# EEE 3571 Electronic Engineering I

## Lecture 1:

## Analog Electronics Semiconductor Diodes

Dr. Daliso Banda

daliso.banda@unza.zm

Department of Electrical & Electronic Engineering, School of Engineering, University of Zambia

# Course Requirements

- ✓It is an **OBLIGATION** for all students taking this course to attend all lectures and lab sessions.

**Prerequisite**

- ✓EEE 2019

**Simulation Software**: Multisim

**Time Allocation**

| | |
|---|---|
| ✓Lectures | **4 hours/week** |
| ✓Labs | **3 hours/week** |

**Assessment**

| | |
|---|---|
| ✓Assignments (8) /Quizzes | **5%** |
| ✓Labs/Mini-Projects | **15%** |
| ✓1 Test (2 hours) | **20%** |
| ✓1 Final Exam (3 hours) | **60%** |

# Course Outline

**Analog Electronics:**

- ❑ Review of semiconductors, Diode and transistor fundamentals. PN junction and bipolar junction transistor theories. Zener and avalanche effects.
- ❑ Transistor small signal models; hybrid parameters.

**The Transistor as an Amplifier:**

- ❑ Common base (CB), common emitter (CE), and common collector (CC) configuration.
- ❑ DC biasing, cut-off, saturation, load lines, signal swing. Voltage and current amplification factors, input and output impedance, Cascading.

**Operational Amplifiers:**

- ❑ Basic characteristics; input and output impedance, open loop gain.
- ❑ The ideal operational amplifier, differential amplifier. Effects of drift, and offset error voltages and currents.
- ❑ Applications: voltage and current follower, inverting and non-inverting, addition and subtraction, analog integration and differentiation, comparator, regulator.

**Wave Generation & Shaping:**

- ❑ Diode clipping and clamping, regenerative comparator (Schmitt trigger). Square and triangular wave generators. Astable, bistable and multistable vibrators.

# References

Our main reference text books in this course are:


1. Neil S., Electronics: A Systems Approach, 4th edition, 2009, Pearson Education Limited, ISBN 978-0-273-71918-2.
2. Boylestad R. L., Nashelsky L., Electronic Devices and Circuit Theory, 11th Ed, 2013, Prentice-Hall, ISBN 978-0-13-262226-4.
3. Smith R. J., Dorf R. C., Circuits Devices and Systems, 5th Ed., 2004, John Wiley, ISBN ISBN 9971-51-172-X.
4. Class Notes: Dr Brilliant Habeenzu


However, feel free to use some additional text which you might find relevant to our course.

# Learning Objectives

At the end of a series of lectures on semiconductor diodes, you ought to:

1. Know the general characteristics of three important semiconductor materials: Si, Ge, GaAs.
2. Understand conduction using electron and hole theory.
3. Be able to describe the difference between *n* - and *p* - type materials.
4. Know basic operation and characteristics of a diode in no-bias, forward-bias, and reverse-bias regions.
5. Be able to calculate the dc, ac, and average ac resistance of a diode from the characteristics.
6. Understand the impact of an equivalent circuit, ideal or practical.
7. Be familiar with the operation and characteristics of a Zener diode and light-emitting diode.

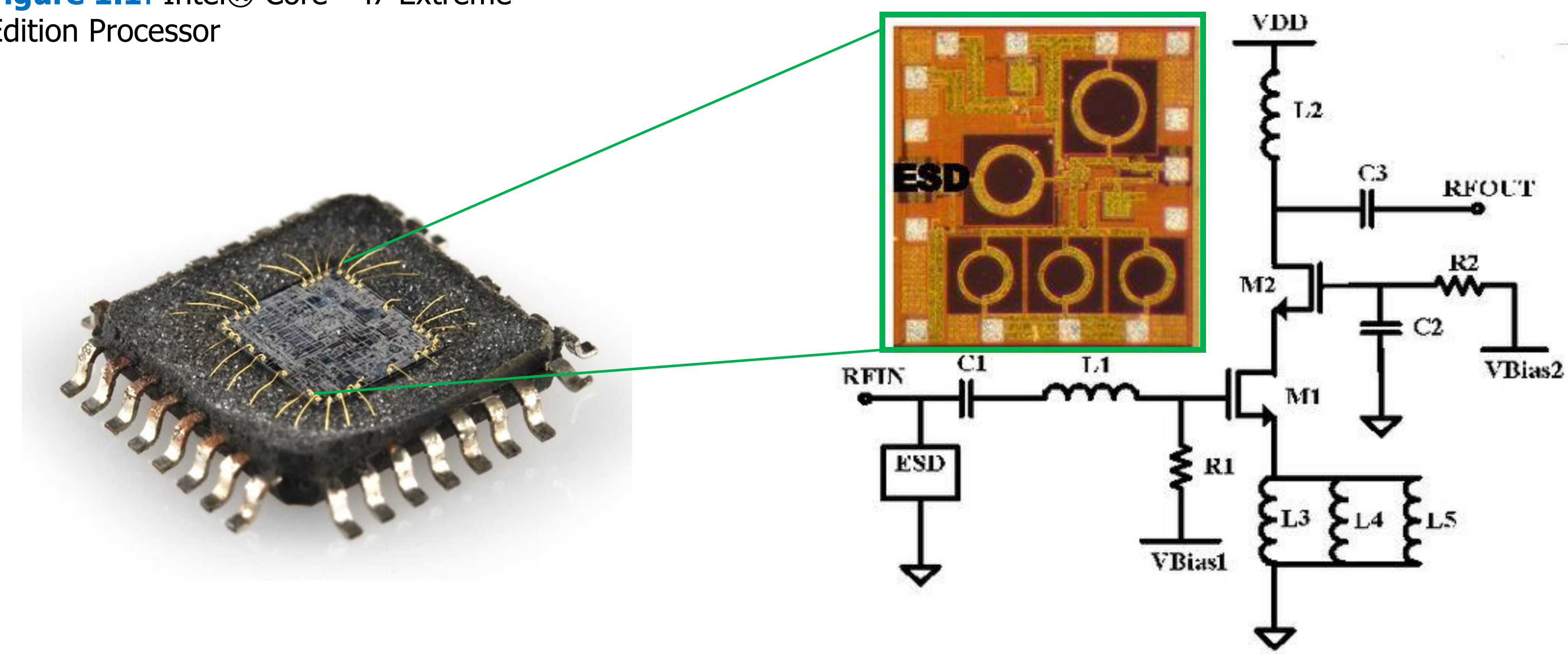
# 1.1 Introduction

- In the field of electronic engineering, engineers design and test circuits that use the electromagnetic properties of electrical components such as resistors, capacitors, inductors, diodes and transistors to achieve a particular functionality.
- One of the noteworthy things in the field of electronics is how little the fundamental principles change over time.
- New gadgets which are incredibly smaller but with remarkable speeds of operation surface everyday as a consequence of advancements in technology.
- However, the majority of all the devices in use were invented decades ago and design techniques dating back to the 1930s are still in use.
- Recent technological advancements include chiefly, improvements in construction techniques, general characteristics and application techniques as opposed to development of new elements and fundamentally new designs.
- The miniaturization that has occurred in contemporary electronic systems has culminated into complete systems appearing on wafers thousands of times smaller than a single element of earlier networks.

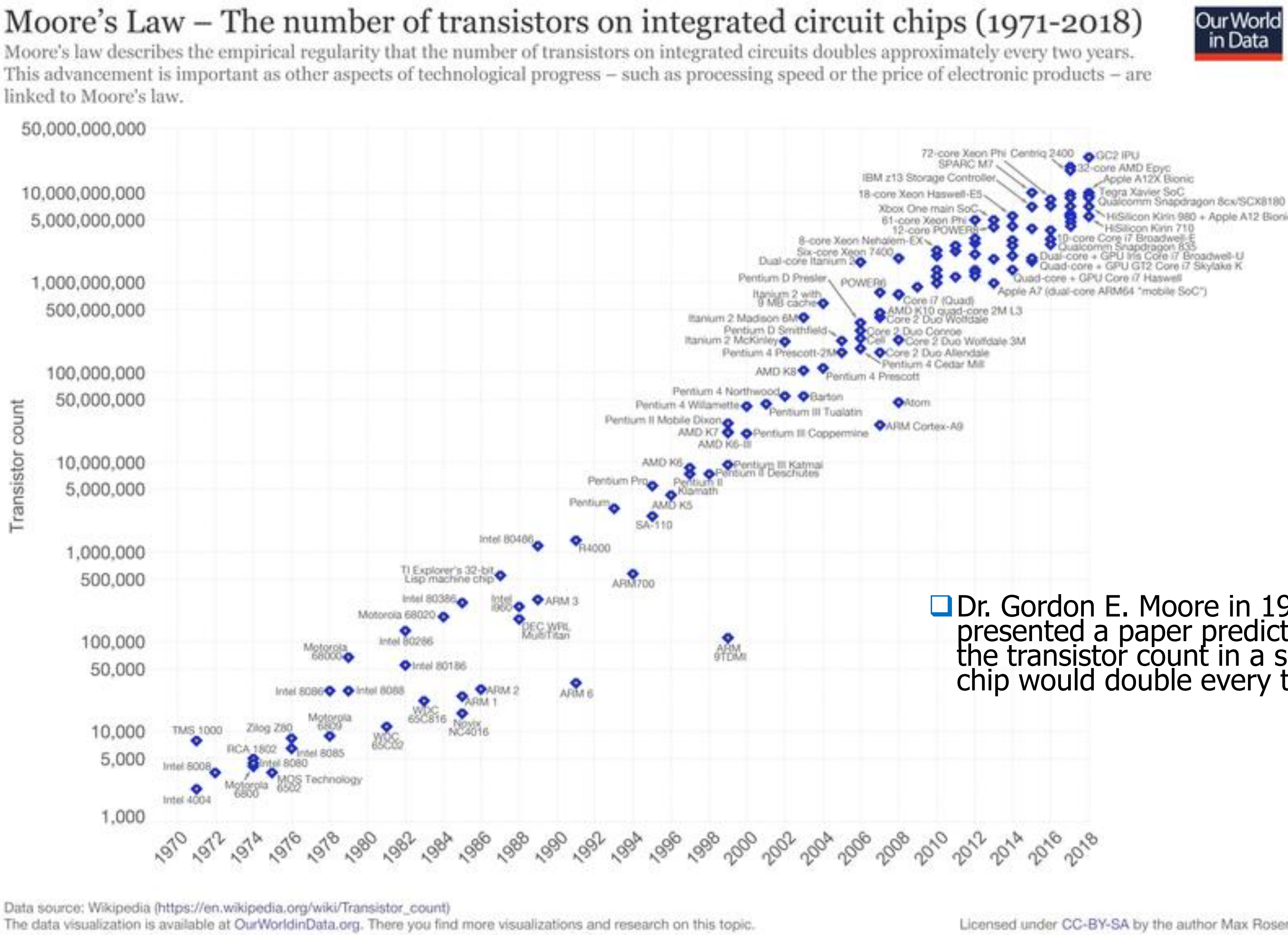
# 1.1 Introduction Cont'd


**Figure 1.1**: Intel® Core™ i7 Extreme Edition Processor

- Today, the Intel® Core™ i7 Extreme Edition Processor shown in Figure 1.1 has 731 million transistors.
- This is made possible via integrated circuit (IC) technology.



# 1.1 Introduction Cont'd



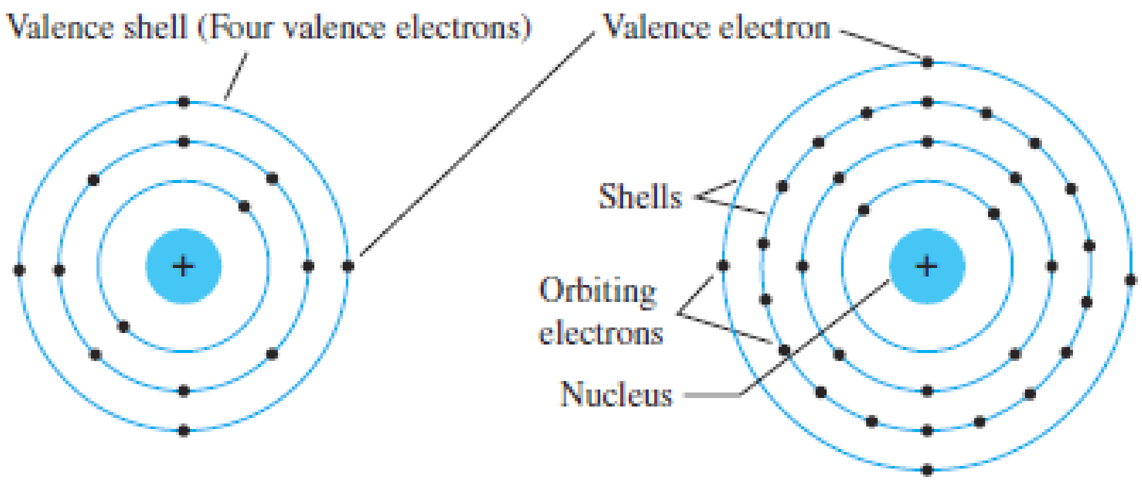

- Dr. Gordon E. Moore in 1965 presented a paper predicting that the transistor count in a single IC chip would double every two years.

# 1.2 Semiconductor Materials

- The construction of every discrete solid-state (hard crystal structure) electronic device or integrated circuits (ICs) begins with a semiconductor material of the highest quality.
- **Semiconductors are a special class of elements having conductivity between that of a good conductor and that of an insulator.**
- Semiconductors are classified as either single-crystal or compound.
- Single-crystal semiconductors include: germanium (Ge) and silicon (Si), which have a repetitive crystal structure.
- Compound semiconductors include: gallium arsenide (GaAs), cadmium sulfide (CdS), gallium nitride (GaN), and gallium arsenide phosphide (GaAsP), which are constructed from two or more semiconductor materials of different atomic structures.
- **The three semiconductors used most frequently in the construction of electronic devices are Ge, Si, and GaAs.**

# 1.3 Covalent Bonding & Intrinsic Materials

- To fully appreciate why Si, Ge and GaAs are semiconductors of choice for the electronic industry, let us review their atomic structures.
- Recall that the fundamental components of an atom are the electron, proton, and neutron, see Bohr model for the three materials in the Figure below.



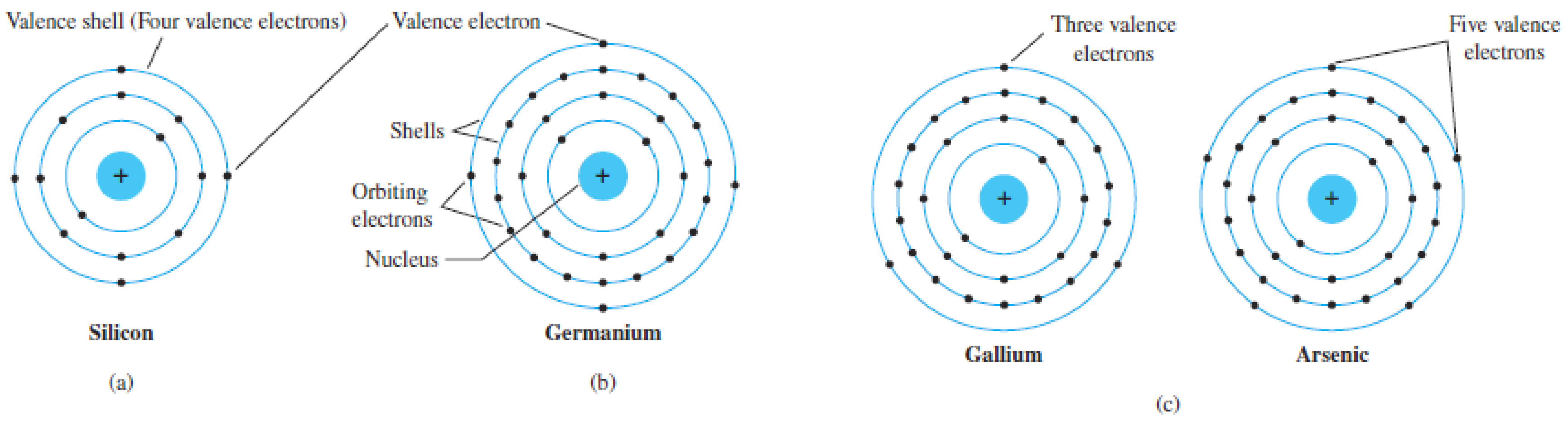

Silicon

(a)

Germanium

(b)

# 1.3 Covalent Bonding & Intrinsic Materials Cont'd




- ❑Notice that Si and Ge have four valence electrons, that is, they are tetravalent.
- ❑Vividly, Ga is trivalent and As is pentavalent.

# 1.3 Covalent Bonding & Intrinsic Materials Cont'd

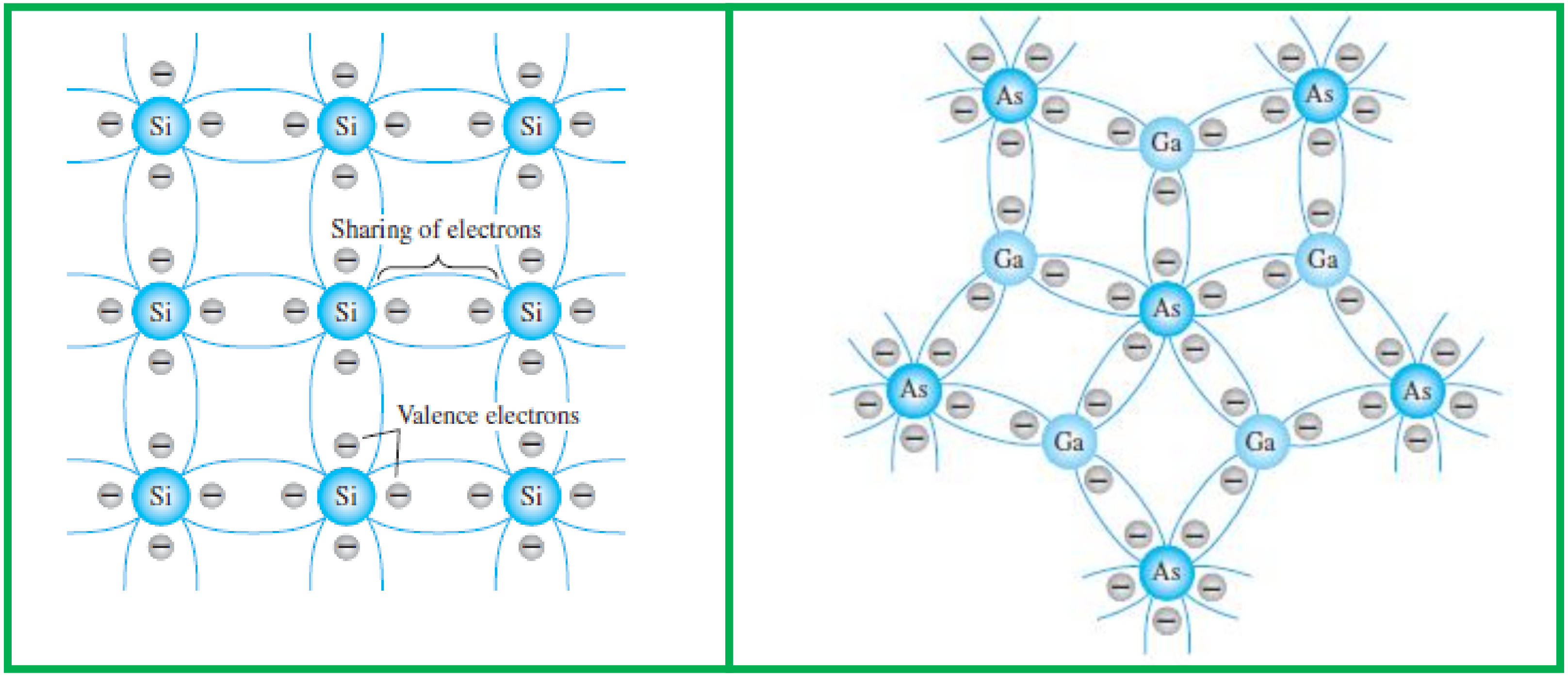



**Figure 1.3**: Covalent bonding of the Si atoms; and of the GaAs crystal.

- In pure Si or Ge crystal, four valence electrons of one atom form covalent bonds with four neighboring atoms.
- Similarly, in GaAs compound the sharing of electrons is between two different atoms to form covalent bonds.

# 1.3 Covalent Bonding & Intrinsic Materials Cont'd

- Much as a covalent bond is a stronger bond between valence electrons, it breaks whenever these electrons absorb sufficient kinetic energy from external natural causes.
- Thus, an electron is in a "free" state when it has separated from a fixed lattice structure and is very sensitive to any applied electric fields such as established by voltage sources.
- The free electrons in a material due to external causes are referred to as intrinsic carriers. Table 1.1 compares the number of intrinsic carriers per cubic centimeter for Ge, Si, and GaAs; and Table 1.2 their relative mobility.

**TABLE 1.1**
*Intrinsic Carriers $n_i$*

| Semiconductor | Intrinsic Carriers (per cubic centimeter) |
|---|---|
| GaAs | $1.7 \times 10^6$ |
| Si | $1.5 \times 10^{10}$ |
| Ge | $2.5 \times 10^{13}$ |

**TABLE 1.2**
*Relative Mobility Factor $\mu_n$*

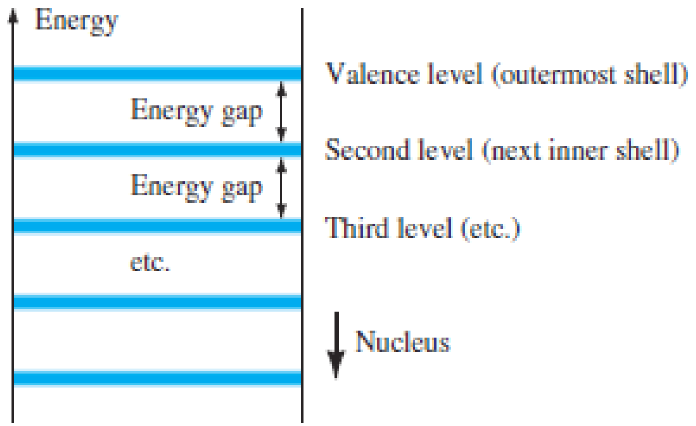
| Semiconductor | $\mu_n$ ($cm^2/V{\cdot}s$) |
|---|---|
| Si | 1500 |
| Ge | 3900 |
| GaAs | 8500 |

# 1.3 Covalent Bonding & Intrinsic Materials Cont'd

- **The term intrinsic is applied to any semiconductor material that has been carefully refined to reduce the number of impurities to a very low level-essentially as pure as can be available through modern technology.**
- As the temperature rises, an increasing number of valence electrons absorb sufficient thermal energy to break the covalent bond and to contribute to the number of free carriers.
- Thus, semiconductor materials have a negative temperature coefficient.

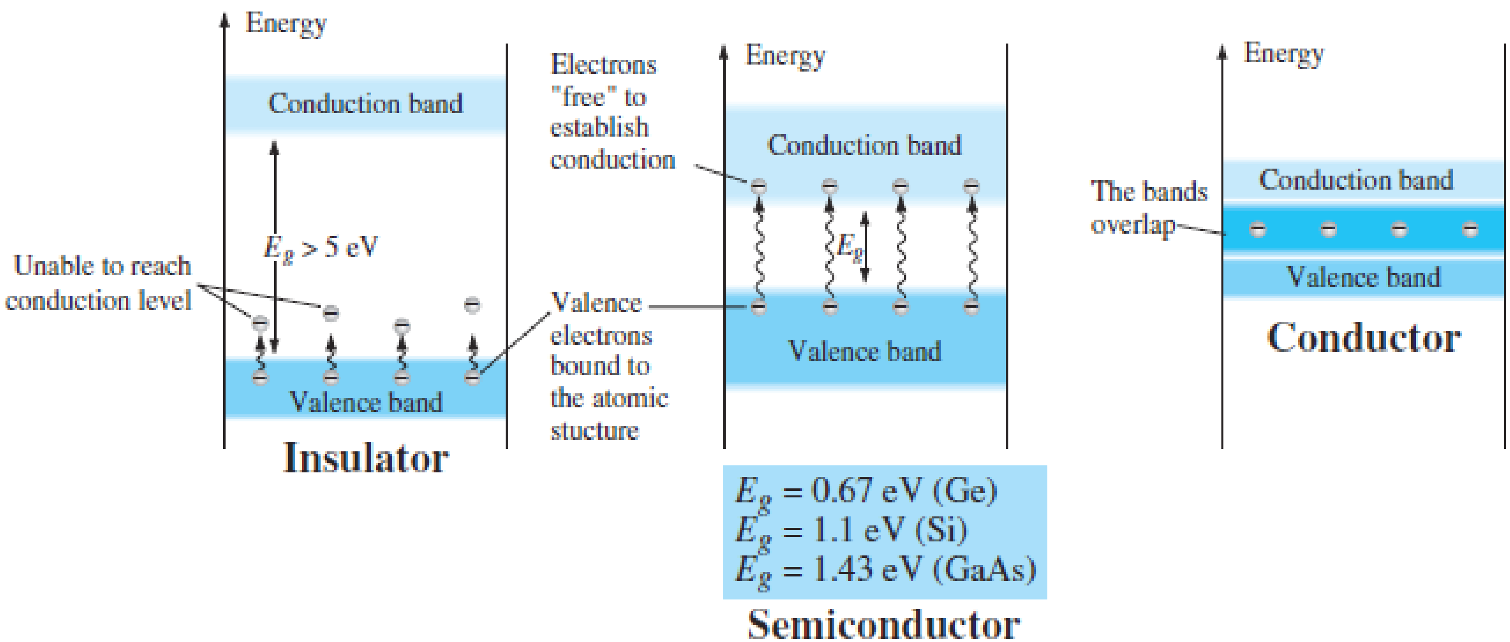
# 1.4 Energy Levels

- Within the atomic structure of each isolated atom there are specific energy levels associated with each shell and orbiting electron.
- Discrete levels in isolated atomic structures
- **In general, the further an electron is from the nucleus, the higher is the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure.**



# 1.4 Energy Levels Cont'd

- Expansion of fixed valence levels into bands result from the interaction of atoms brought closer together in a crystal lattice.



# 1.4 Energy Levels Cont'd

- The previous Figure clearly reveals that there is an energy gap between the valence and conduction bands which a valence electron must overcome to become a free carrier.
- Notice that in Figure 1.4 a new unit of measurement of energy, electron volts (eV), has been introduced, i.e.,

$$W\left(\text{energy}\right) = QV \qquad \textbf{[1.1]}$$

- Where $V$ is voltage or potential difference, $Q$ is charge.
- Thus, given the charge of one electron and a p.d of 1V this yields an energy level of 1eV, i.e.,

$$W\left(\text{energy}\right) = QV = \left(1.6\times10^{-19}\,\text{C}\right)\left(1\,\text{V}\right) = 1.6\times10^{-19}\,\text{J}$$

- Thus,

$$\boxed{1\,\text{eV} = 1.6\times10^{-19}\,\text{J}} \qquad \textbf{[1.2]}$$

# 1.5 *n*-TYPE and *p*-TYPE Materials

- ✓Since Si is the most often used substrate material in the construction of solid-state electronic devices, we thus base our discussion on it.
- ✓Notice that this can easily be extended to Ge and GaAs too.
- ✓Recall that the characteristics of an intrinsic semiconductor material can be altered by addition of specific impurity atoms through process known as doping.
- ✓**Thus, a semiconductor material that has been subjected to the doping process is called an extrinsic material.**

## *n*-Type Material

- ✓ Formed by addition of pentavalent impurity elements, from Group V of the periodic table, such as antimony, arsenic, and phosphorous to a Si base or substrate, see Figure 1.5.
- ✓ Diffused pentavalent impurities are called donor atoms.

# 1.5 *n*-TYPE and *p*-TYPE Materials Cont'd

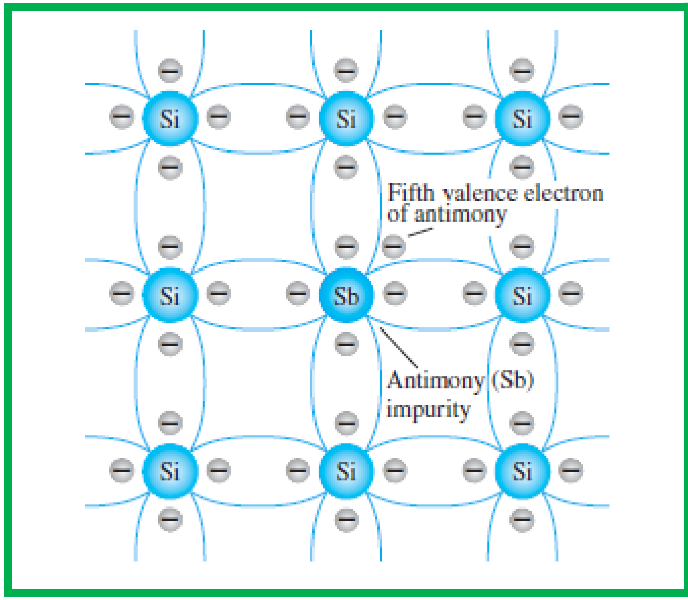



**Figure 1.5**: Antimony impurity in *n*-type material.

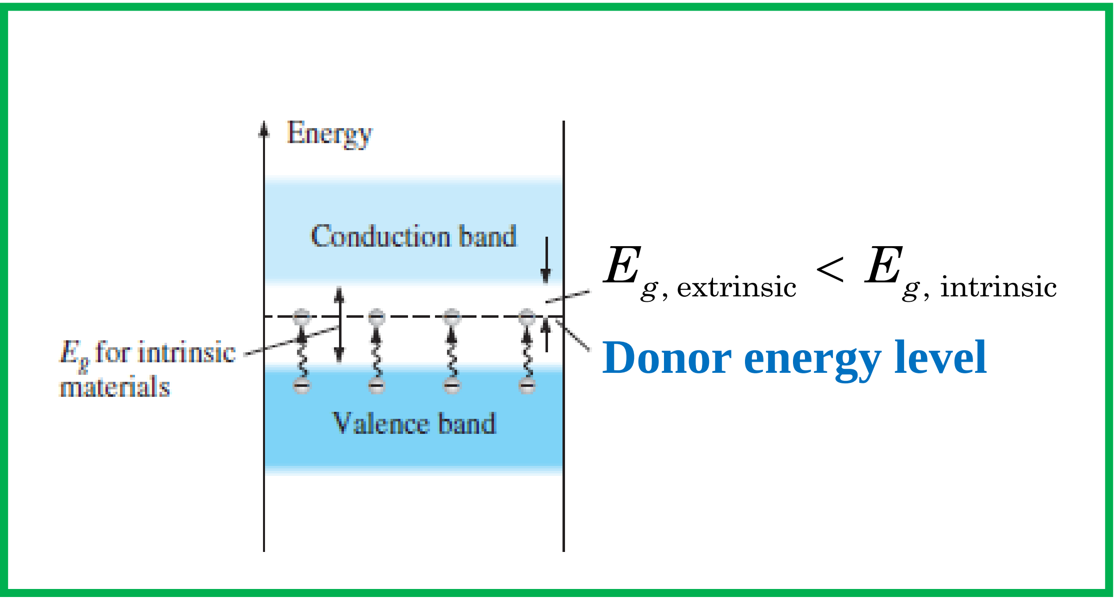



**Figure 1.6**: Effect of donor impurities on the energy band structure.

✓At r.t.p (room temperature) in an intrinsic Si material there is about one free electron for every $10^{12}$ atoms.

✓Thus, for a dosage level of 1 in 10 million, i.e., $10^{12}/10^{7} = 10^{5}$, the carrier concentration has increased by a ratio of 100,000:1.

# 1.5 *n*-TYPE and *p*-TYPE Materials Cont'd

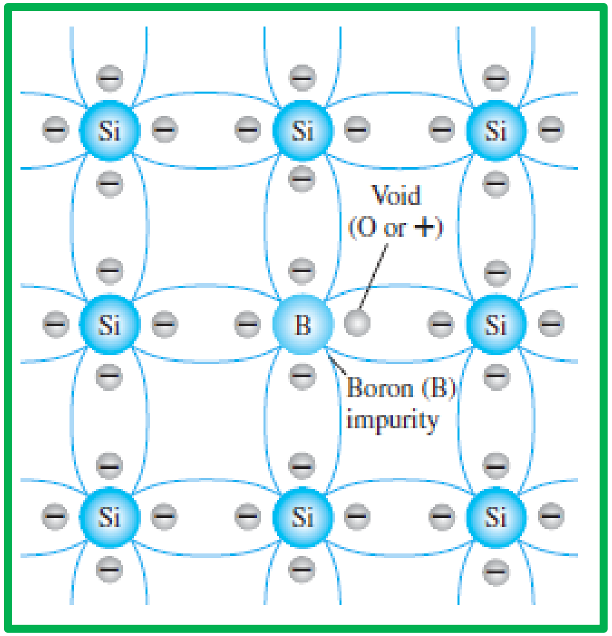



**Figure 1.7**: Boron impurity in *p*-type material.

## *p*-Type Material

- ✓Formed by doping an intrinsic (pure) Ge or Si crystal with trivalent atoms.
- ✓Elements from Group III of the periodic table most frequently used are boron, gallium and, indium.
- ✓The resulting vacancy of an electron is called a hole represented by a circle or a plus sign.
- ✓Since the holes will readily accept a free electron, thus,
- ✓The diffused trivalent impurities are called acceptor atoms.

# 1.5 *n*-TYPE and *p*-TYPE Materials Cont'd

## Electron versus Hole Flow

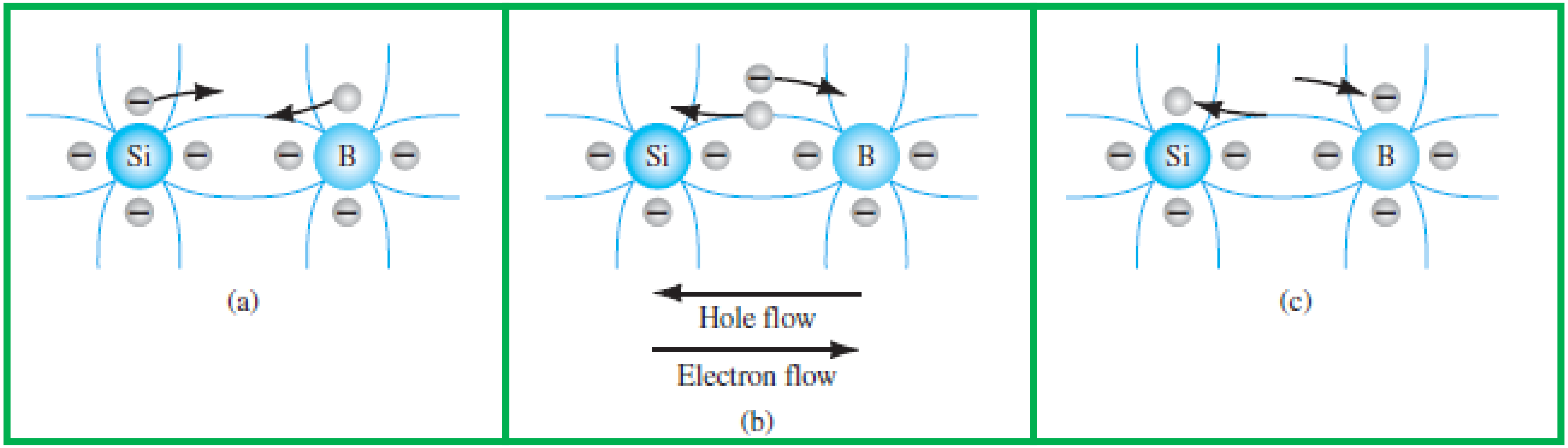



**Figure 1.8**: Electron versus hole flow.

- If a valence electron acquires sufficient kinetic energy to break its covalent bond and fills the void created by a hole, then a hole appears in the covalent bond that released the electron.
- Thus, we will be using the conventional flow of electrons and holes as shown above.

# 1.5 *n*-TYPE and *p*-TYPE Materials Cont'd

## Majority and Minority Carriers

- ✓In an *n*-type material the number of electrons still outweighs the number of holes (resulting from electrons which have entered the conduction band).
- ✓**Thus, in an *n*-type material the electron is called the majority carrier and the hole the minority carrier.**

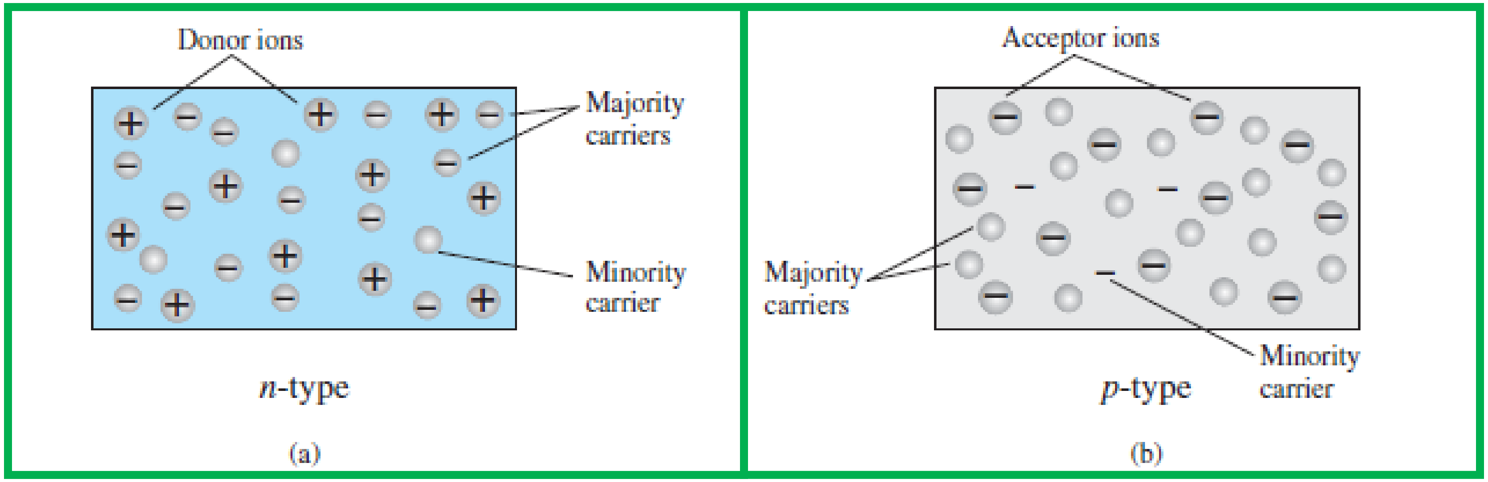



**Figure 1.9**: (a) *n*-type material; (b) *p*-type material.

- ✓ **Similarly, in a *p*-type material the hole is the majority carrier and the electron is the minority carrier.**

# 1.6 Semiconductor Diode (*p*-*n* Junction)

✓A p–n junction is a boundary or interface between two types of semiconductor materials, p-type and n-type, inside a single crystal of semiconductor.

## No Applied Bias (*V* = 0 V)

✓ At the junction; the interface of the p and n-type, electrons and the holes in the region will combine, resulting in a lack of free carries in this region as shown in Figure 1.10a.

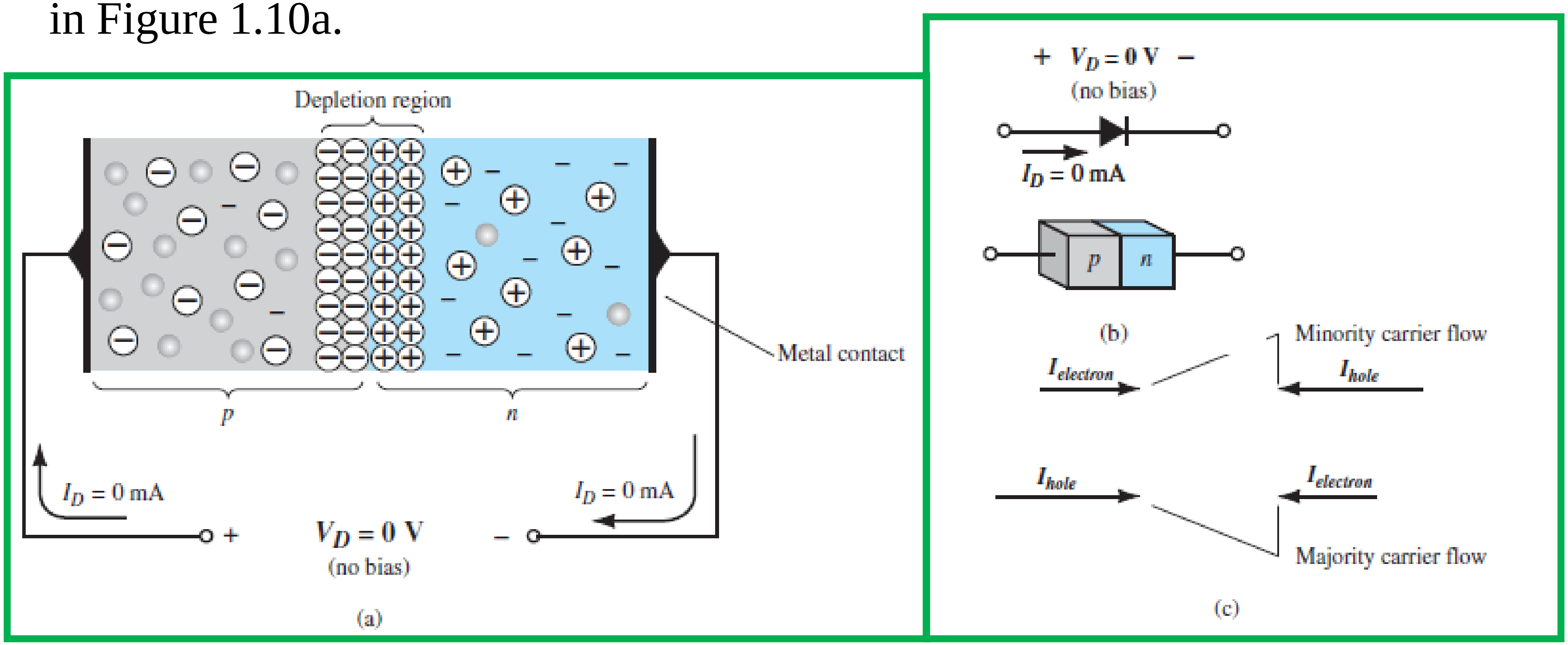



**Figure 1.10**: (a) internal distribution of charge; (b) diode symbol; (c) demo that net carrier flow is zero.

# 1.6 Semiconductor Diode Cont'd

✓The region of uncovered positive and negative ions is called the depletion region due to the "depletion" of free carriers in the region. See Figure 1.10a in the previous slide.

## Reverse-Bias Condition $(V_D < 0\,\mathrm{V})$

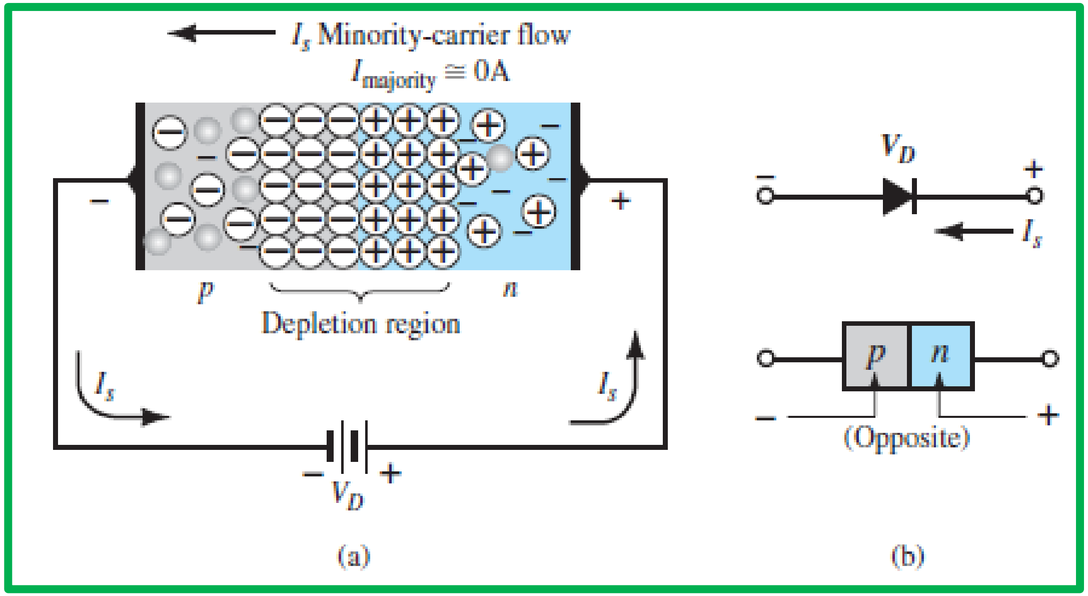



**Figure 1.11**: (a) internal distribution of charge under reverse-bias; (b) reverse-bias polarity & reverse saturation current direction.

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

- **The depletion region widens.**
- **The electrons in the *n*-type material are attracted by the positive terminal of the voltage source.**
- **The holes in the *p*-type material are attracted toward the negative terminal of the voltage source.**

✓**The current that exists under reverse and forward-bias conditions is called the reverse saturation current and is represented by** $I_s$

# 1.6 Semiconductor Diode Cont'd

## Forward-Bias Condition $(V_D > 0\,\text{V})$

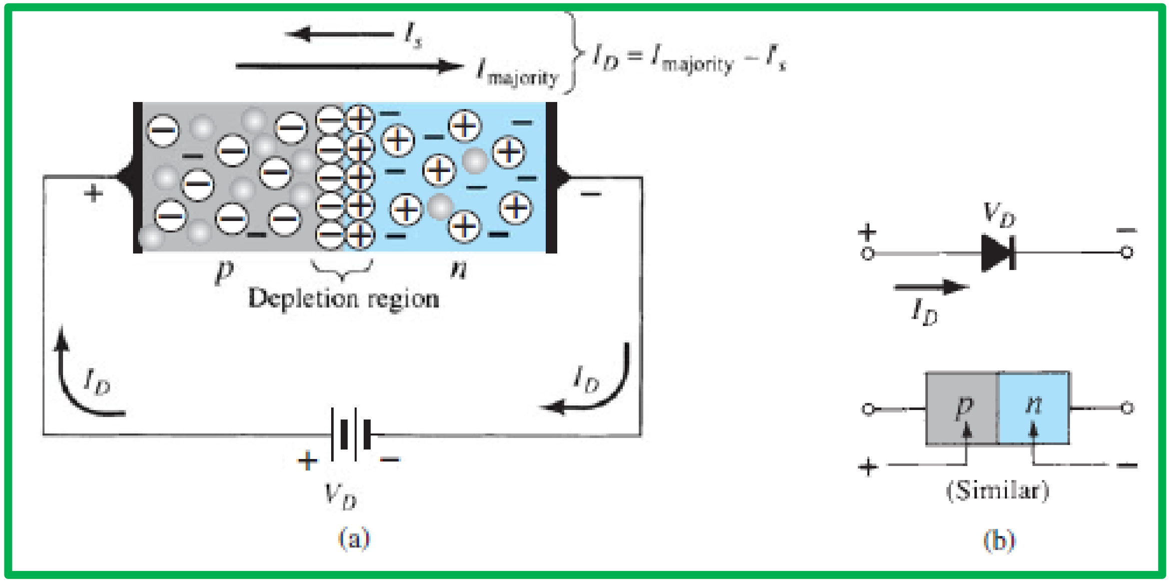



**Figure 1.12**: (a) internal distribution of charge under reverse-bias; (b) Forward-bias polarity & resulting current direction.

- ✓ **Applying a forward-bias potential will "pressure" electrons in the *n*-type material and holes in the *p*-type material to recombine with the ions near the boundary.**
- ✓ **This reduces the width of the depletion region as shown in Figure 1.12.**
- ✓ **The electrons and holes have sufficient energy to cross the *p*-*n* junction (provided high enough voltage is applied)**

# 1.6 Semiconductor Diode Cont'd

✓From solid-state physics the **general characteristics of a semiconductor diode** are defined by the **Shockley's** equation, for the forward and reverse-bias regions.

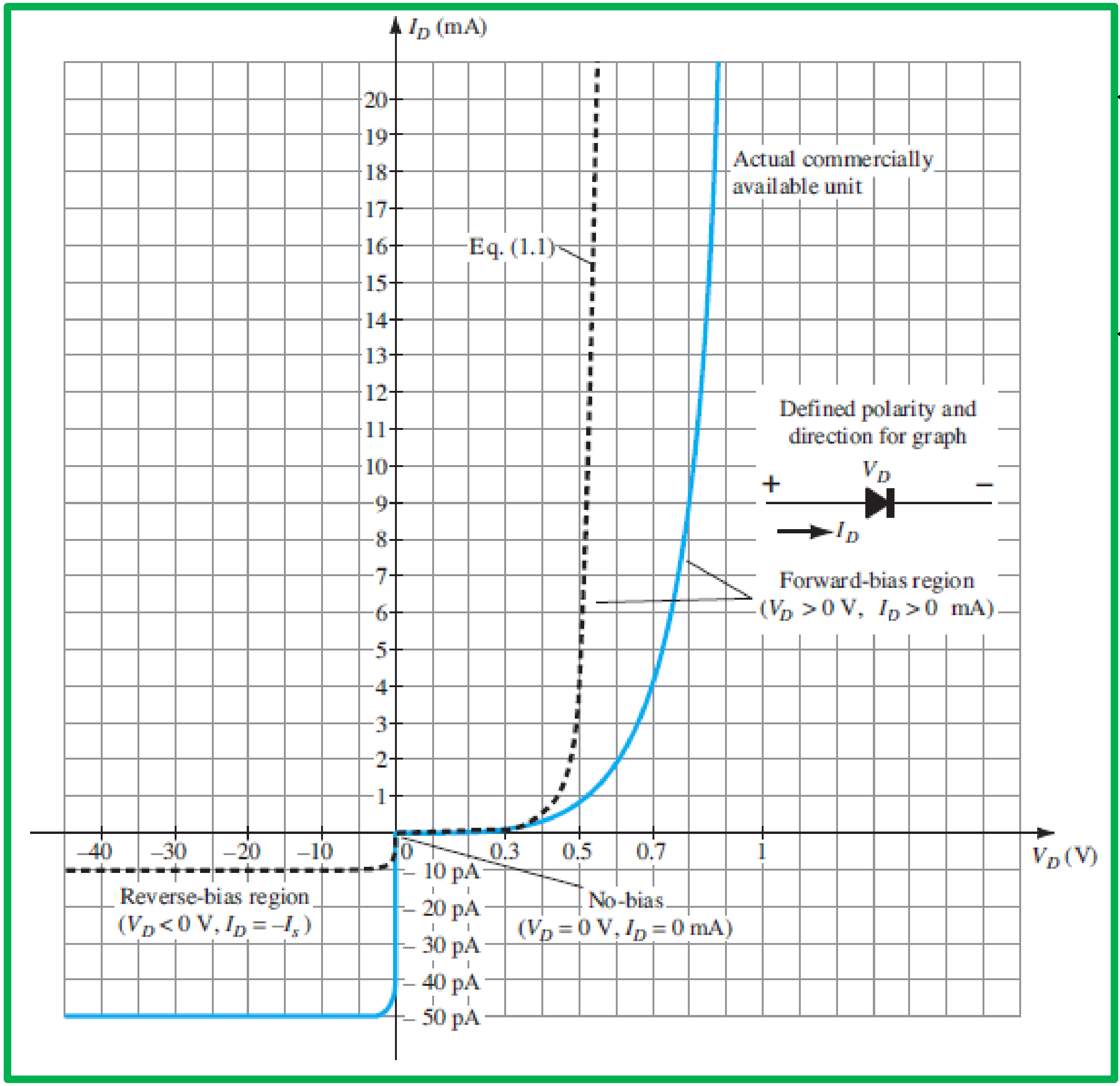
$$I_D = I_s\left(e^{V_D/nV_T} - 1\right) \qquad \textbf{[1.3]}$$

✓ *Where*; $I_s$ is the reverse saturation current; $V_D$ is the applied forward-bias voltage across the diode; $n$ is an ideality factor with values between 1 and 2; $V_T$ is the thermal voltage determined by

$$V_T = \frac{kT_K}{q} \qquad \textbf{[1.4]}$$

✓ *Where*; $k$ is the Boltzmann's constant = $1.38\times10^{-23}\ \mathrm{J/K}$ ; $T_K$ is the absolute temperature in kelvins = $273 + \text{Temp in } ^{\circ}\mathrm{C}$ ; $q$ is the magnitude of electronic charge = $1.6\times10^{-19}\ \mathrm{C}$ .

# 1.6 Semiconductor Diode Cont'd




- ✓A plot of Eq. [1.3] is depicted in Figure 1.13 and when $I_s = 10\,\text{pA}$ the plot is shown as the dashed line.
- ✓Clearly for positive values of $V_D$ the 1st term is much larger than the 2nd term in Eq. [1.3] which yields

$$I_D \cong I_s e^{V_D/nV_T} \quad (V_D \text{ positive})$$

**Figure 1.13**: Si semiconductor diode characteristics.

# Example 1.1 Semiconductor Diodes

✓At a temperature of $27\ ^{\circ}\mathrm{C}$ (common temperature for components in an enclosed operating system), determine the thermal voltage $V_T$.

**[Solution]:**

✓Substituting into Eq. [1.4] yields,

$$T = 273 + T_{^{\circ}\mathrm{C}} = 273 + 27 = 300\,\mathrm{K}\ ;$$

$$\Rightarrow\ V_T = \frac{kT_K}{q} = \frac{\left(1.38\times10^{-23}\ \mathrm{J/K}\right)\left(300\,\mathrm{K}\right)}{1.6\times10^{-19}\ \mathrm{C}}\ ;$$

$$\therefore\ V_T = 25.875\,\mathrm{mV} \cong 26\,\mathrm{mV}$$

# 1.6 Semiconductor Diode Cont'd

## Breakdown Region

✓With increase in reverse bias, the depletion layer widens and this stops the flow of majority carrier current to almost zero.

✓Beyond this voltage, the reverse saturation current (minority carrier current) takes over and is generated in two forms:

(1) Zener Breakdown

(2) Avalanche Breakdown:

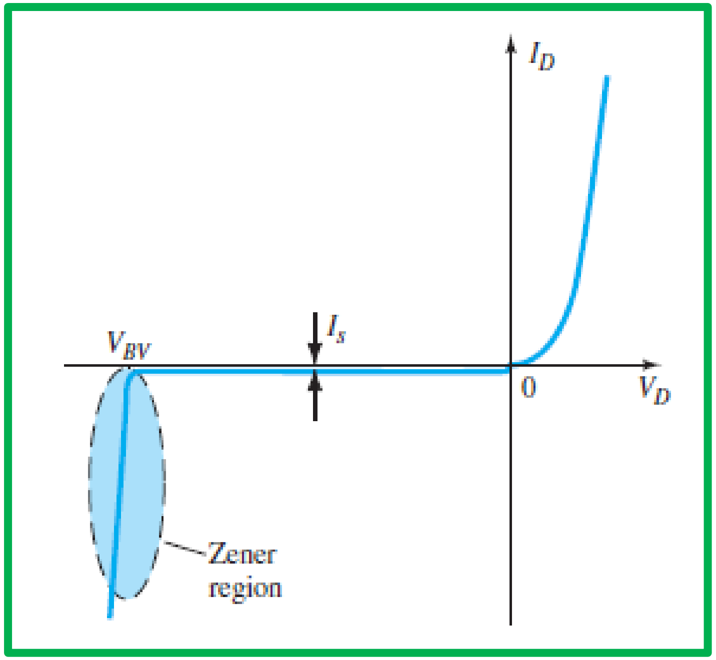



**Figure 1.14**: Breakdown region.

**(1) Zener Breakdown**:

- ❑ **As the applied electric field in the depletion region gets so strong that it breaks bonds and creates electron/hole pairs which constitute a large current with a negligible increase in the junction voltage.**

- ❑ The maximum reverse voltage that won't take a diode into the Zener region is called the **peak inverse voltage (PIV)** or **peak reverse voltage (PRV)**.

- ❑ The voltage that causes a diode to enter the Zener region of operation is called the **Zener voltage** $(V_Z)$ or breakdown voltage $(V_{BV})$ .

# 1.6 Semiconductor Diode Cont’d

**(2)Avalanche Breakdown**:

- As the reverse bias voltage across the diode increases, the velocity of the minority carriers increases such that their kinetic energy $\left(W_K = \frac{1}{2}mv^2\right)$ will be sufficient to release additional carriers through collisions with stable atoms.
- This aids the ionization process to the point where a high **avalanche current** is established and the **avalanche breakdown** region determined.
- Thus, the diode breaks down and the reverse saturation current increases dramatically whilst the voltage $(V_{BV})$ across the junction remains constant.

✓ **Doping and breakdown**: Zener breakdown happens in heavily doped while avalanche breakdown happens in lightly doped semiconductors; both occur but one dominate the other.

# 1.6 Semiconductor Diode Cont'd

## 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.

**TABLE 1.3**
*Knee Voltages $V_K$*

| Semiconductor | $V_K$(V) |
|---|---|
| Ge | 0.3 |
| Si | 0.7 |
| GaAs | 1.2 |

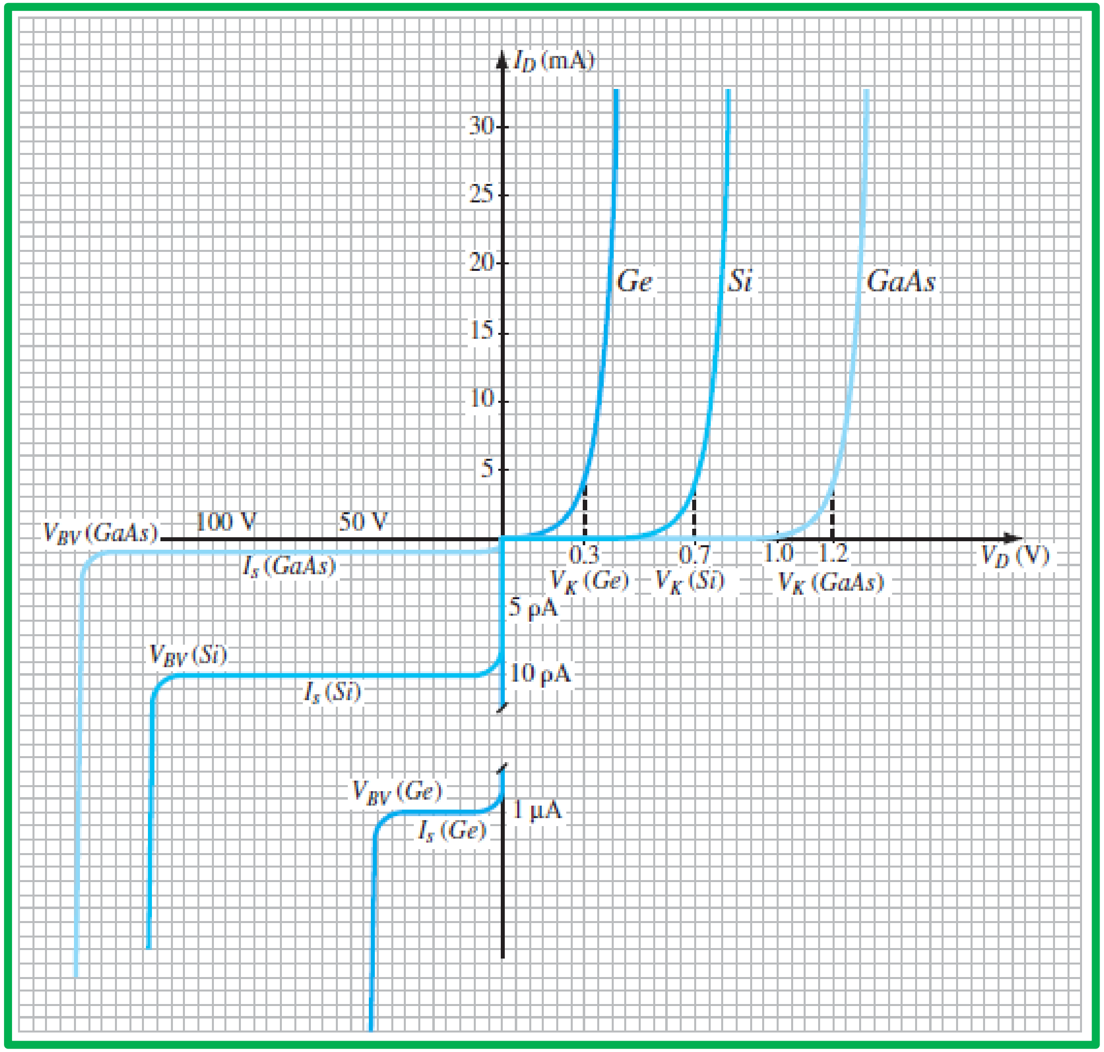
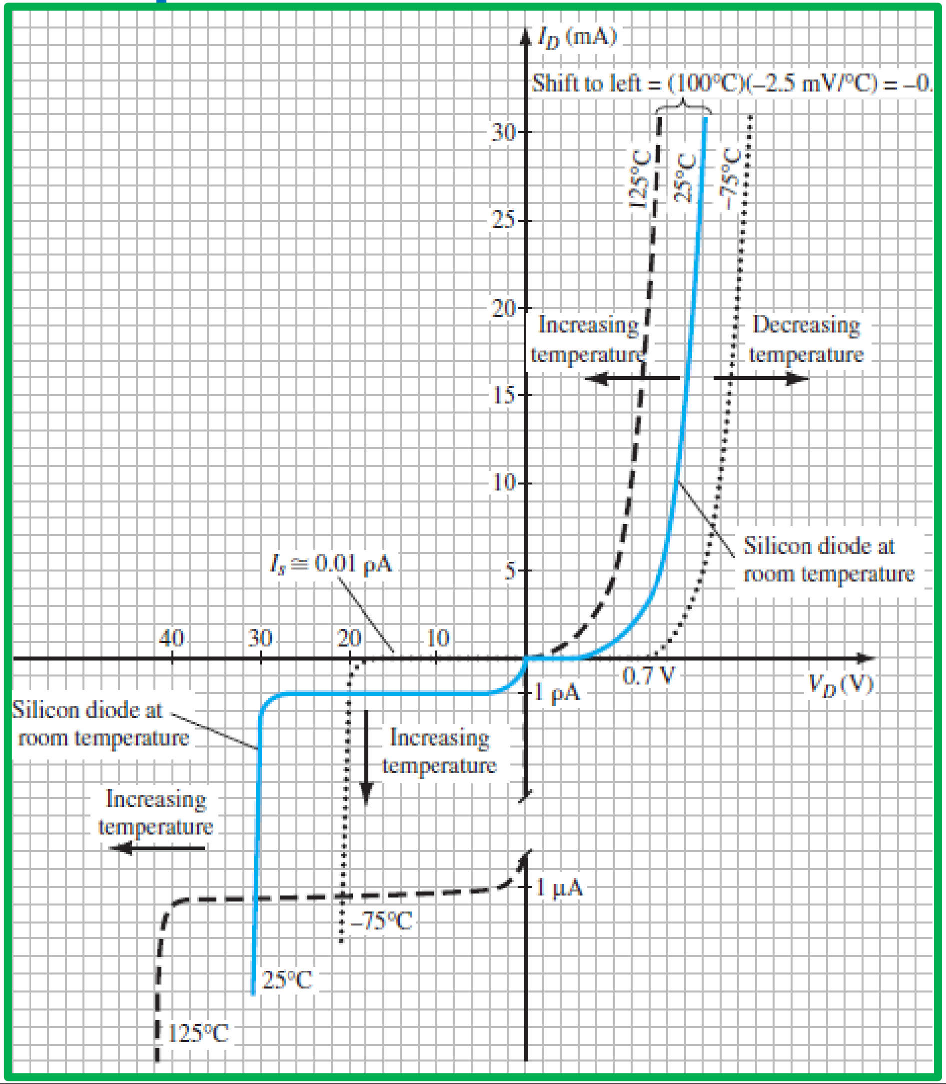


**Figure 1.15**: Comparison of Ge, Si and GaAs Commercial diodes.

# 1.6 Semiconductor Diode Cont'd

## Temperature Effects




As temperature increases it adds energy to the diode.

- It reduces the required forward bias voltage for forward-bias conduction.
- 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.

**Figure 1.16**: Variation in Si diode characteristics with temp. change.

# 1.7 Ideal Versus Practical Diode

- ❑The semiconductor diode behaves in a manner similar to mechanical switch in that it can control whether current will flow between its two terminals.
- ❑The semiconductor diode is different from a mechanical switch in the sense that when the switch is closed it will only permit current to flow in one direction.

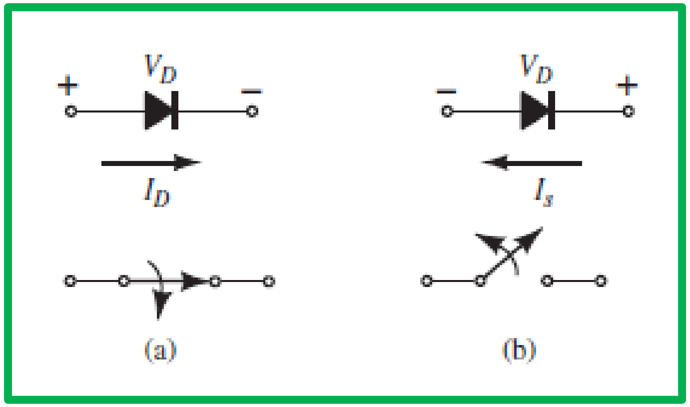



**Figure 1.17**: Ideal semiconductor diode: (a) forward-biased; (b) reverse-biased.

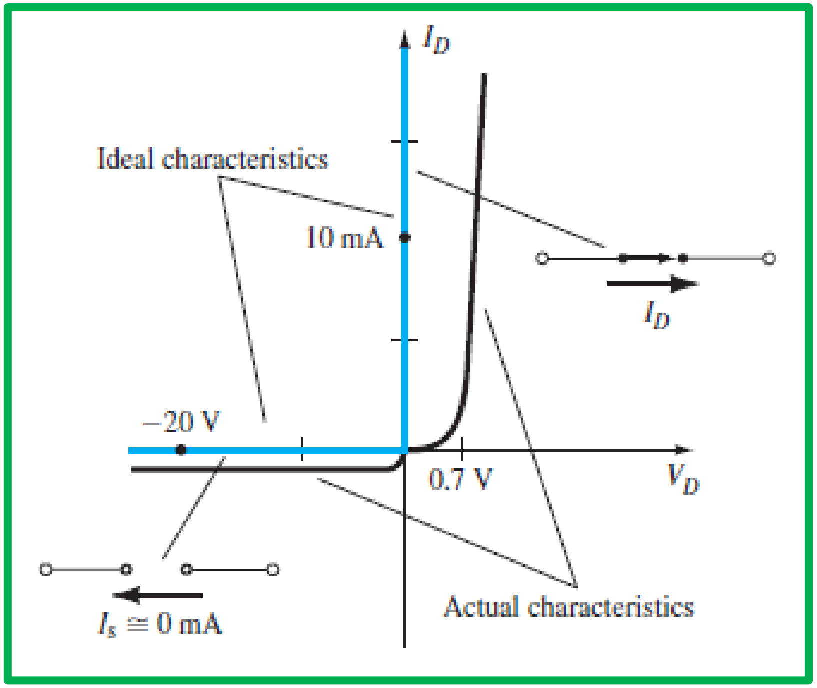



**Figure 1.18**: Ideal versus actual semiconductor characteristics.

# 1.8 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**

# 1.8 Resistance Levels Cont'd

## DC (Static) Resistance

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

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

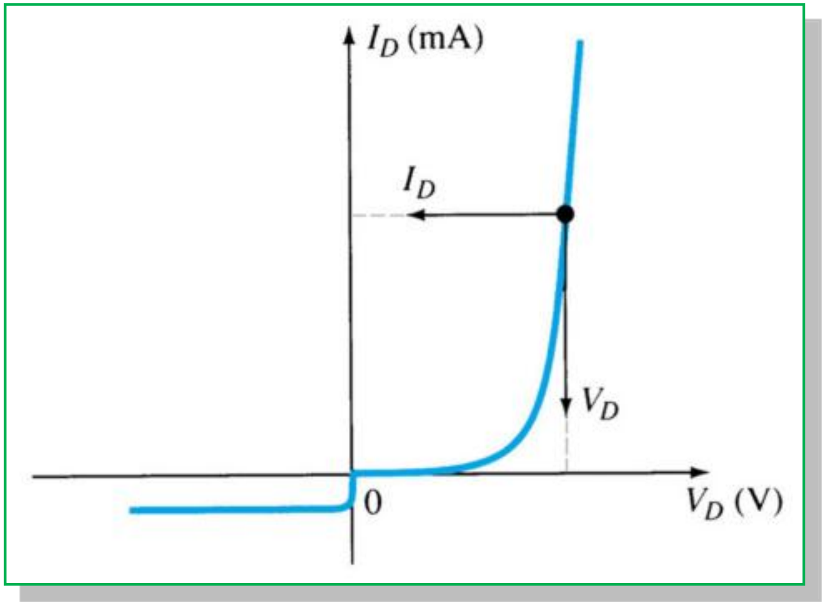



**Figure 1.19**: Determining the dc resistance of a diode at a particular operating point

# 1.8 Resistance Levels Cont'd

## 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.

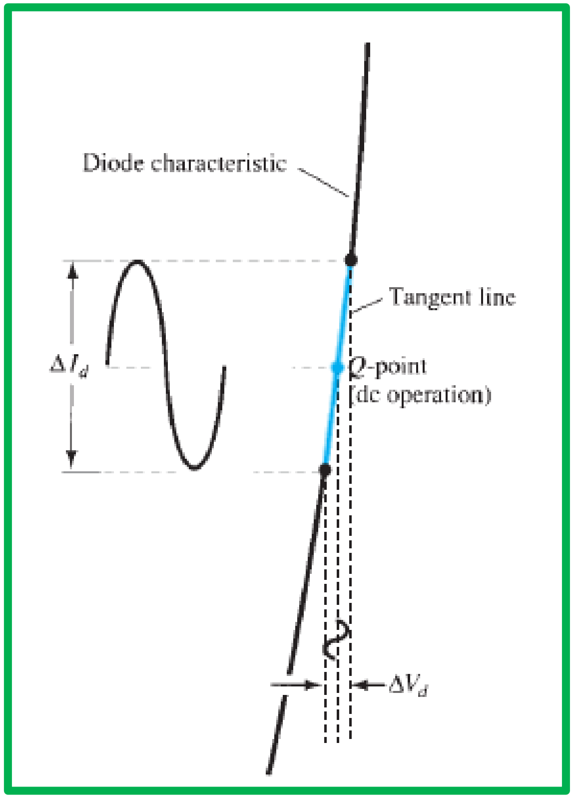



**Figure 1.20**: Defining the dynamic or ac resistance.

In the reverse bias region:

$$r'_d = \infty$$

The resistance is effectively infinite. The diode acts like an open. (there is a caveat)

# 1.8 Resistance Levels Cont'd

## Average AC Resistance

$$r_{av} = \frac{\Delta V_d}{\Delta I_d} \bigg|_{\text{pt. to pt.}}$$

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

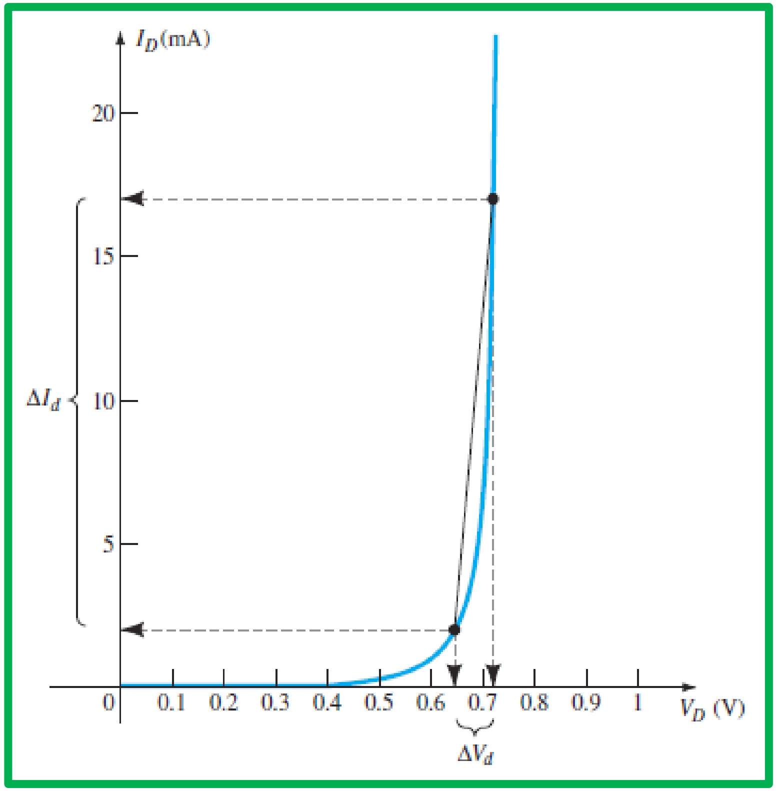
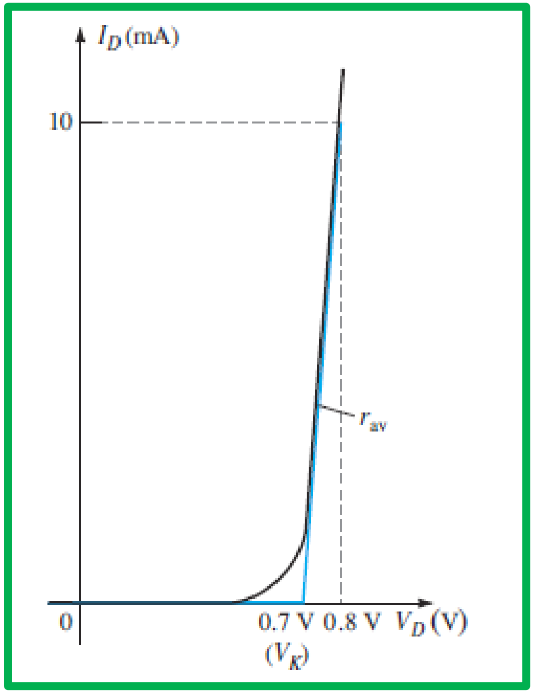



**Figure 1.21**: Determining the average ac resistance between indicated limits.

# 1.9 Diode Equivalent Circuit

An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device or system in a particular operating region.

## Piecewise-Linear Equivalent Circuit



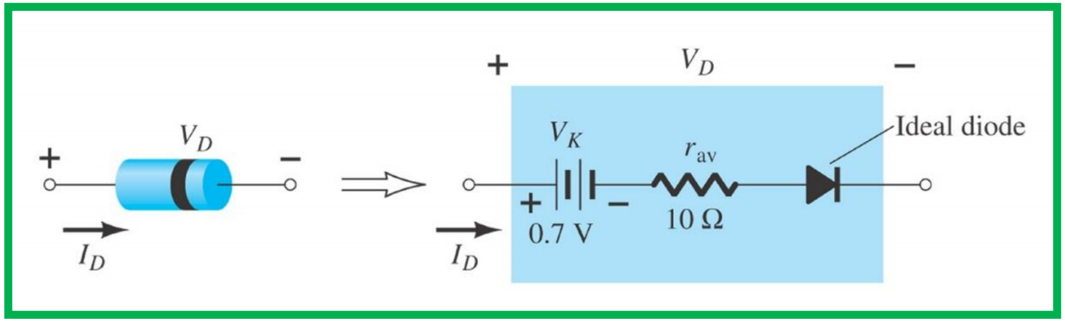




**Figure 1.23**: Components of the piecewise-linear equivalent circuit.

**Figure 1.22**: Defining the piecewise-linear equivalent circuit using straight-line segments to approximate the characteristic curve.

# 1.9 Diode Equivalent Circuit Cont'd

## Simplified Equivalent Circuit

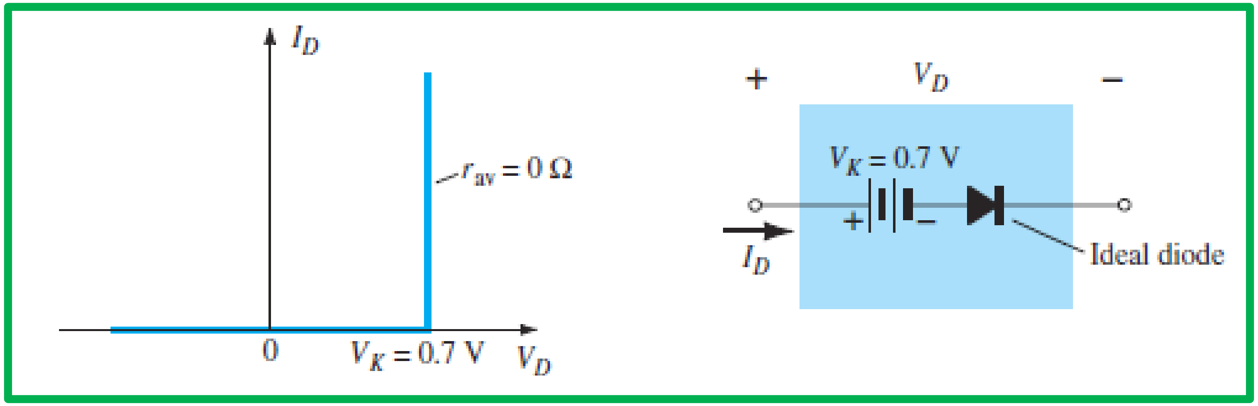



**Figure 1.24**: Simplified equivalent circuit for a **Si** diode.

## Ideal Equivalent Circuit

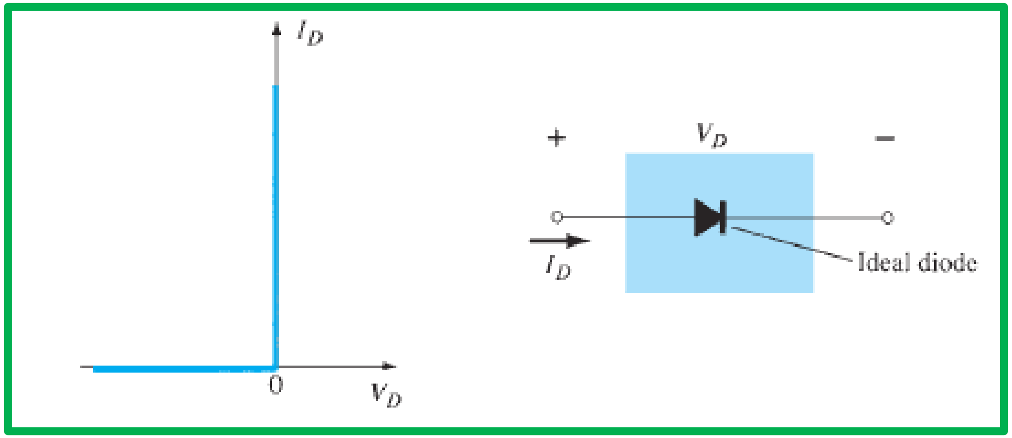



**Figure 1.25**: Ideal equivalent circuit for a diode and its characteristics.

# 1.10 Transition and Diffusion Capacitance

## Diode Capacitance

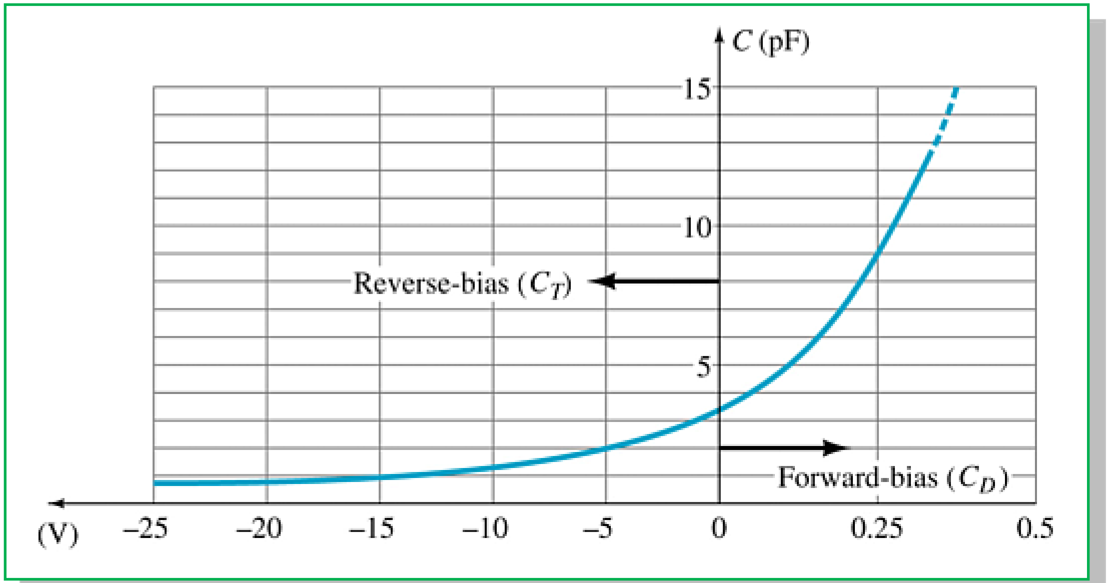



**Figure 1.26**: Transition and diffusion capacitance versus applied bias for **Si** diode

- **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.**

# 1.11 Reverse Recovery Time

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

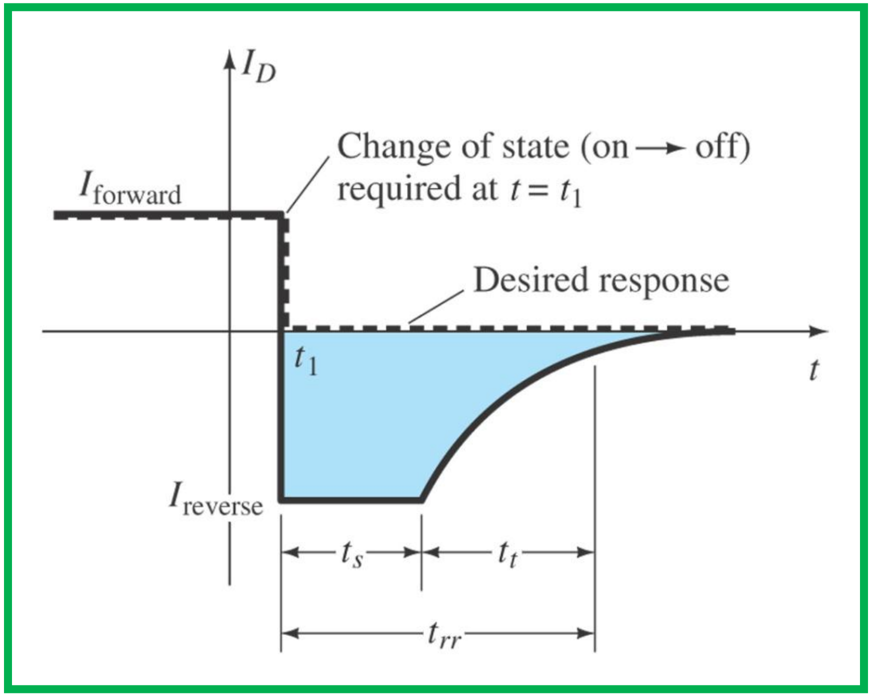



**Figure 1.27:** Defining the reverse recovery time.

# 1.12 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**

# 1.13 Semiconductor Diode Notation

## Diode Symbol and Packaging

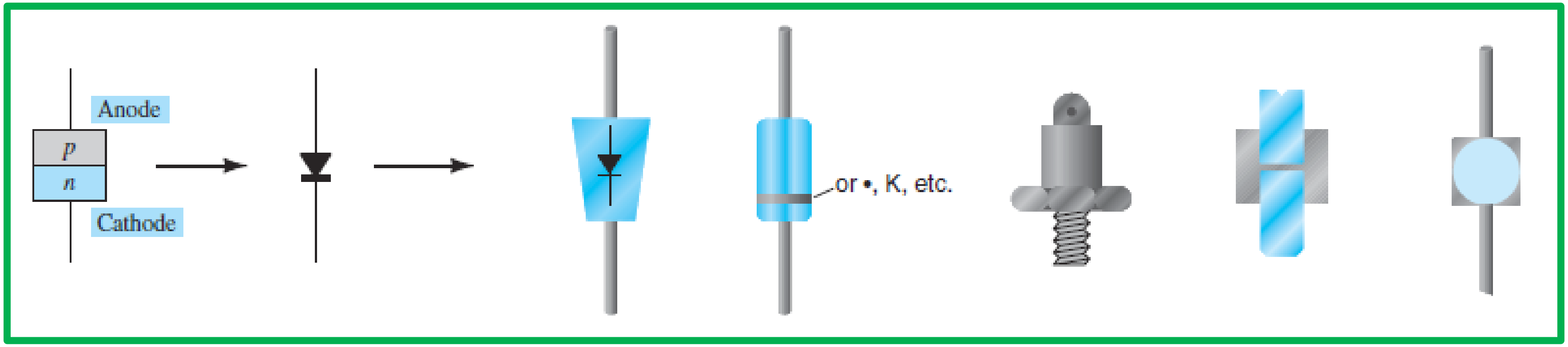



**Figure 1.28**: Semiconductor diode notation.

**The anode is abbreviated A**
**The cathode is abbreviated K**

# 1.14 Diode Testing

## Diode Checking Function

**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**

**Microwave oven fix example:**

**Forward voltage much higher why?**

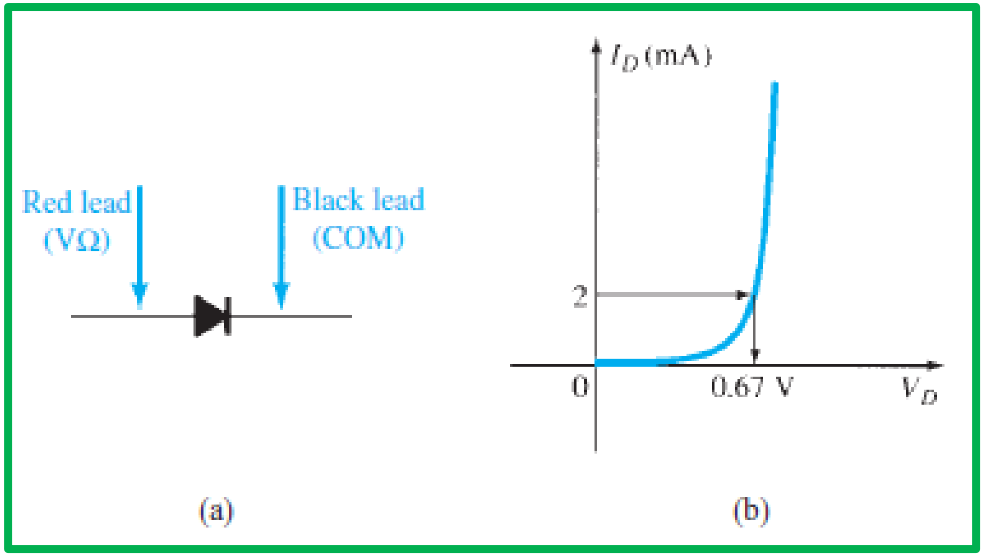



**Figure 1.29**: Checking a diode in the forward-bias state.

# 1.14 Diode Testing Cont'd

## Ohmmeter Testing

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

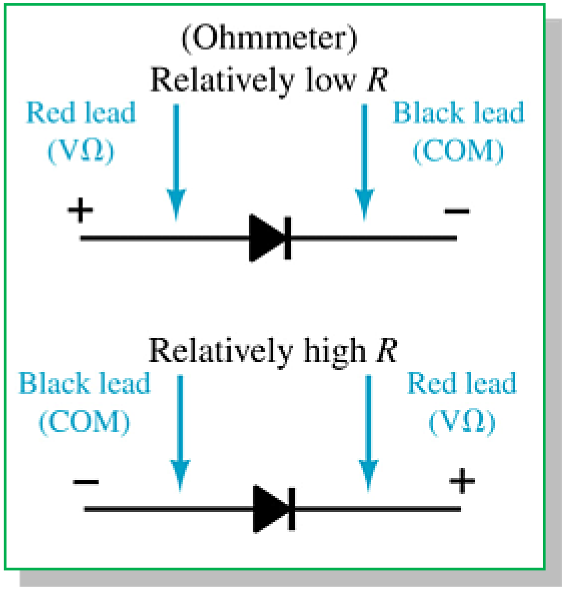



**Figure 1.30**: Checking a diode with an ohmmeter.

# 1.14 Diode Testing Cont'd

## 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.

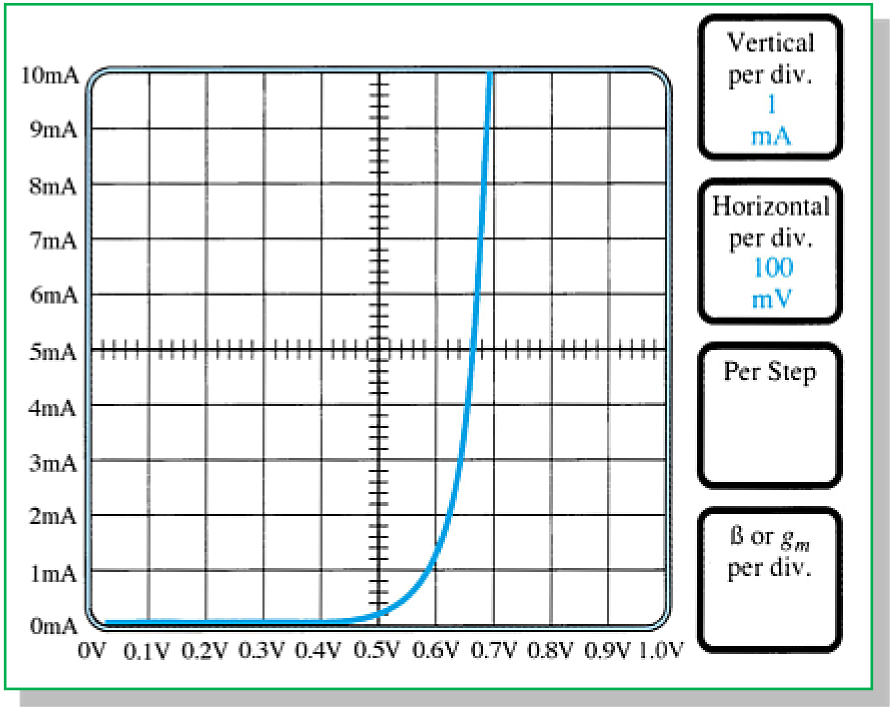



**Figure 1.31**: Curve tracer response to IN4007 silicon diode.

# 1.15 Zener Diodes

A Zener is a diode operated in reverse bias at the Zener voltage ($V_Z$).

Common Zener voltages are between 1.8 V and 200 V

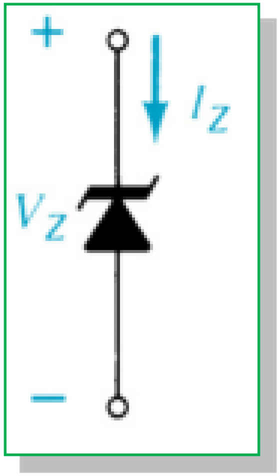
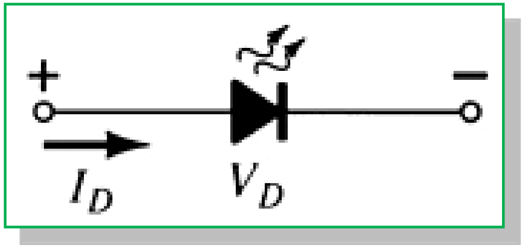



**Figure 1.32**: Zener diode circuit symbol.

# 1.16 Light-Emitting Diodes (LED)




- An LED emits photons when it is forward biased.
- These can be in the infrared or visible spectrum.
- The forward bias voltage is usually in the range of 2 V to 3 V.

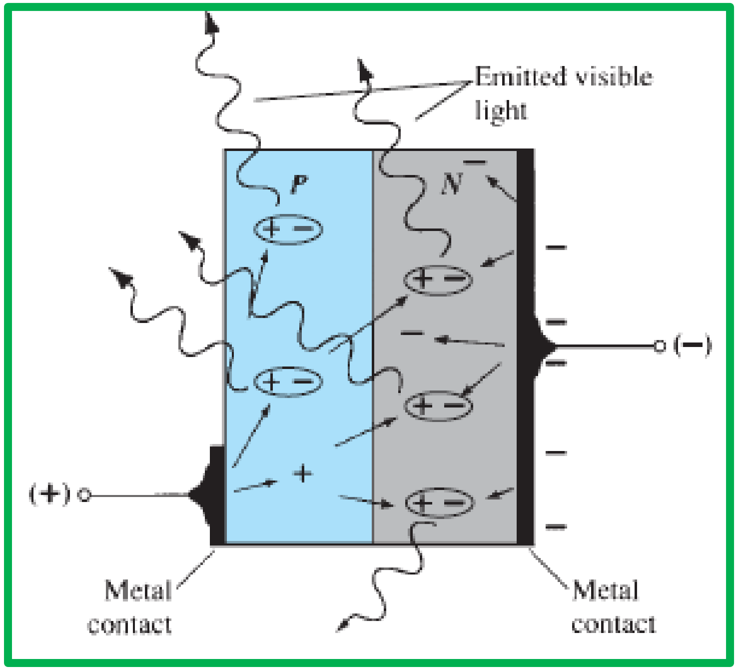
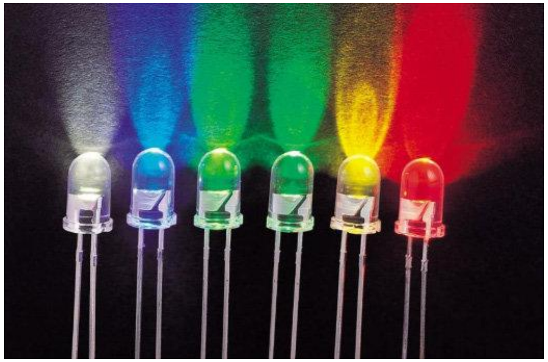
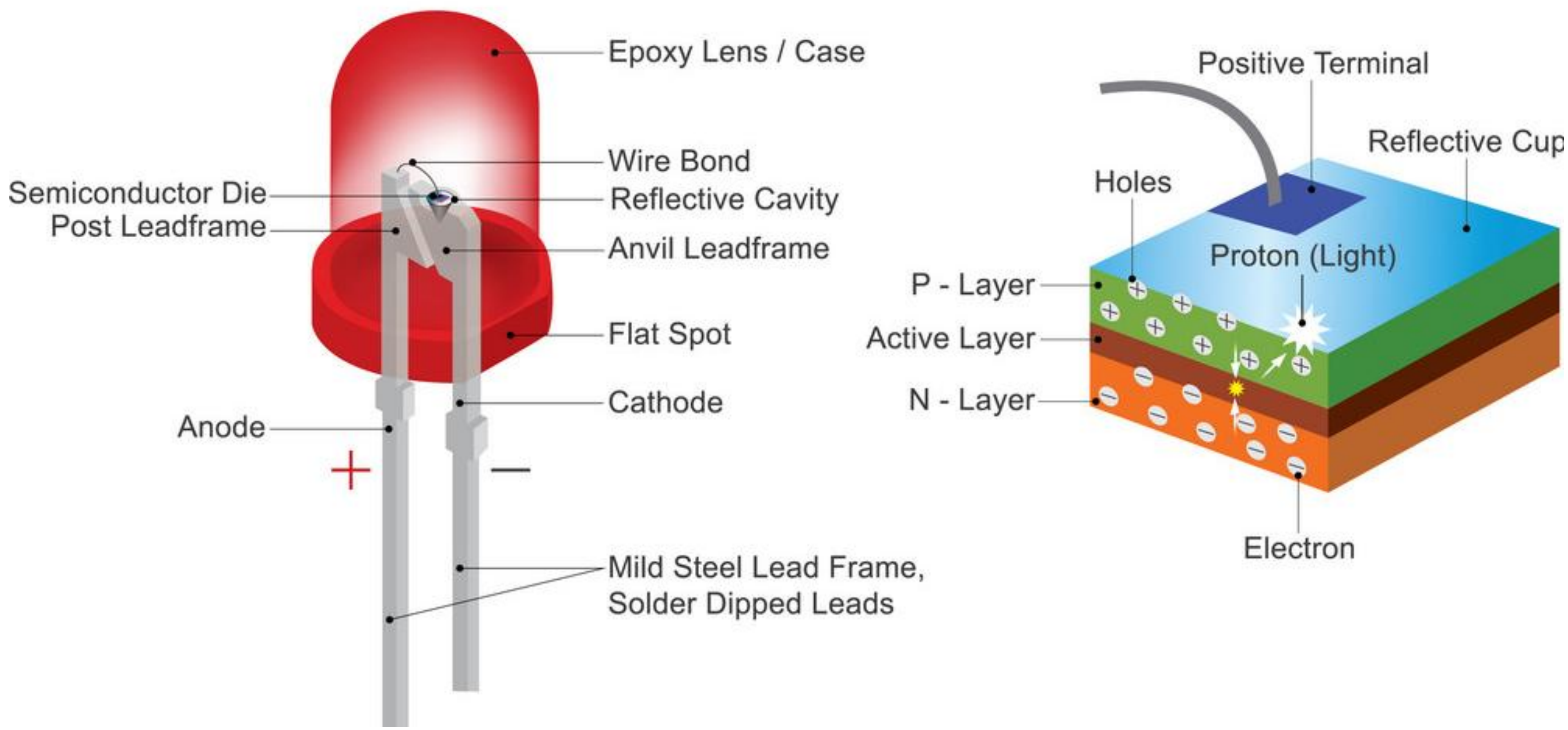



**TABLE 1.9**
*Light-Emitting Diodes*

| Color | Construction | Typical Forward Voltage (V) |
|---|---|---|
| Amber | AlInGaP | 2.1 |
| Blue | GaN | 5.0 |
| Green | GaP | 2.2 |
| Orange | GaAsP | 2.0 |
| Red | GaAsP | 1.8 |
| White | GaN | 4.1 |
| Yellow | AlInGaP | 2.1 |



# 1.16 Light-Emitting Diodes (LED)

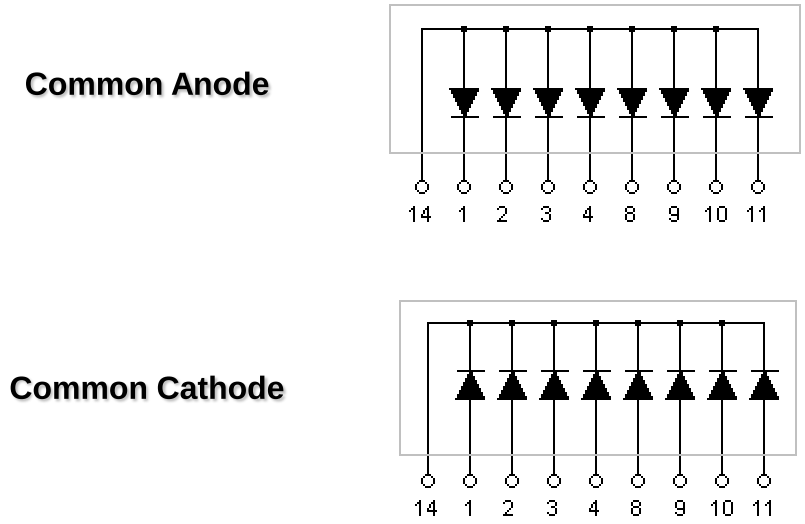


# 1.17 Diode Arrays

## Diode Arrays

- Multiple diodes can be packaged together in an integrated circuit (IC).

- A variety of combinations exist.



# End of Lecture 1

***Thank you for your attention!***