Module Introduction

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Dept. of Electrical & Electronic Engineering

Assessment Method

Sequence	Assessment Type	Method	Duration	% of final mark
# 1	EXAM	Final Exam	3 hours	60
# 2	CW	Assignment		10
# 3	CW	Lab Assessment–1		15
# 4	CW	Lab Assessment–2		15

❖ Assignment – 3 Assignments will be given by 3 individual teachers and the average of them is considered for this assessment.

Students’ Performance in 2021-22

Assessment Component (eg. midterm; coursework; exam; project)	Weighting	Credit Weight	No. of Candidates	No. of Absentees	Average Mark	Median	Standard Deviation	Minimum Mark	Maximum Mark	No. of Failures	% of Failure
FORMAL EXAM (70%)	70%	3.5	271	20	52.96	51	24.41	0	96	67	24.72
MIDTERM TEST (10%)	10%	0.5	271	10	50.05	51	25.73	0	99	98	36.16
LAB ASSESSMENT 1 (10%)	10%	0.5	271	20	65.91	70	18.11	0	95	17	6.27
LAB ASSESSMENT 2 (10%)	10%	0.5	271	27	76.26	80	15.79	0	100	7	2.58
Final Marks (100%)	100%	5	271	7	53.56	54	23.89	0	94	74	27.31

Students' Performance in 2022-23

Assessment Component (eg. midterm; coursework; exam; project)	Weighting	Credit Weight	No. of Candidates	No. of Absentees	Average Mark	Median	Standard Deviation	Minimum Mark	Maximum Mark	No. of Failures	% of Failure
FORMAL EXAM (70%)	70%	3.5	348	21	60.38	62	20.64	0	100	39	11.21
MIDTERM TEST (10%)	10%	0.5	348	25	61.81	63	17.34	0	96	28	8.05
LAB ASSESSMENT 1 (10%)	10%	0.5	348	34	70.59	77	21.44	6	100	36	10.34
LAB ASSESSMENT 2 (10%)	10%	0.5	348	58	63.42	69	20.25	0	95	39	11.21
Final Marks (100%)	100%	5	348(10)	9(2)	58.68	62	20.22	0	97	50(3)	14.37

Students' Performance in 2023-24

Assessment Component (eg. midterm; coursework; exam; project)	Weighting	Credit Weight	No. of Candidates	No. of Absentees	Average Mark	Median	Standard Deviation	Minimum Mark	Maximum Mark	No. of Failures	% of Failure
FORMAL EXAM (70%)	70%	3.5	424	24	40.32	41	20.24	0	97	165	38.92
IN-CLASS TEST (10%)	10%	0.5	424	28	51.6	51	22.61	0	95	106	25
LAB ASSESSMENT 1 (10%)	10%	0.5	424	16	78.64	84	17.9	0	100	19	4.48
LAB ASSESSMENT 2 (10%)	10%	0.5	424	30	76.42	82	16.73	4	96.5	21	4.95
Final Marks (100%)	100%	5	424	7(3)	46.95	48	18.61	0	96	126(16)	29.72

Lab Session

The Design of an Operational Amplifier using LTSpice

Session 1:

1) The common emitter amplifier
2) The current mirror circuit
3) The emitter follower

Session 2:

1) The differential input stage
2) The complete operational amplifier circuit

Time: *Week 7 & 13* (***Attendance will be recorded***)

Aims

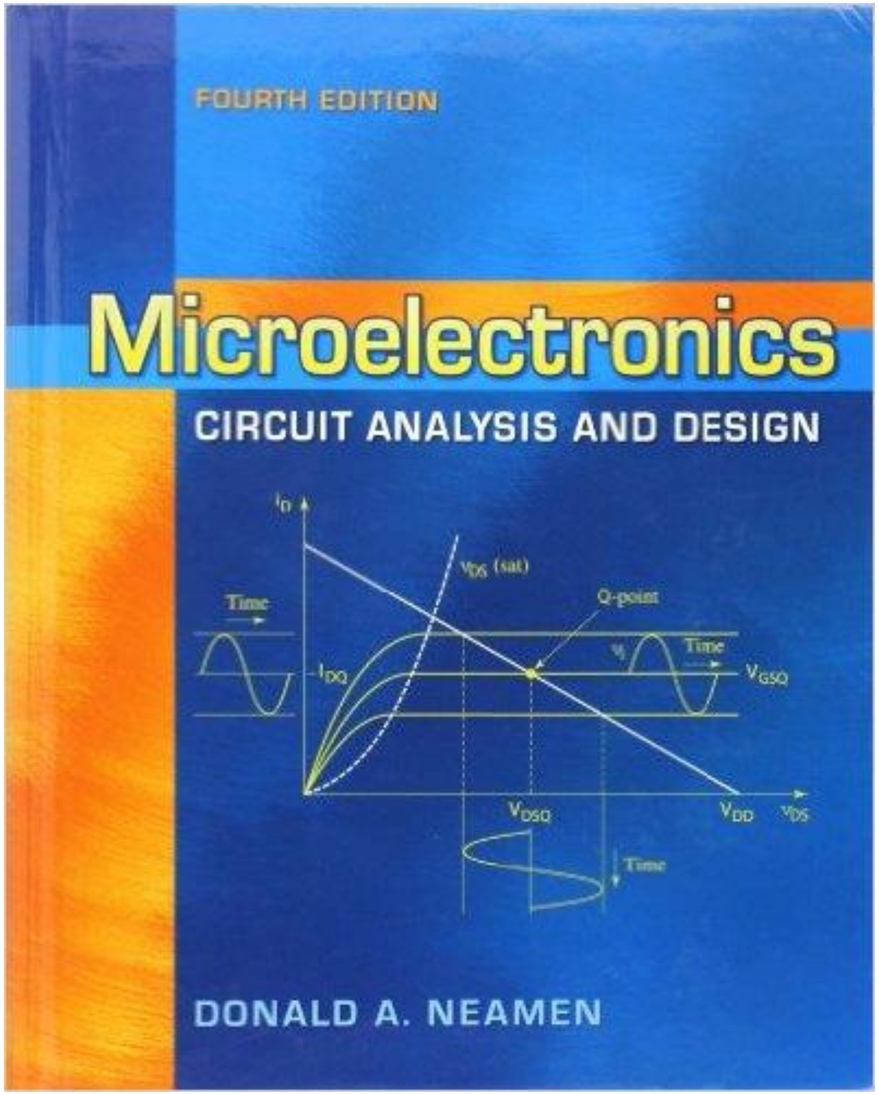
- ✓ To understand how electronic circuits are ***designed***.
- ✓ To understand how electronic devices can be represented by simple, ***linear*** equivalent circuits.
- ✓ To show how complex circuits can be ***sub-divided*** into building blocks and these blocks in turn represented by linear equivalent circuits which can be analyzed using standard circuit techniques.
- ✓ To understand the interaction between the building blocks to allow estimation of important systems parameters such as ***gain***, ***input output resistance*** etc.
- ✓ To appreciate the importance of ***negative feedback*** in improving electronic systems performance and tolerance.

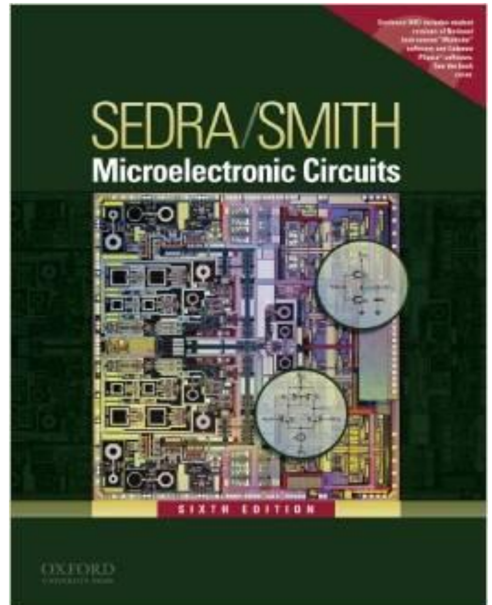
Intellectual Abilities

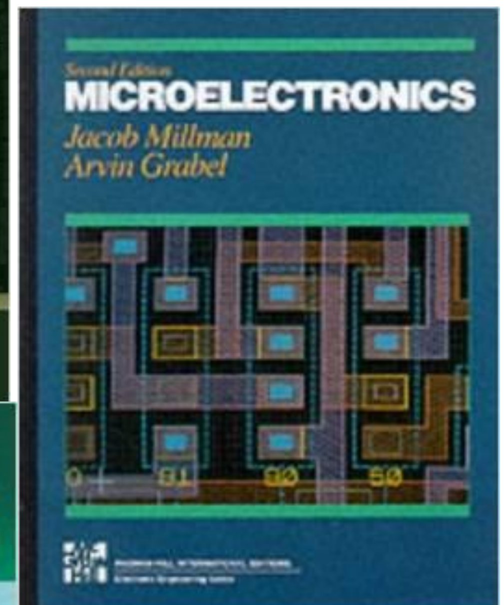
On successful completion of this module, the student should be able to:

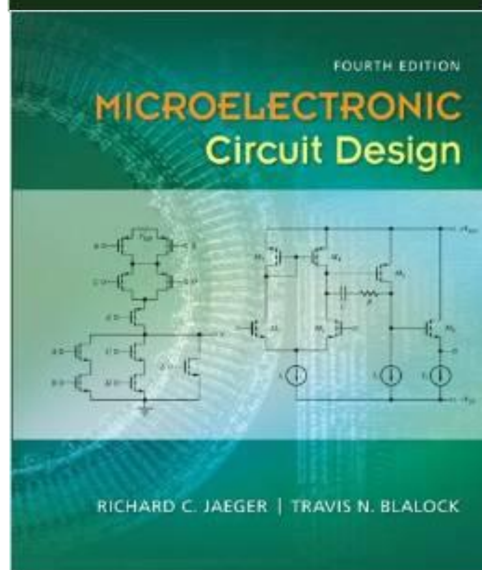
- Compare ***physical device operation*** to ***engineering models***.
- Analyze simple building blocks and show how they can be ***combined to form more complex electronic systems***.
- Analyze ***transistor amplifier performance*** and its ***stability***.
- Construct transistor amplifier circuit.
- Test and analyze electronic circuits.

Text Books (Recommended)









What do you think of the word "Electronics" ?

Televisions

Laptop computers

iPods

Cellphones

Cameras

Electronic Systems – electronic circuits

Includes – amplifiers, signal sources, power supplies, and digital logic circuits

What do you think of the word "Electronics" ?

Electronics:

Science of the motion of charges in a gas, vacuum, or semiconductor – used early in 20th century to distinguish from electrical engineering.

Today, electronics generally involves transistors and transistor circuits.

Microelectronics:

Refers to integrated circuit (IC) technology – can produce a circuit with multimillions of components on a single piece of semiconductor material

A typical electrical engineer will perform many diverse functions – likely to use, design, or build systems incorporating some form of electronics. No clear division between electrical & electronic engineering disciplines.

Review – Electronic Circuits

Passive devices: Resistors, capacitors, and inductors

Inductors and capacitors can store energy, but cannot deliver an average power greater than zero over an infinite time interval.

Active devices: DC power supplies, batteries & ac signal generators

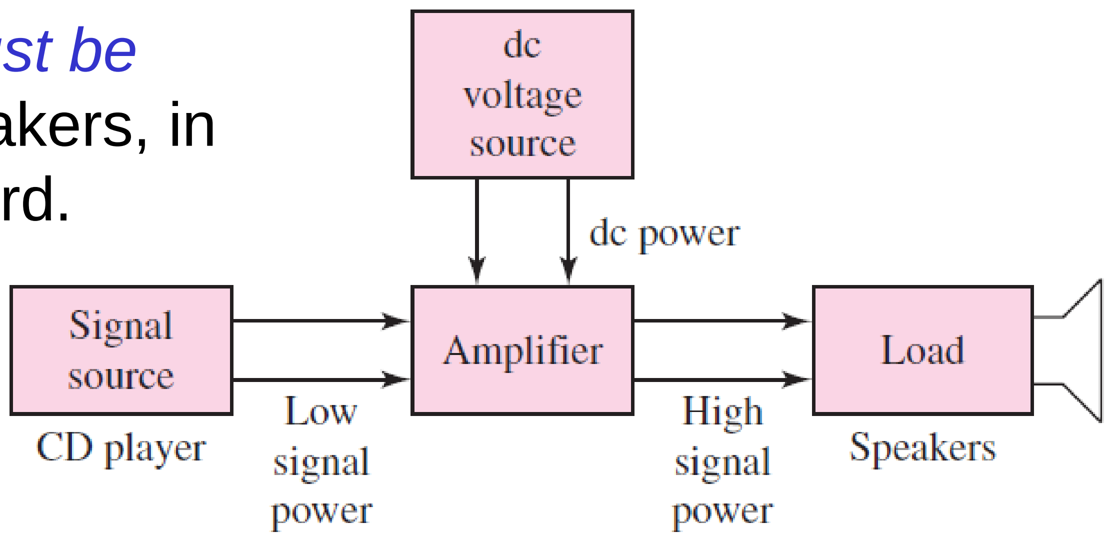
Transistors are also considered as *active devices* in that they are capable of supplying more signal power to a load than they receive – *amplification*.

Review – Electronic Circuits

In most electronic circuits, there are *two inputs* – 1) a *power supply* that provides dc voltages & currents to establish proper biasing for transistors, 2) a *signal* (time-varying signals very often need to be *amplified*).

- ✓ Output music signal from CD system consists of a *small time-varying voltage and current* – means that the signal power is relatively small.
- ✓ Power required to drive the speakers is *larger* than the output signal from CD player.

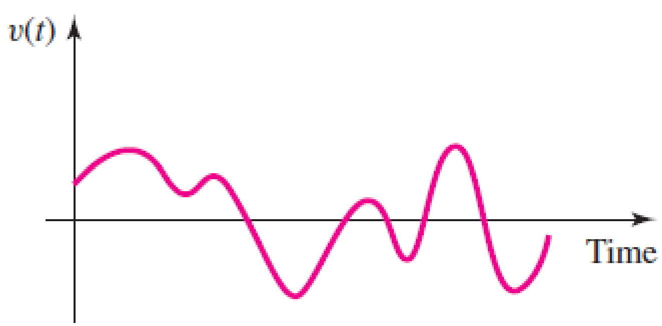
Therefore, the *CD signal must be amplified* before driving speakers, in order that sound can be heard.



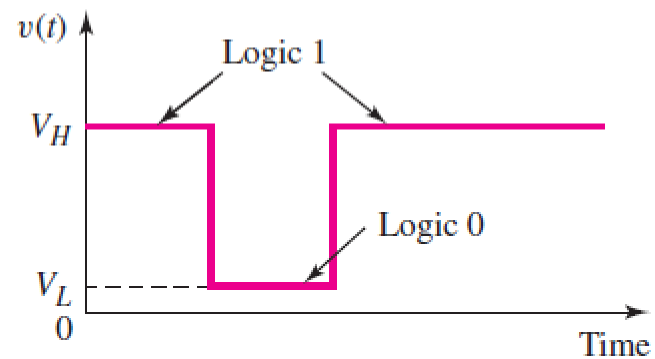
Review – Analog and Digital Signals

Analog signals: Magnitude of an analog signal can take on any value within limits & may vary continuously with time. *Linear amplifier* magnifies an input signal and produces an output signal whose amplitude is larger and directly proportional to the input signal. Vast majority of signals in the "real" world are *analog*.

Digital signals: Since digital signal has discrete values, it is said to be quantized. In many electronic systems, signals are processed, transmitted, and received in digital form. Digital processing allows a wide variety of functions to be performed that would be impractical using analog means.



Analog signal



Digital signal

Semiconductor Materials and Diodes

Outline

✓ Semiconductor Materials and Diodes

- Introduction
- Intrinsic Semiconductors
- Extrinsic Semiconductors
- The pn Junction – Reverse-biased & Forward-biased pn Junctions
- The pn Junction Diode
- Diode Circuits: DC Analysis & Models
- Diode Circuits: AC Equivalent Circuit

Semiconductor Materials – Introduction

Most electronic devices are fabricated by using semiconductor materials along with conductors and insulators.

To gain better understanding of the behavior of electronic devices, it is necessary to understand the characteristics of semiconductor material.

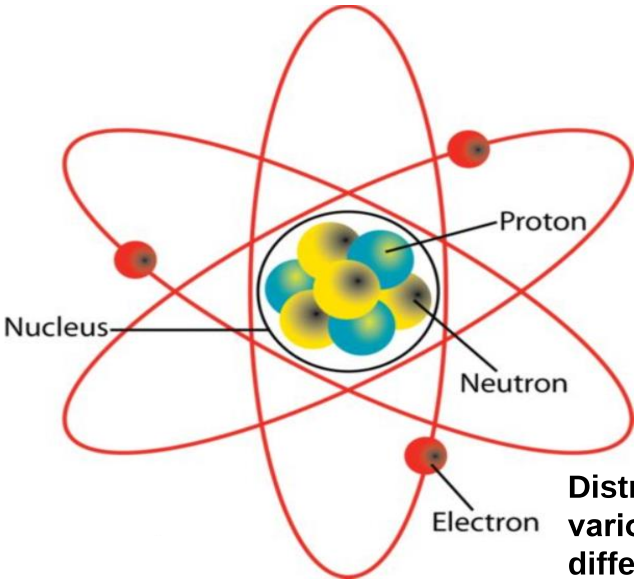
✓ Silicon is by far the most common semiconductor material used for semiconductor devices and integrated circuits.

Elemental semiconductors		Compound semiconductors	
Si	Silicon	GaAs	Gallium arsenide
Ge	Germanium	GaP	Gallium phosphide
		AlP	Aluminum phosphide
		AlAs	Aluminum arsenide
		InP	Indium phosphide

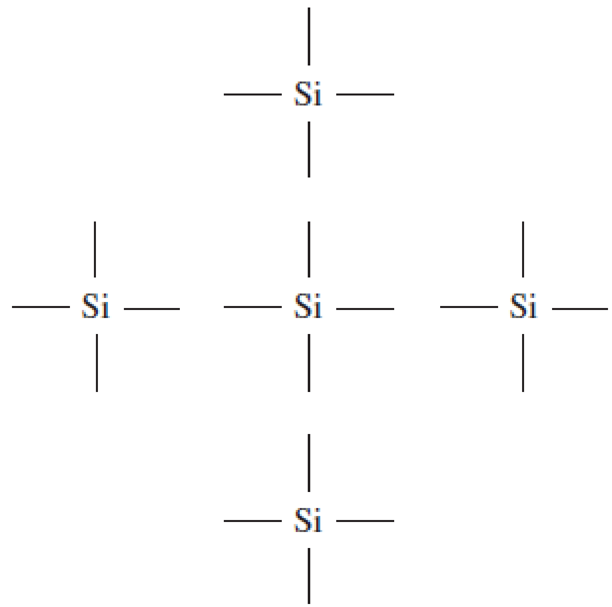
Used for specialized applications – like high speed devices and optical devices.

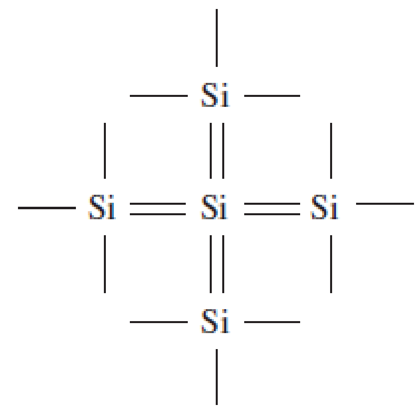
List of semiconductor materials

Semiconductor Materials – Intrinsic



Distributed in various "shells" at different distances from nucleus.



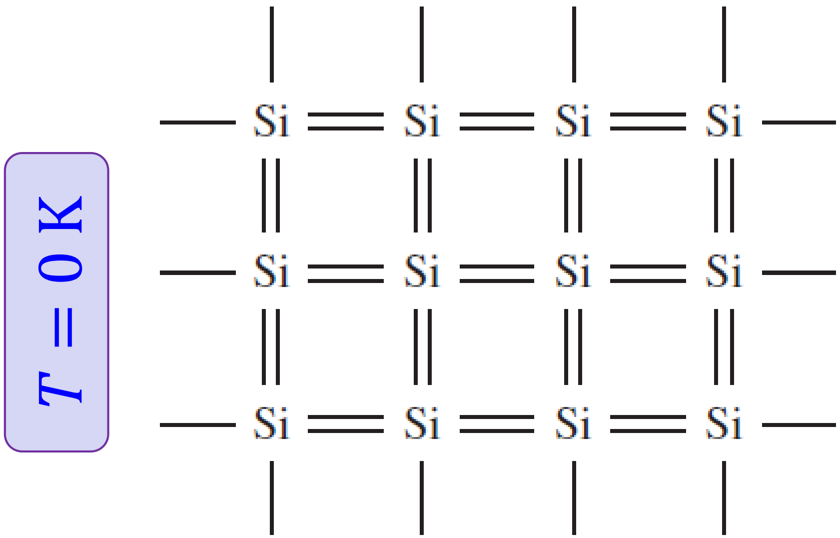


2-dimensional representation showing covalent bonding

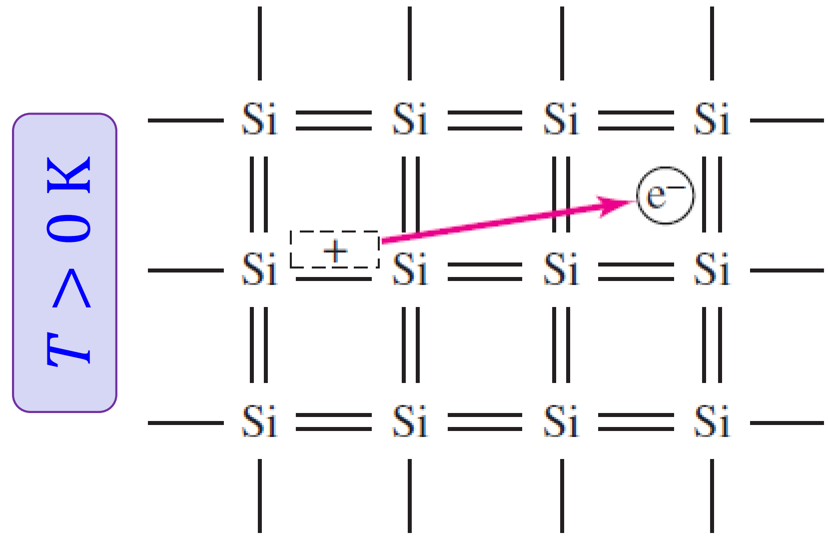
- ✓ Semiconductors, such as silicon (Si) are *made up of atoms bonded together* to form a uniform structure.
- ✓ An *atom consists of a nucleus,* contains positively charged *protons* and neutral *neutrons*, and negatively charged *electrons* that, orbit the nucleus.
- ✓ Each silicon atom has four *valence electrons* which are shared, forming covalent bonds with the *four surrounding Si atoms*.

Electrons in the outermost shell are called "valence electrons"

Semiconductor Materials – Intrinsic



All valence electrons are bound to Si atoms by covalent bonding

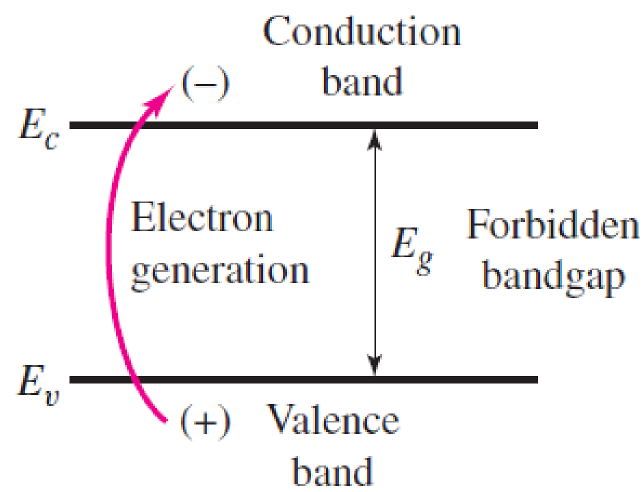


The breaking of covalent bonding, creating an electron in the conduction band & a positively charged "empty state"

- ✓ At $T = 0\ \mathrm{K}$, each electron is in its *lowest possible energy state* – Si is an insulator, no charge flows through it.
- ✓ If the *temperature increases*, the valence electrons may gain thermal energy and break covalent bond, *move away from its original position*.

Semiconductor Materials – Intrinsic

In order to break the covalent bond, the valence electron must gain a minimum energy, called *bandgap energy*. Electrons gain this energy now exist in the conduction band – *free electrons. Net flow of these free electrons generates current.*



Electron gaining enough energy and moving into the conduction band – positively charged "empty state " in the valence band.

Bandgap energy (E_g) is the difference between minimum energy of conduction band (E_c) and maximum energy of valence bond (E_v).

- ✓ Materials that have large bandgap energies, are *insulators*, because, at room temperature, *no free electrons exist* in the conduction band.
- ✓ In contrast, materials that contain very large numbers of free electrons at room temperature are *conductors.*

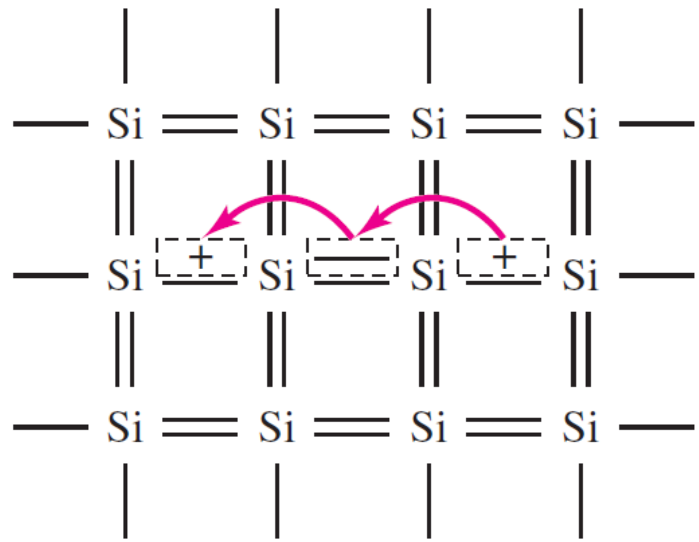
Semiconductor Materials – Intrinsic

- ✓ As the temperature increases, more covalent bonds are broken, and more free electrons and positive empty states are created.

A valence electron that has a certain thermal energy and is *adjacent* to an empty state may move into that position, making it appear as if a positive charge is moving through the semiconductor.

Positively charged “particle” is called a *hole*.

- ✓ In semiconductors, two types of charged particles *contribute* to the current: 1) the negatively charged free electron, 2) the positively charged hole.
- ✓ *Note that the charge of a hole has same magnitude as the charge of an electron.*



A two-dimensional representation of the silicon crystal showing the movement of positively charged “empty state”.

Semiconductor Materials – Extrinsic

Since the electron and hole concentrations in an intrinsic semiconductor are *relatively small, only very small currents are possible*.

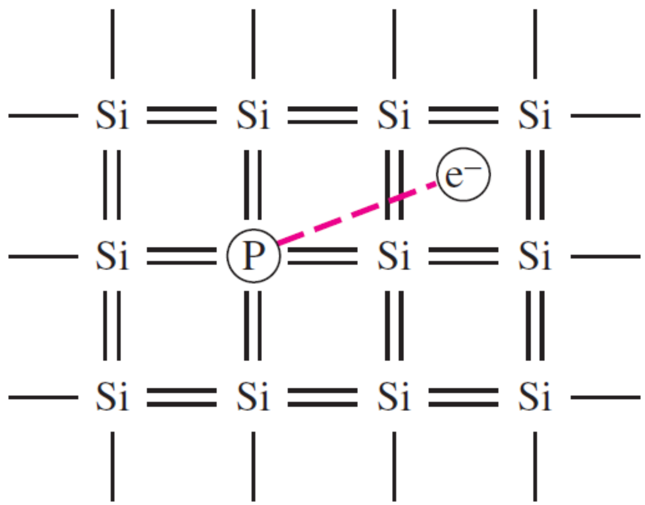
However, these concentrations can be *greatly increased* by *adding* controlled amounts of *certain impurities.* For Silicon, the substitutional impurities are from group V elements (*Ex:* phosphorus (P) and arsenic).

- ✓ When a P atom substitutes for a Si atom, four of its valence electrons are used to satisfy the covalent bond. At room temperature, the fifth valence electron is free to move through the crystal and creates a positively charged P *ion*.

- ✓ *The P atom is called a donor impurity as it donates an electron that is free to move.*

- ✓ *Doping*

A semiconductor that contains donor impurity atoms is called an ***n-type semiconductor*** and has preponderance of electrons compared to holes.

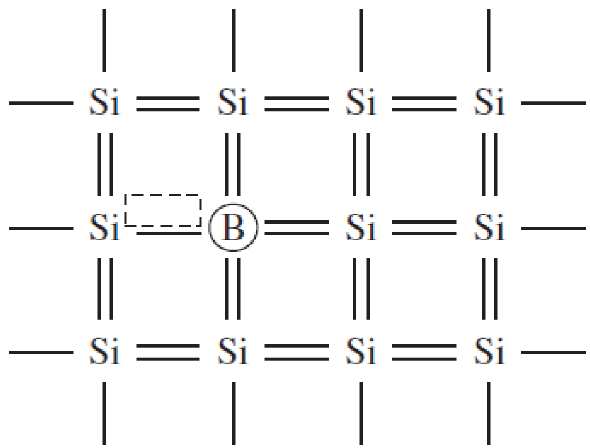


A two-dimensional representation of the silicon lattice doped with phosphorous atom, showing fifth phosphorous valence electron.

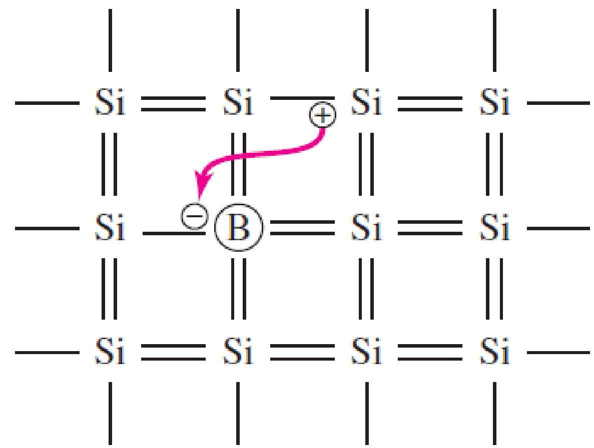
Semiconductor Materials – Extrinsic

- ✓ *Boron* from group III element can also be used for Si doping. When boron atom replaces Si, its 3 valence electrons are used to satisfy covalent bond requirements for 3 of 4 nearest Si atoms – leaves one bond position open.
- ✓ At *room temperature*, adjacent Si move into this position, creates a *hole*.
- ✓ Boron is an *acceptor impurity,* as it has accepted a valence electron.
- ✓ Acceptor atoms lead to the creation of holes without electrons being generated – this process is also called doping.

A semiconductor that contains acceptor impurity atoms is called an ***p-type semiconductor*** and has preponderance of holes compared to electrons.



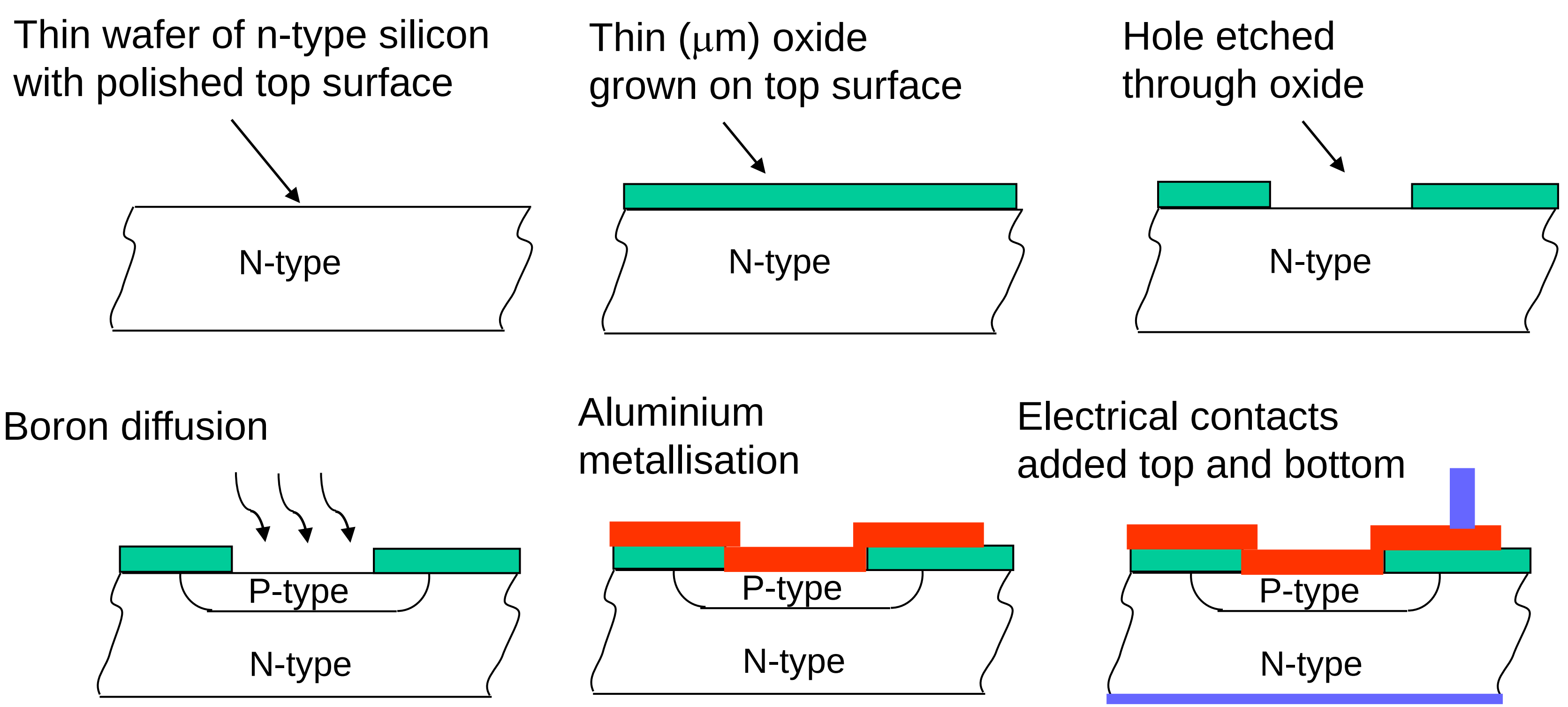
A two-dimensional representation of the silicon lattice doped with boron atom, showing the vacant covalent bond position.



The resulting negatively charged boron ion after it has accepted an electron from the valence band – positively charged hole is created.

Semiconductor Materials – The pn junction

- The real power of semiconductor electronics occurs when p- and n-regions are directly adjacent to each other, forming a ***pn junction.***
- Diodes are often made by starting with n-type silicon and adding boron in well defined regions – hence creating a pn junction.

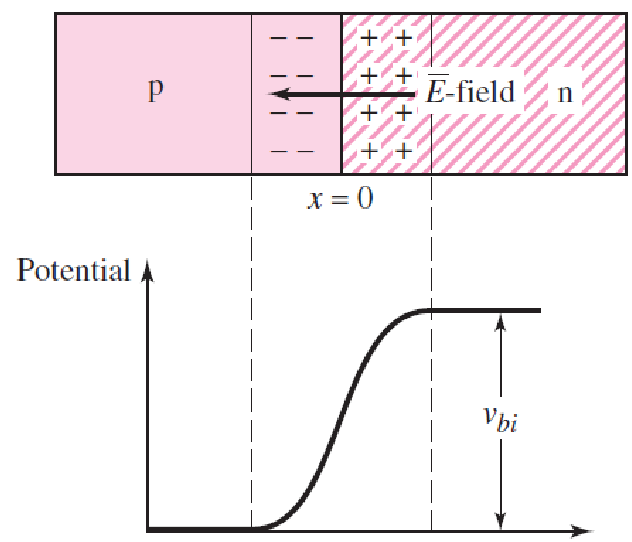


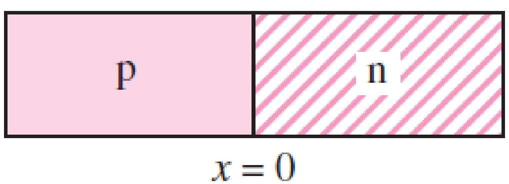
Semiconductor Materials – The pn junction

- ✓ Initially, a diffusion of holes from the p-region into n-region, and a diffusion of electrons from the n-region into the p-region – *creates an electric field*.
- ✓ If no voltage is applied to pn junction, the diffusion of holes and electrons must eventually cease – direction of the induced electric field will cause the resulting force to repel the diffusion of holes & electrons respectively.

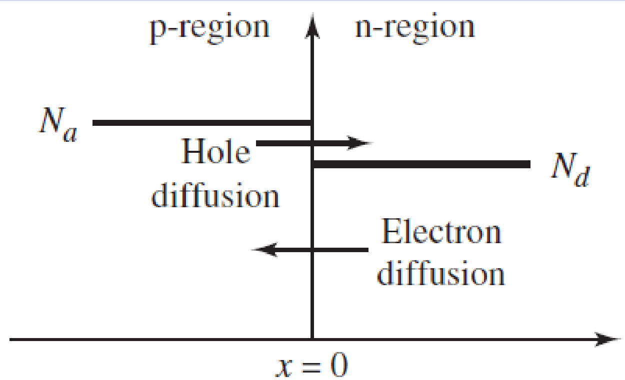
Built-in potential barrier, $V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{{n_i}^2}\right) = V_T \ln\left(\frac{N_a N_d}{{n_i}^2}\right)$

$V_T = 0.026\,V@300\,K,$ thermal voltage; $k =$ Boltzmann's constant;
$T =$ absolute temperature; $e =$ magnitude of electronic charge;
$n_i =$ intrinsic carrier concentration





PN junction – interface $x = 0$ is metallurgical junction.



Initial diffusion of electrons and holes across metallurgical junction

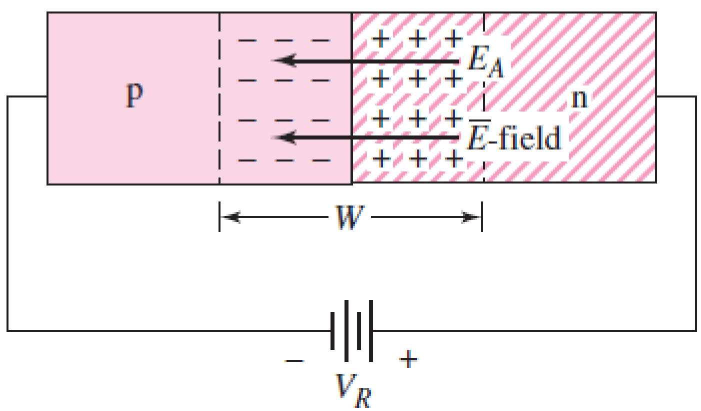
Electric field from n- to p- region & potential through the junction

Reverse-biased pn junction

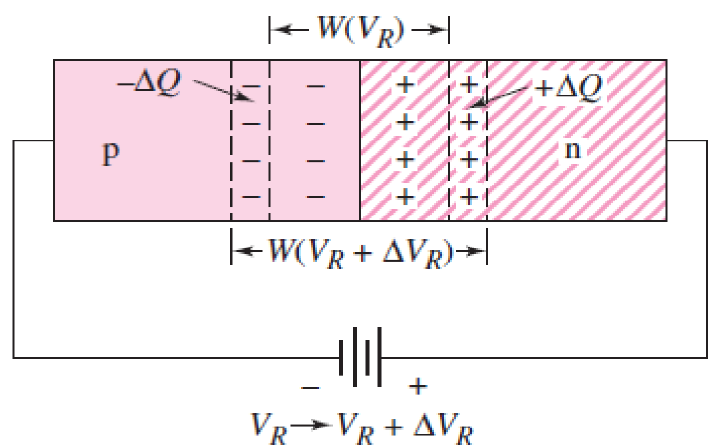
- ✓ Assume a positive voltage (V_R) is applied to the n-region of a pn junction – induces an electric field (E_A) in the semiconductor – *direction is same*.
- ✓ Magnitude of electric field *in* the space-charge region increases above the thermal equilibrium value – it holds back the holes in p-region & electrons in n-region, therefore, *no current* across the pn junction, *reverse bias polarity.*
- ✓ Due to increase in space-charge width with increase in reverse-bias voltage, *additional charges ($\pm\Delta Q$) will be induced*, which leads to junction capacitance, or depletion layer capacitance (C_j) .

$$C_j = C_{jo}\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2}$$

C_{jo} – junction capacitance at zero applied voltage.



PN junction with an applied reverse-bias voltage. Both electric fields are in the same direction.



Increase in space-charge width with an increase in reverse-bias voltage.

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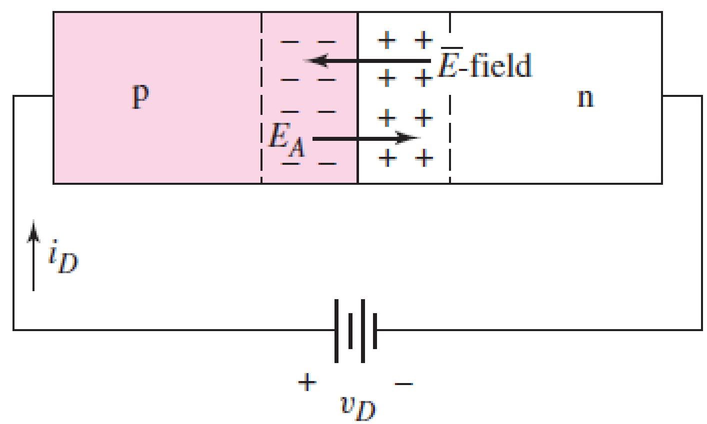
Forward-biased pn junction

- ✓ If positive voltage (v_D) is applied to p-region – *potential barrier decreases*.
- ✓ Applied electric field (E_A) is in the *opposite direction to the thermal equilibrium space charge E-field* – the net electric field in the space-charge region is lower than the thermal equilibrium
- ✓ Majority carrier electrons from n-region diffuse into the p-region & majority carrier holes from the p-region diffuse into the n-region, it continues as long as v_D is applied – *creates a current in the pn junction*.

The theoretical relationship between the voltage and current in the pn junction is

$$i_D = I_S\left[e^{\left(\frac{v_D}{nV_T}\right)} - 1\right]$$

$I_S -$ reverse-bias saturation current; 10^{-18} to 10^{-12} A
$n -$ emission coefficient & its range is $1 \leq n \geq 2$.



Smaller net electric field and smaller barrier between p- and n-regions

An Example–1

Exercise–1: Determine the current in a pn junction diode. Consider a pn junction at $T = 300\ K$ in which $I_S = 10^{-14} A$ and $n = 1$. Find the diode current for $v_D = +0.7\ V\ \&\ -0.7\ V$.

Solution

For $v_D = +0.7\ V$, the pn junction is *forward-biased* and we can get

$$i_D = I_S\left[e^{\left(\frac{v_D}{nV_T}\right)} - 1\right] = 10^{-14}\left[e^{\left(\frac{+0.7}{1(0.026)}\right)} - 1\right] = 4.93\ mA$$

For $v_D = -0.7\ V$, the pn junction is *reverse-biased* and we can get

$$i_D = I_S\left[e^{\left(\frac{v_D}{nV_T}\right)} - 1\right] = 10^{-14}\left[e^{\left(\frac{-0.7}{1(0.026)}\right)} - 1\right] \cong -10^{-14} A$$

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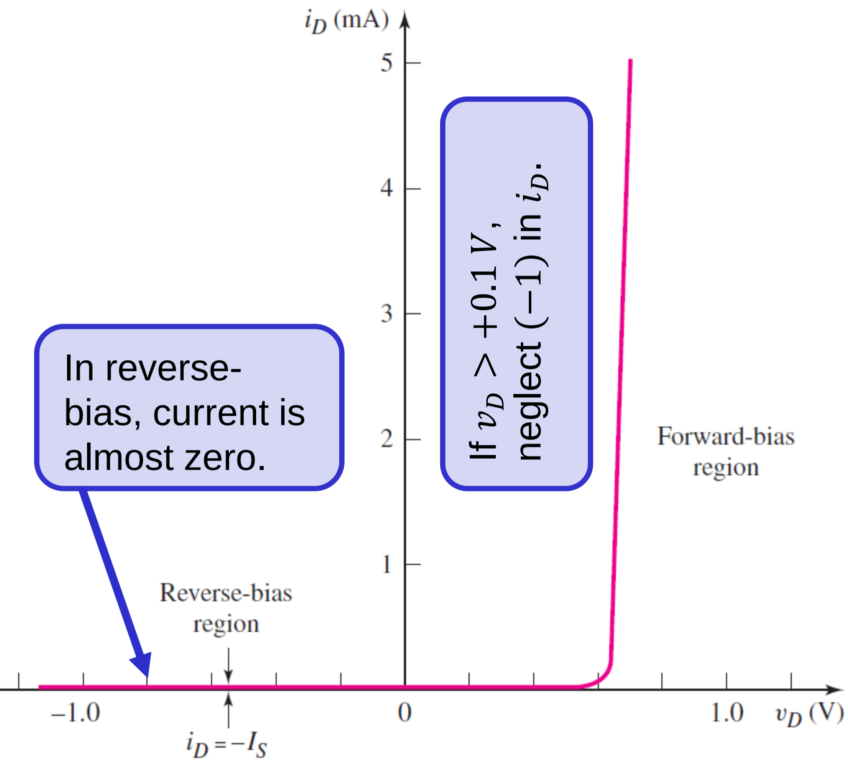
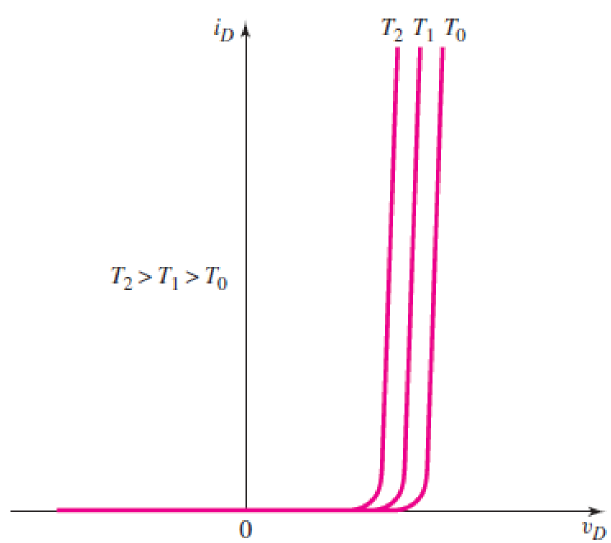
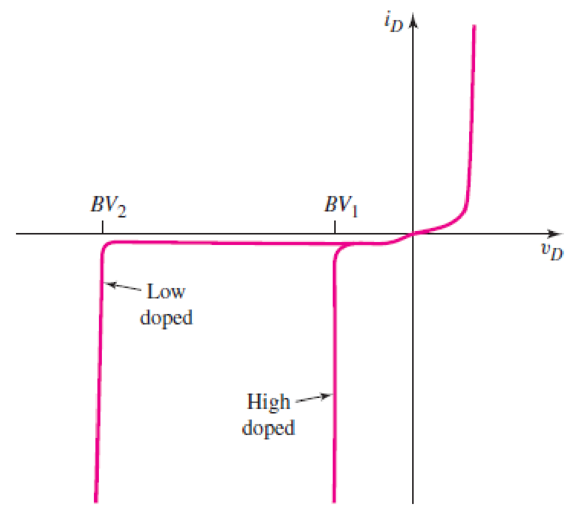
Ideal I–V characteristics of pn junction diode

For a forward-bias voltage, the current is an exponential function of voltage. Since I_S & V_T are functions of temperature, diode characteristics also vary with temperature. When reverse bias voltage is applied to a pn junction, the electric field in the space charge region increases – creates *breakdown*.





Forward-biased pn junction characteristics vs temperature.



Reverse-biased diode characteristics .

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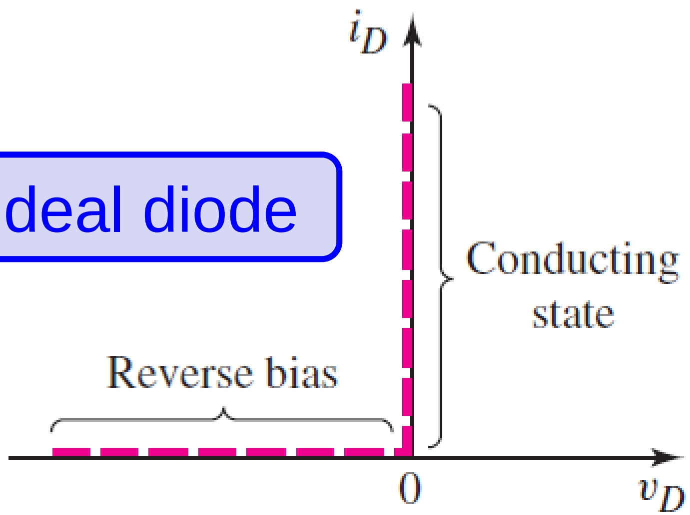
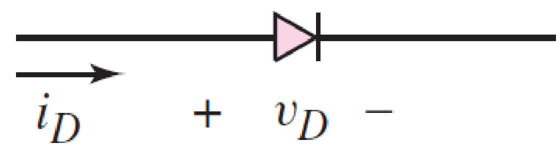
Diode Circuits: DC Analysis and Models

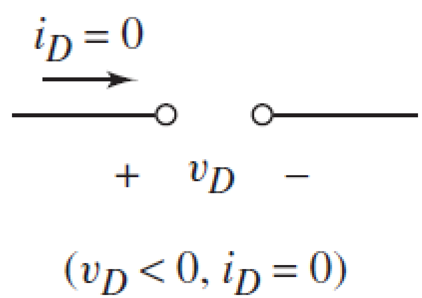
- ✓ The diode is a two-terminal device with *nonlinear $i - v$ characteristics*. *Analysis* of nonlinear electronic circuits is *not straightforward*.
- ✓ *Mathematical relationships*, or *models*, simplify the analysis of diode circuits and make the analysis of relatively complex circuits *much easier*.
- ✓ Consider a small-signal model of the diode that describes the behavior of pn junction with small changes in voltages and currents.

Ideal diode

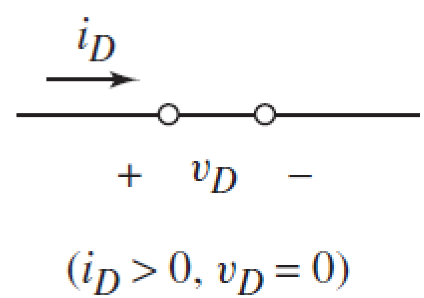


$I - V$ characteristics of ideal diode.





Equivalent circuit in under reverse-bias.



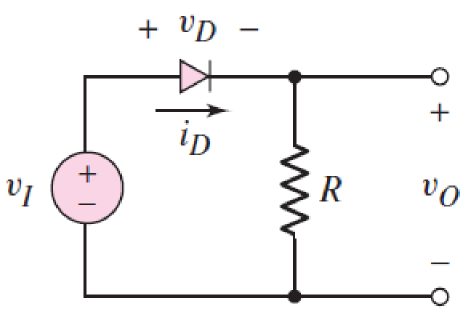
Equivalent circuit in the conduction state.

Diode Circuits: DC Analysis and Models

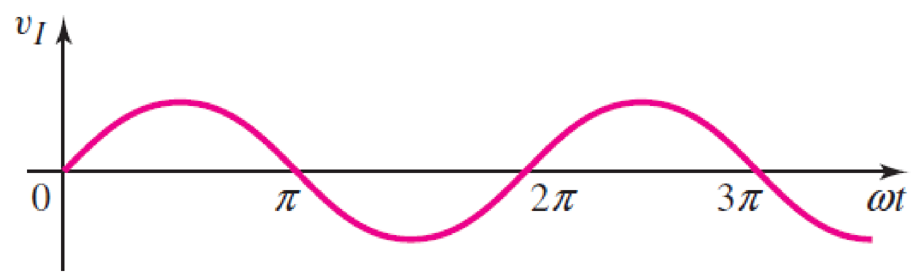
<u>Example: Rectifier as a diode circuit</u>

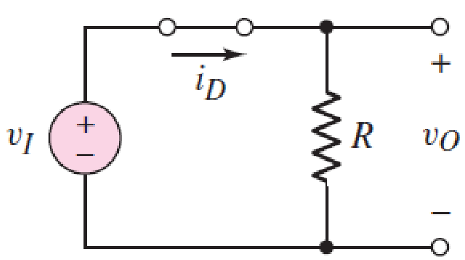
✓ Assume that the input voltage v_I is sinusoidal signal & diode is ideal diode.

✓ The output signal contains only positive values & therefore has a positive average value – rectified the input signal & generates *dc voltage* from *ac*.

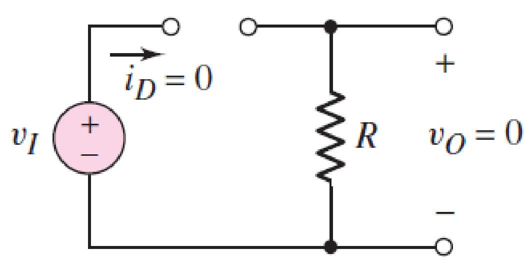


(a)

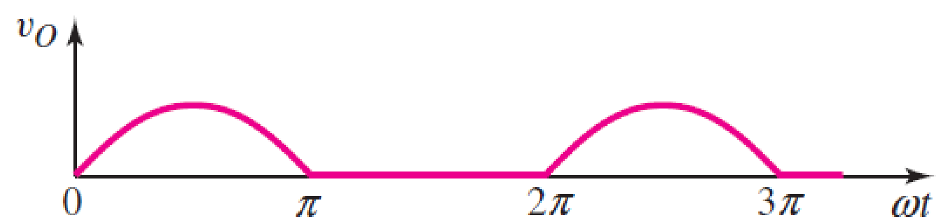




$v_I > 0$



$v_I < 0$

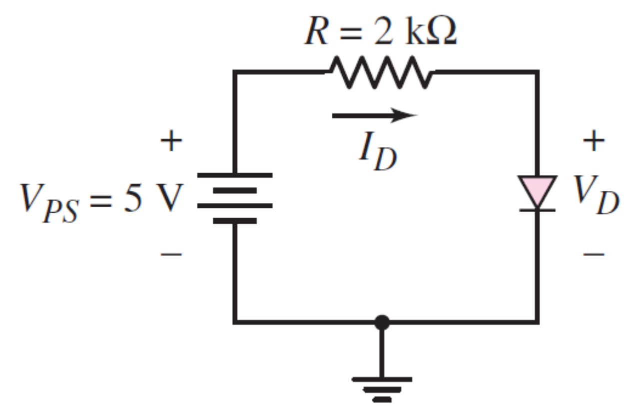


Sinusoidal input signal and the corresponding rectified output signal.

Diode Circuits: DC Analysis and Models

Three approaches to the dc analysis of diode circuits:

1. Iteration and graphical analysis: *Iteration* means trial and error process; *graphical analysis* involves plotting two simultaneous equations & locating their point of intersection.



$$V_{PS} = I_D R + V_D \;\rightarrow\; I_D = \frac{V_{PS}}{R} - \frac{V_D}{R}$$

But, we know, $I_D = I_S\left[e^{\left(\frac{V_D}{V_T}\right)} - 1\right]$

We can combine and write, $V_{PS} = I_S R\left[e^{\left(\frac{V_D}{V_T}\right)} - 1\right] + V_D$

This equation is a transcendental equation and cannot be solved directly. *Use iteration to find the value for unknown value V_D.*

Try to determine the values for V_D and I_D using iteration method for $I_S = 10^{-13} A$.

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Diode Circuits: DC Analysis and Models

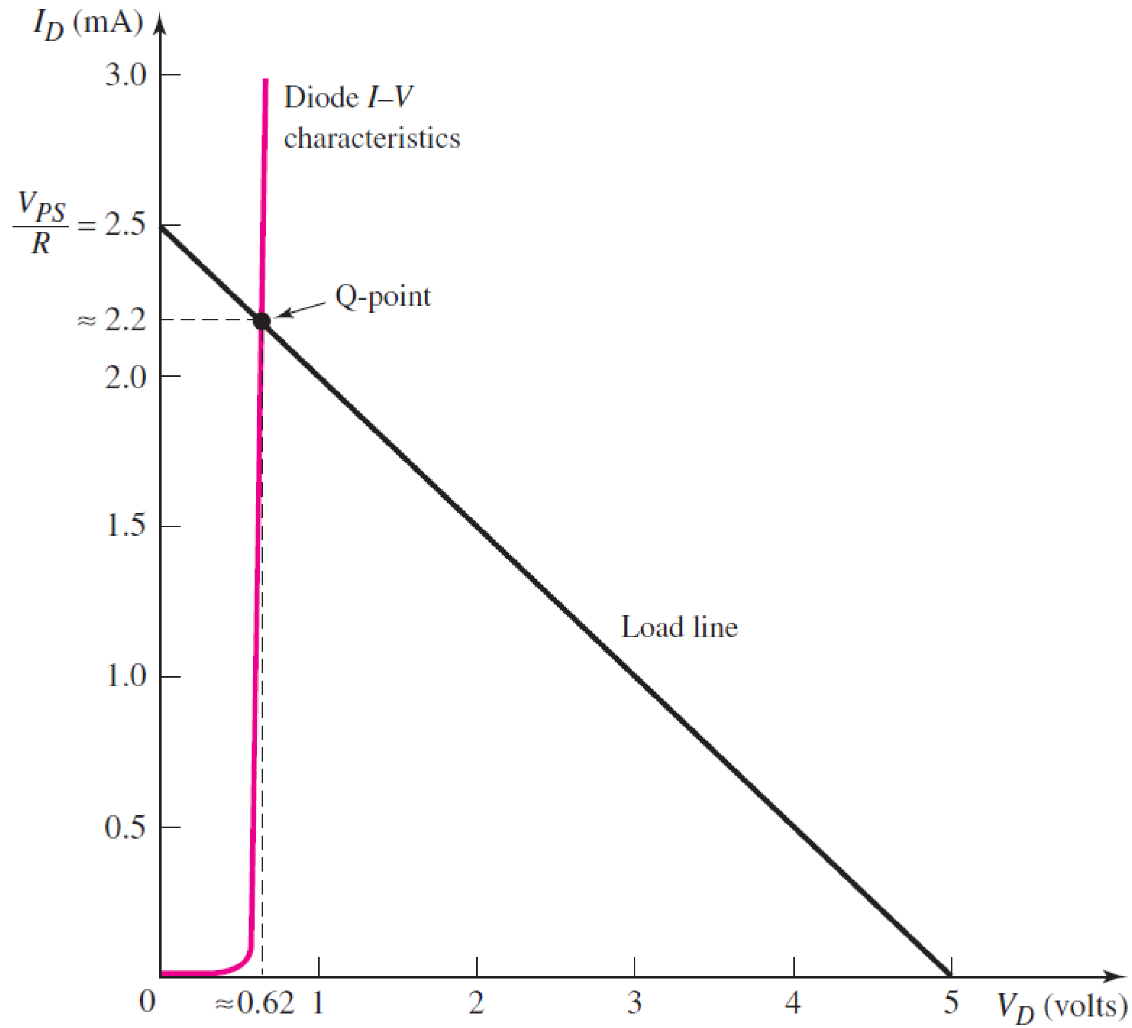
Consider the following equation to use a graphical approach to analyze circuit

$$I_D = \frac{V_{PS}}{R} - \frac{V_D}{R}$$

It gives a linear relation between I_D & V_D for a given supply voltage V_{PS} and resistor R – circuit ***load line***.

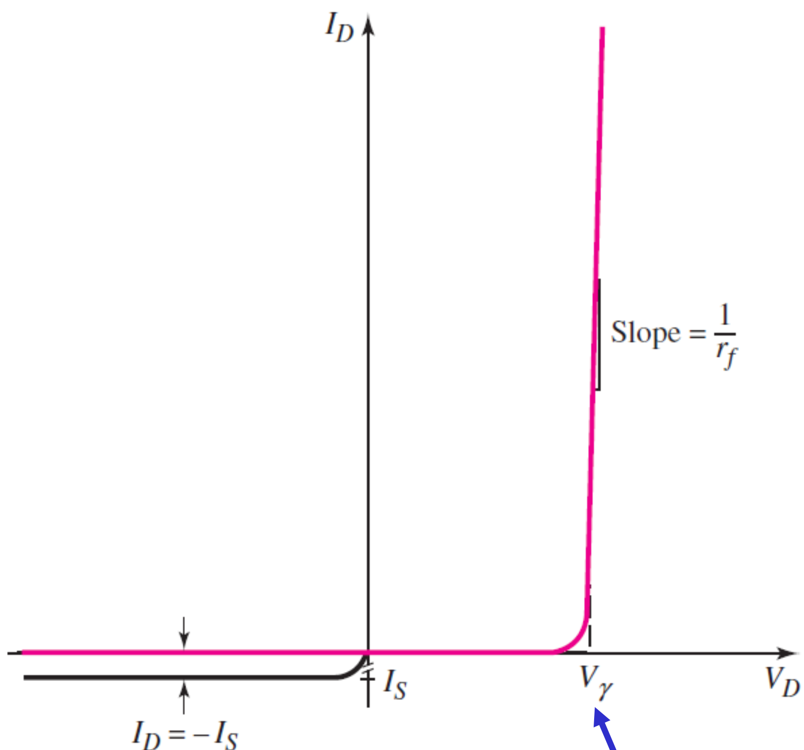
Using the values in the previous exercise problem, we can plot the straight line as shown here

Intersection of load line and device characteristics curve provides $I_D \approx 2.2\ mA$ through diode & $V_D \approx 0.62\ V$ across the diode – this point is called ***quiescent*** or ***Q-point***.



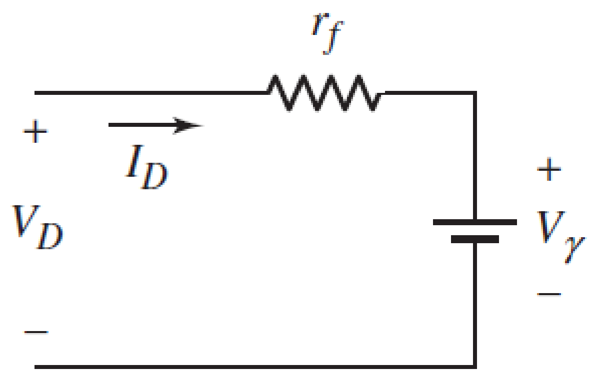
Diode Circuits: DC Analysis and Models

2. Piecewise linear model: analyze diode circuits to *approximate* the diode's current-voltage characteristics, using linear relationships or straight lines.

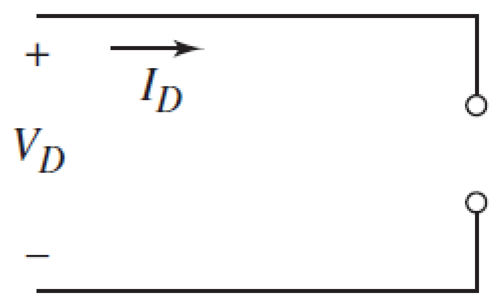


Diode $I - V$ characteristics and two linear approximations.

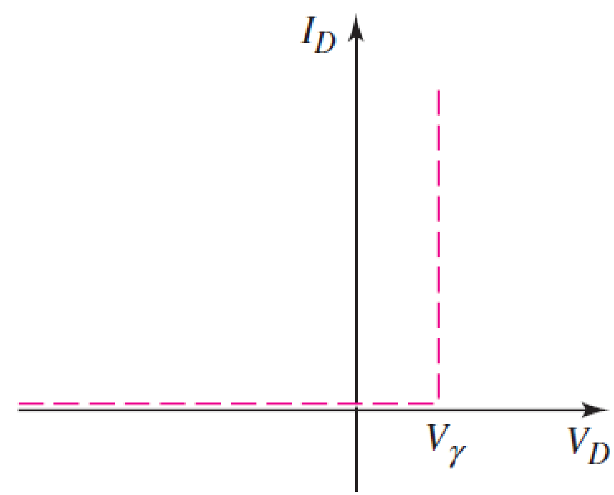
Turn-on, or cut-in voltage



$V_D \geq V_\gamma$



$V_D < V_\gamma$



Piecewise linear approximations when $r_f = 0$.

Diode Circuits: DC Analysis and Models

3. Computer simulation: Todays computers are capable of using detailed simulation models of various components and performing complex circuit analyses quickly and relatively easily.

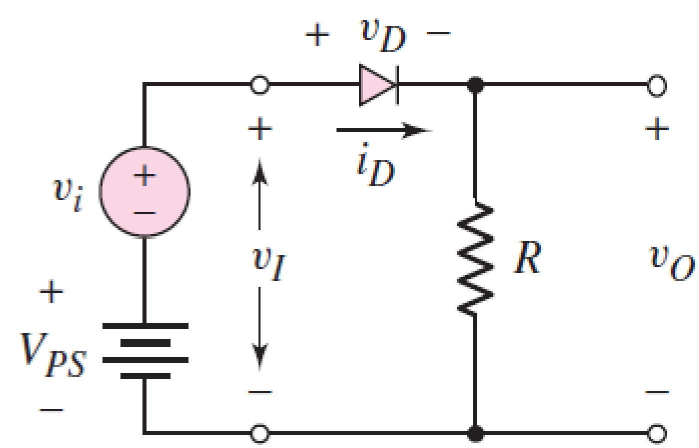
One of the earliest and now mostly widely used, circuit analysis programs SPICE, developed at the University of California at Berkeley, 1973.

You will use recent version **LTSpice** to program during your lab sessions.

Diode Circuits: AC Equivalent Circuit

When semiconductor devices with pn junctions are used in *linear amplifier* circuits, the *time-varying, or ac*, characteristics become important, because *sinusoidal signals may be superimposed* on the dc current and voltages.

- ✓ The voltage source v_i is assumed to be a sinusoidal, or time-varying signal.
- ✓ The total input voltage v_I is *composed* of a dc component V_{PS} and an ac component v_i superimposed on the dc value.



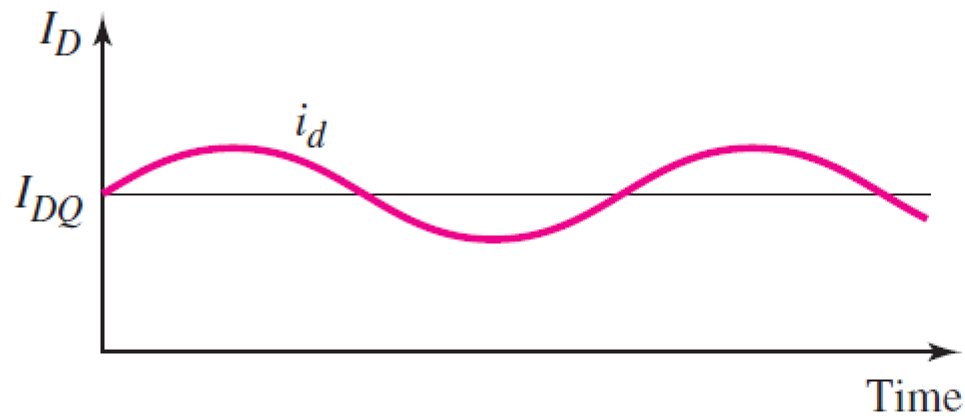
To investigate this circuit, two types of analyses are considered:

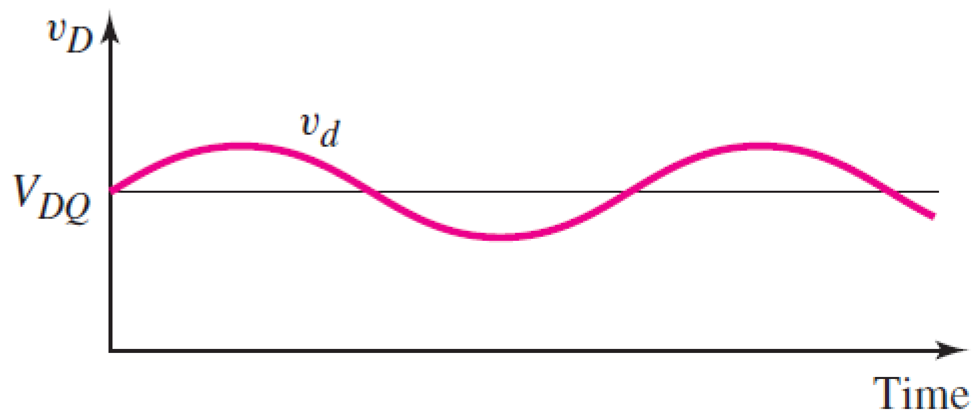
1) A *dc analysis* involving only the *dc voltage and currents*,

2) An *ac analysis* involving only the *ac voltage and currents*.

Diode Circuits: AC Equivalent Circuit

- ✓ Since input voltage contains a dc component with an ac signal superimposed, the diode current will also contain dc component with ac signal superimposed – I_{DQ} is the dc *quiescent diode current*.
- ✓ In addition, the diode voltage will contain a dc value with an ac signal superimposed.
- ✓ Assume that the *ac signal is small compared to the dc component*, so that a linear ac model can be developed.





Diode Circuits: AC Equivalent Circuit

The relationship between the diode current and voltage can be written as

$$i_D \cong I_S e^{\left(\frac{v_D}{V_T}\right)} = I_S e^{\left(\frac{V_{DQ}+v_d}{V_T}\right)} = I_S \left[e^{\left(\frac{V_{DQ}}{V_T}\right)}\right]\left[e^{\left(\frac{v_d}{V_T}\right)}\right]$$

Neglect – 1 term

where, V_{DQ} is the dc quiescent voltage and v_d is the ac component. If the ac signal is small, $v_d \ll V_T$, and *expand the exponential term* into linear series,

$e^{\left(\frac{v_d}{V_T}\right)} \cong 1 + \frac{v_d}{V_T}$ and quiescent diode current can be written as $I_{DQ} = I_S e^{\left(\frac{V_{DQ}}{V_T}\right)}$.

Therefore, the diode current-voltage relationship can be deduced as,

$$i_D = I_{DQ}\left(1 + \frac{v_d}{V_T}\right) = I_{DQ} + \frac{I_{DQ}}{V_T}\, v_d = I_{DQ} + i_d$$

r_d & g_d are diffusion resistance and conductance

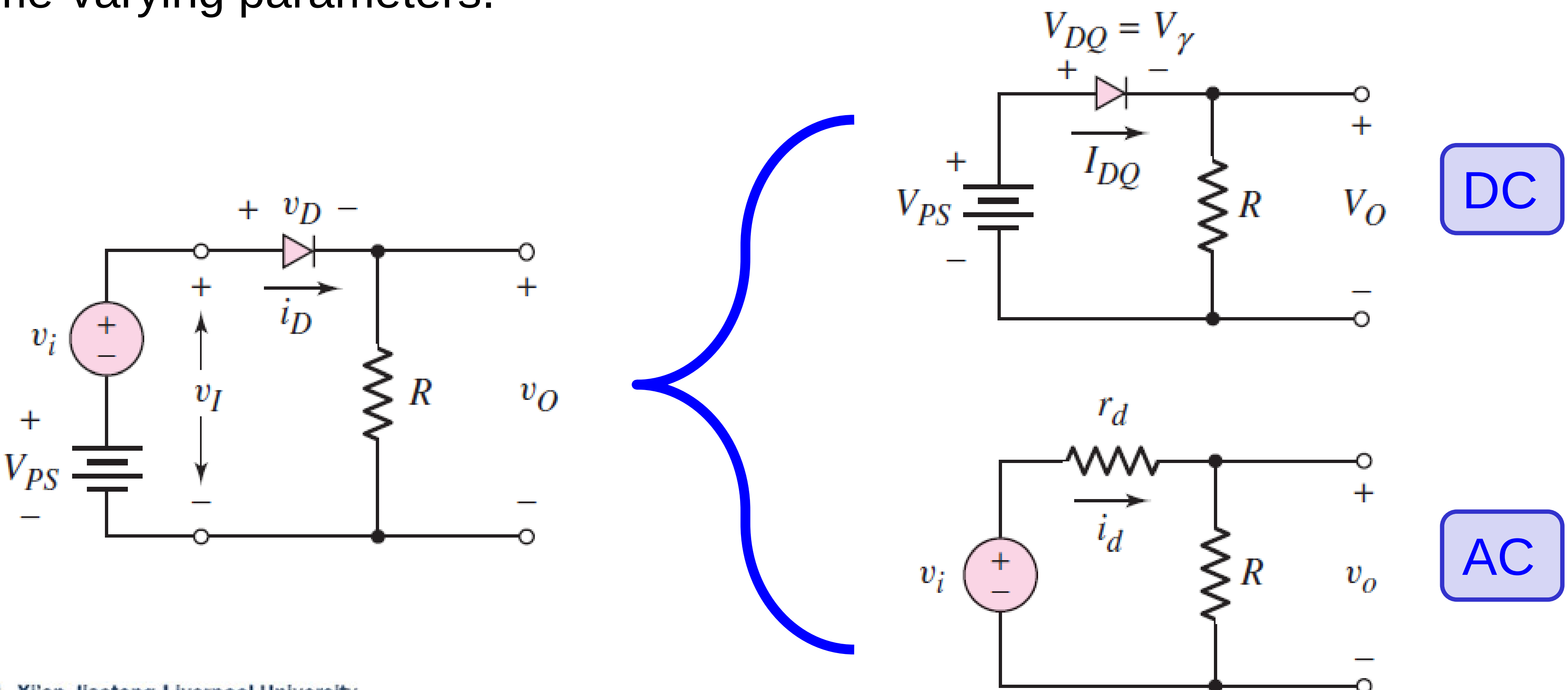
Here, $i_d = \left(\frac{I_{DQ}}{V_T}\right) \times v_d = g_d \times v_d$ is the ac component of diode current and

$$v_d = \left(\frac{V_T}{I_{DQ}}\right) \times i_d = r_d \times i_d;$$

$$r_d = \frac{1}{g_d} = \frac{V_T}{I_{DQ}}$$

Diode Circuits: AC Equivalent Circuit

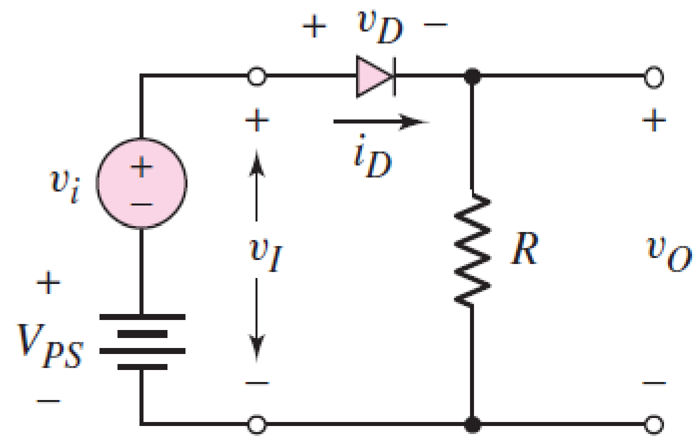
Circuit analysis: We first perform dc analysis and then an ac analysis – they use two equivalent circuits. In the ac equivalent circuit, the diode has been replaced by its equivalent resistance r_d and all parameters are small-signal time-varying parameters.



Equivalent circuits

Diode Circuits: AC Equivalent Circuit

Exercise–2: Assume circuit and parameters of $V_{PS} = 5\,V, R = 5\,k\Omega, V_\gamma = 0.6\,V$, and $v_i = 0.1\sin\omega t\ V$. Analyze the circuit.



Solution:

For the *dc* analysis, we set $v_i = 0$ & find I_{DQ}.

$$I_{DQ} = \frac{V_{PS} - V_\gamma}{R} = \frac{5-0.6}{5} = 0.88\,mA$$

The *dc* value of output voltage is, $V_o = I_{DQ}R = 0.88 \times 5 = 4.4\,V$.

For the ac analysis, we consider only ac signals and parameters in the circuit. By using KVL, $v_i = i_d r_d + i_d R = i_d(r_d + R)$.

The $r_d = \frac{V_T}{I_{DQ}} = \frac{0.026}{0.88} = 0.0295\,k\boldsymbol{\Omega}$. Then, $i_d = \frac{v_i}{r_d + R} = \frac{0.1\sin\omega t}{0.0295+5} \rightarrow 19.9\sin\omega t\ \mu A$

The ac component of output voltage is

$$v_o = i_d R = 0.0995\sin\omega t\ V$$

Summary:–

- ✓ Silicon is by far the most common semiconductor material used for semiconductor devices and integrated circuits – *Intrinsic* and *Extrinsic*.
- ✓ The real power of semiconductor electronics occurs when p- and n-regions are directly adjacent to each other, forming a *pn junction.*
- ✓ The theoretical relationship between the voltage and current in the pn junction is

$$i_D = I_S \left[e^{\left(\frac{v_D}{nV_T}\right)} - 1 \right]$$

- ✓ *Mathematical relationships*, or *models*, simplify the analysis of diode circuits and make the analysis of relatively complex circuits *much easier*.
- ✓ A linear relation between I_D & V_D for a given supply voltage V_{PS} and resistor R – called circuit *load line.*
- ✓ Intersection of load line & device characteristics curve provides Q –point.

See you in the next class

The End