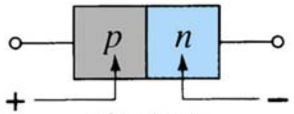


(Opposite)

Forward Bias Condition

- External voltage is applied across the p-n junction in the same polarity of the p- and n-type materials.
- The depletion layer is narrow.
- The electrons from the n-type material and 'holes' from the p-type material have sufficient energy to cross the junction.





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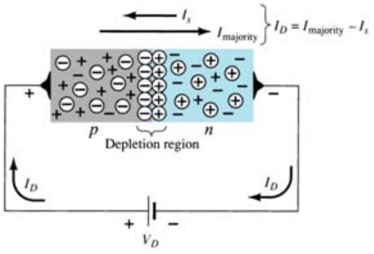
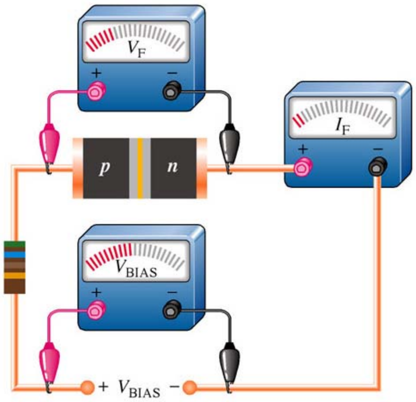


Forward Bias Measurements With Small Voltage Applied

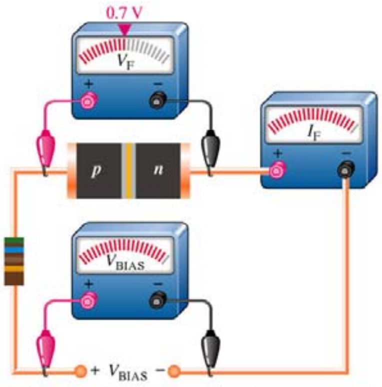
In this case with the voltage applied is less than the barrier potential so the diode for all practical purposes is still in a non-conducting state. Current is very small.



(a) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

Forward Bias Measurements With Applied Voltage Greater Than the Barrier Voltage

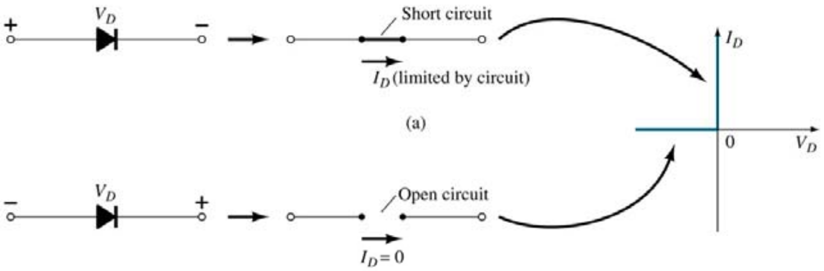
With the applied voltage exceeding the barrier potential the now fully forward biased diode conducts. Note that the only practical loss is the .7 Volts dropped across the diode.



(b) Forward voltage reaches and remains at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

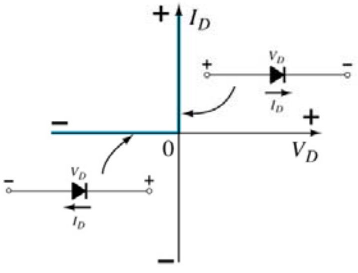
Basic operation

Ideally it conducts current in only one direction



and acts like an open in the opposite direction

Characteristics of an ideal diode: Conduction Region



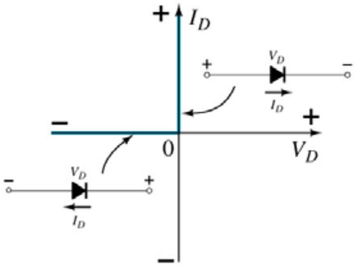
(b)

Look at the vertical line!

In the conduction region, ideally

- the voltage across the diode is 0V,
- the current is ∞,
- the forward resistance (RF) is defined as RF = VF/IF,
- the diode acts like a short.

Characteristics of an ideal diode: Non-Conduction Region



(b)

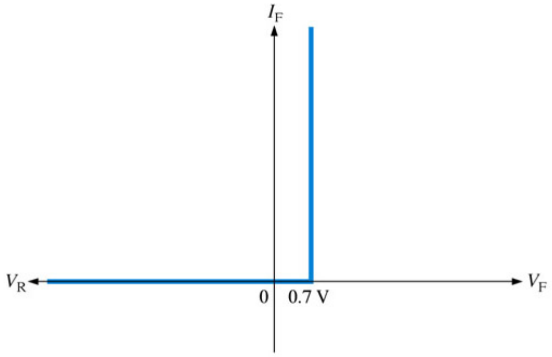
Look at the horizontal line!

In the non-conduction region, ideally

- all of the voltage is across the diode,
- the current is 0A,
- the reverse resistance (RR) is defined as RR = VR/IR,
- the diode acts like open.

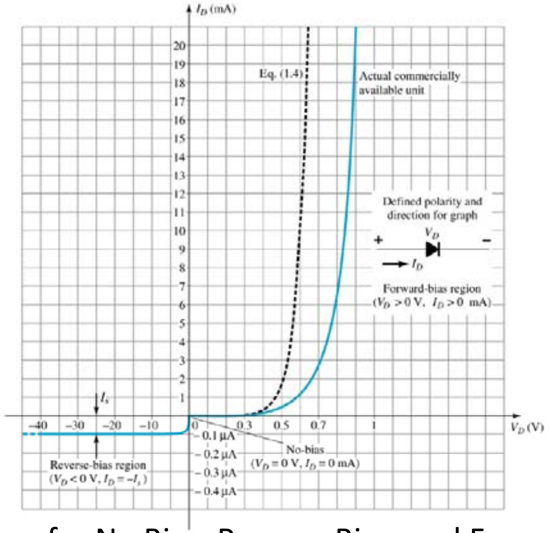
Practical Diode Characteristic Curve

In most cases we consider only the forward bias voltage drop of a diode. Once this voltage is overcome the current increases proportionally with voltage.This drop is particularly important to consider in low voltage applications.



(c) Characteristic curve (silicon)

Actual Diode Characteristics



Note the regions for No Bias, Reverse Bias, and Forward Bias conditions.
Look closely at the scale for each of these conditions!

Temperature Effects

•As temperature increases it adds energy to the diode.
It reduces the required Forward bias voltage in Forward Bias condition.

•It increases the amount of Reverse current in Reverse Bias condition.

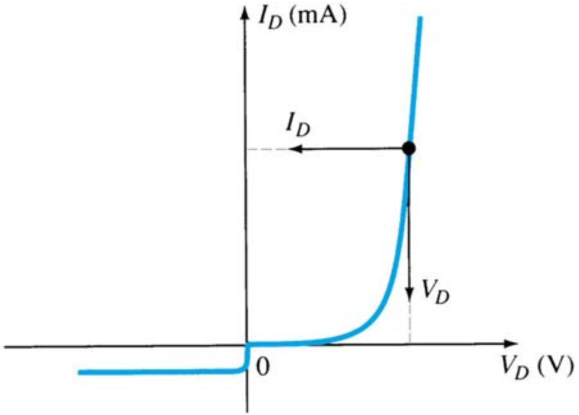
•Germanium diodes are more sensitive to temperature variations than Silicon Diodes.

Resistance Levels

Semiconductors act differently to DC and AC currents. There are 3 types of resistances.

- DC or Static Resistance
- AC or Dynamic Resistance
- Average AC Resistance

DC or Static Resistance



$R_D = V_D/I_D$ [Formula 1.5]

For a specific applied DC voltage V_D, the diode will have a specific current I_D, and a specific resistance R_D.
The amount of resistance R_D, depends on the applied DC voltage.

AC or Dynamic Resistance

Forward Bias region:

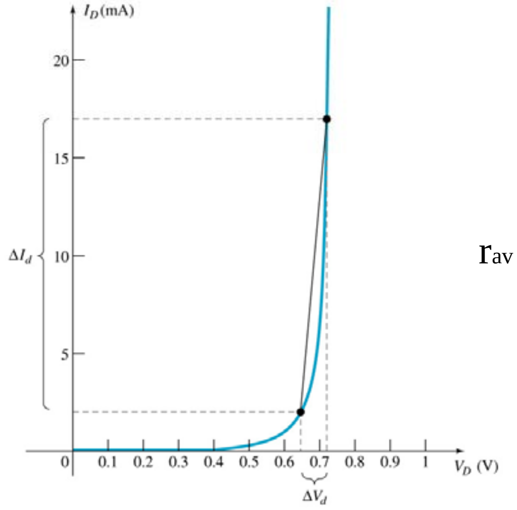
$$r'_d = \frac{26mV}{I_D} + r_B$$ [Formula 1.8]

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

$$r'_d = \infty$$

•Reverse Bias region: The resistance is essentially infinite. The diode acts like an open.

Average AC Resistance



$$r_{av} = \frac{\Delta V_d}{\Delta I_d} \text{(point to point)}$$

[Formula 1.9]

AC resistance can be determined by picking 2 points on the characteristic curve developed for a particular circuit.

Diode Testing

- Diode Checker
- Ohmmeter
- Curve Tracer

A. Diode Checker

Many DMM’s have a diode checking function.
A normal diode will exhibit its Forward Bias voltage (VF).
The diode should be tested out of circuit.

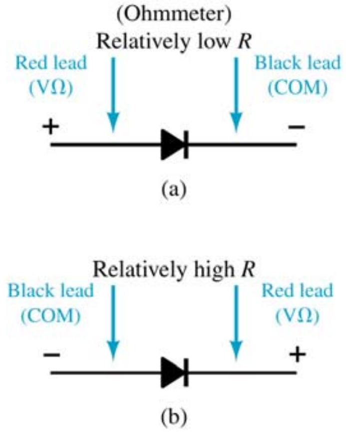
Silicon diode ≅ 0.7V
Germanium diode ≅ 0.3V

B. Ohmmeter

An ohmmeter set on a low ohms scale can be used to test a diode.

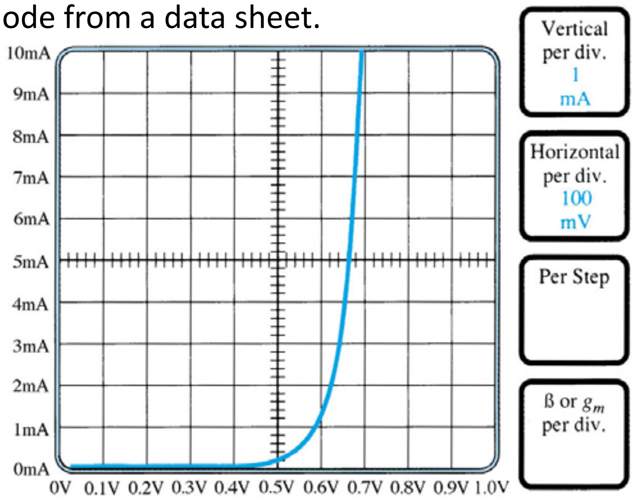
A normal diode will have the following readings.

The diode should be tested out of circuit.



C. Curve Tracer

A curve tracer is a specialized type of test equipment. It will display the characteristic curve of the diode in the test circuit. This curve can be compared to the specifications of the diode from a data sheet.



Summary

- ➢ Diodes, transistors, and integrated circuits are all made of semiconductor material.
- ➢ P-materials are doped with trivalent impurities
- ➢ N-materials are doped with pentavalent impurities
- ➢ P and N type materials are joined together to form a PN junction.
- ➢ A diode is nothing more than a PN junction.
- ➢ At the junction a depletion region is formed. This creates barrier which requires approximately .3 V for a Germanium and .7 V for Silicon for conduction to take place.

Summary

- ➢ A diode conducts when forward biased and does not conduct when reverse biased
- ➢ When reversed biased a diode can only withstand so much applied voltage. The voltage at which avalanche current occurs is called reverse breakdown voltage.
- ➢ There are three ways of analyzing a diode. These are ideal, practical, and complex. Typically we use a practical diode model.