EE Lecture 2: Circuits 2 & Diodes

MS101 Makerspace

2024-25/II (Spring)

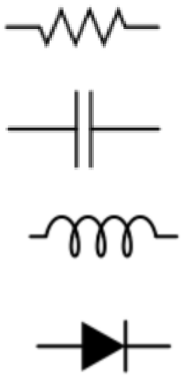
A. Analog Electronic Sub-systems

- Two-terminal (Single-port) devices
  - diodes (and special types of diodes)
- Three-terminal (Two-port) active devices
  - Bipolar Junction Transistors (BJT), and
  - Metal-oxide Semiconductor Field-effect Transistors (MOSFET)
- Passive circuits
  - Made of R, L, and C. Eg. Filters (Low-pass filter, high-pass filter, band-pass filter)
- Active circuits (made using BJTs/MOSFETs, and passive elements R, L and C)
  - Amplifiers
  - Voltage Regulators
  - Sinusoidal oscillators
  - Waveform generators

A1. Two-terminal (single-port) Devices

- Single-port devices: those with two terminals
    - Eg. Resistors, Capacitors, Inductors, Diodes

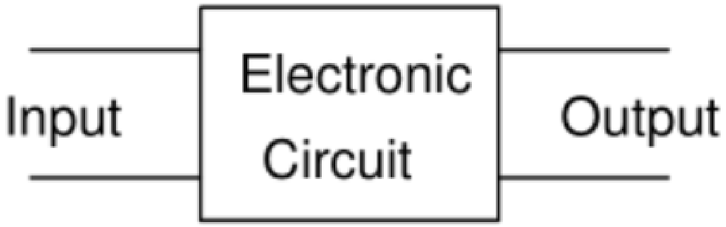
- Single-port devices can be fully described by their *i-v* characteristic
    - Resistor: $v = i\,R$
    - Capacitor: $v = 1/C \int i\, dt$
    - Inductor: $v = L \dfrac{di}{dt}$
    - Diode: $i = I_S\,[exp(v/V_T) - 1]$,
      where I_S=reverse saturation current,
      V_T = thermal voltage

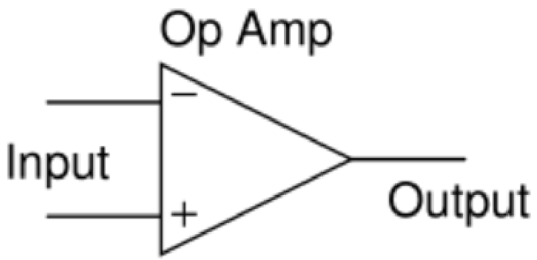


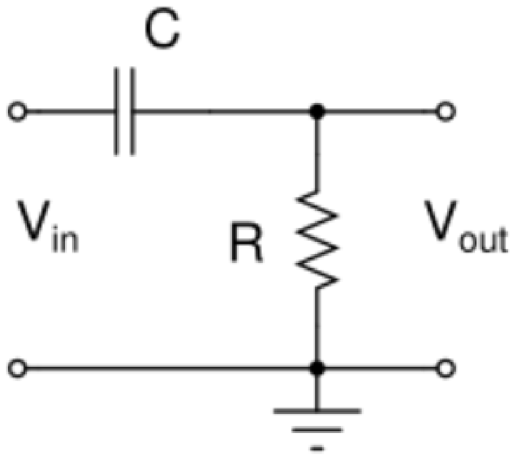
Two-port devices

- Examples:
  - Electronic devices - Bipolar Junction Transistor (BJT), Metal Oxide Semiconductor Field Effect Transistor (MOSFET).

  - Electronic Circuits – Amplifiers, Oscillators, Filters
    - The two ports are, input and output ports.



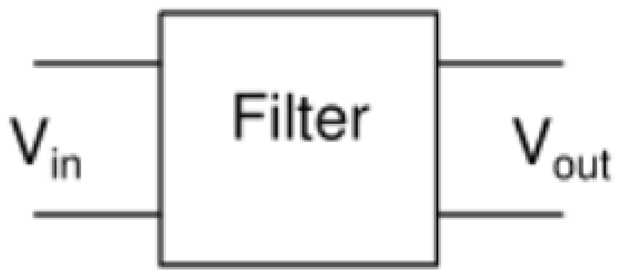




RC high-pass filter circuit

A2. Passive Frequency Selective Circuits

- Circuits whose output responses to sinusoidal signal vary as a function of the frequency of the input signal are called frequency selective circuits or filters.
- Passive filters can be made using *R*, *L* and *C* (eg. low-pass, high-pass, band-pass or band-stop filters).
- Using just one *R* and one *C*, one can build simple filters, such as a low-pass filter or a high-pass filter.



Impedance

- When the voltage input to a resistor, an inductor or a capacitor is a sinusoidal function of time, it is possible to define a voltage-current ratio called **impedance**.
- Impedance of a resistor = R.
- Impedance of an inductor = $j\omega L$.
- Impedance of a capacitor = $1/(j\omega C)$.

where j = sqrt(-1), and $\omega = 2\pi f$. Frequency f is in Hz and angular frequency ω is in rad/s.

- Impedance of R is independent of frequency, impedance of L is proportional to frequency, and impedance of C is inversely proportional to frequency.
- For DC (zero frequency), an inductor acts as a short circuit (zero impedance) and a capacitor acts as an open circuit (infinite impedance).

Low-Pass and High-Pass RC Filters

- Low-pass filters offer less attenuation to frequencies f below a cut-off frequency f_c (or in other words they pass lower range of frequencies).

  i.e. for $f << f_c$, $|V_{out}/V_{in}| \approx 1$.

- Similarly, high-pass filters offer less attenuation to frequencies above a cut-off frequency f_c (or they pass higher range of frequencies).

  i.e. for $f >> f_c$, $|V_{out}/V_{in}| \approx 1$.

- Cut-off frequency (f_c) of an RC filter depends on the individual values of R and C.

RC High-Pass Filter

- Circuit diagram of a high-pass filter is shown.
- V_{out}/V_{in} in terms of impedances of R and C:

  $V_{out}/V_{in} = R/[R + (1/(j\omega C))] = 1 /[1+1/(j\omega CR)]$

  where $\omega = 2\pi f$
- Gain = magnitude of (V_{out}/V_{in}):

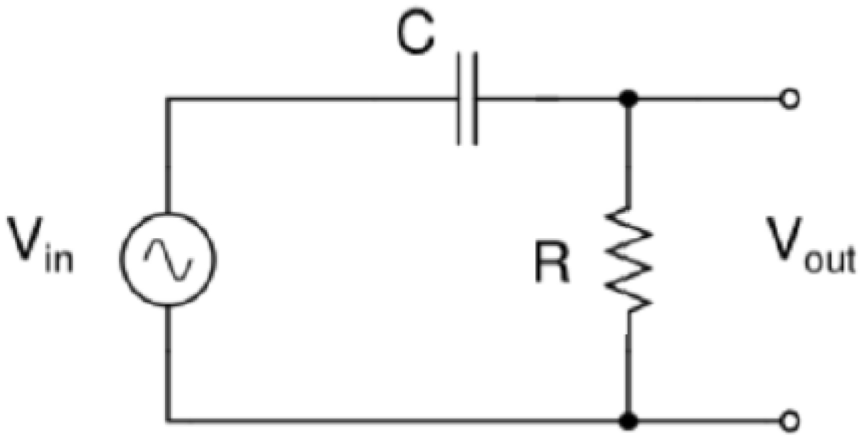
$$A = \left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{[1+1/(\omega CR)^2]^{1/2}}$$

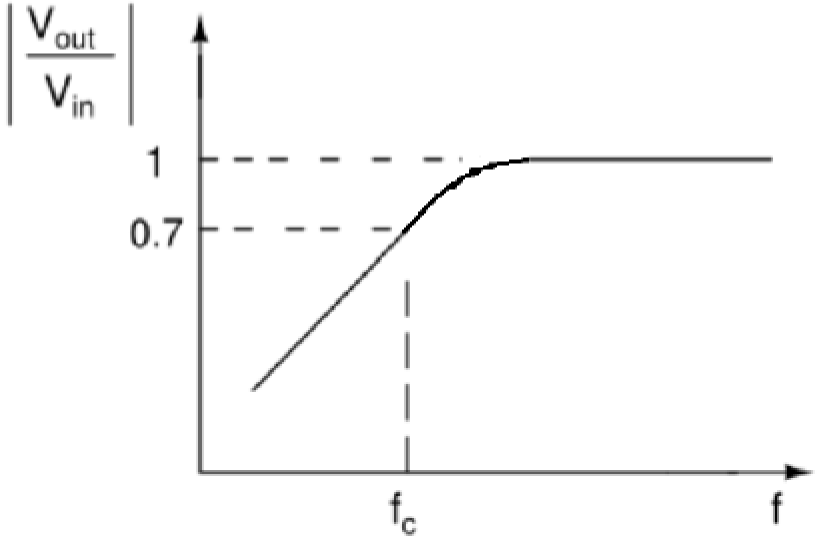
$$= \frac{1}{[1+(\omega_c/\omega)^2]^{1/2}} = \frac{1}{(1+(f_c/f)^2)^{1/2}}$$

where $\omega_c = 1/(RC)$ and $f_c = 1/(2\pi RC)$.

- The sketch shows $|V_{out}/V_{in}|$ as a function of f.

At $f = f_c$, $A = 1/2^{1/2} \approx 0.707$.





RC Low-Pass Filter

- Circuit diagram of a Low-pass filter is shown.
- V_{out}/V_{in} in terms of impedances of R and C:
  $V_{out}/V_{in} = (1/j\omega C) / [R + (1/j\omega C)] = 1/[1+j\omega CR]$,
  where $\omega = 2\pi f$
- Gain = magnitude of (V_{out}/V_{in}):

$$A = \left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\left[1+(\omega CR)^2\right]^{1/2}}$$

$$= \frac{1}{[1+(\omega/\omega_c)^2]^{1/2}} = \frac{1}{[1+(f/f_c)^2]^{1/2}}$$

where $\omega_c = 1/(RC)$ and $f_c = 1/(2\pi RC)$.

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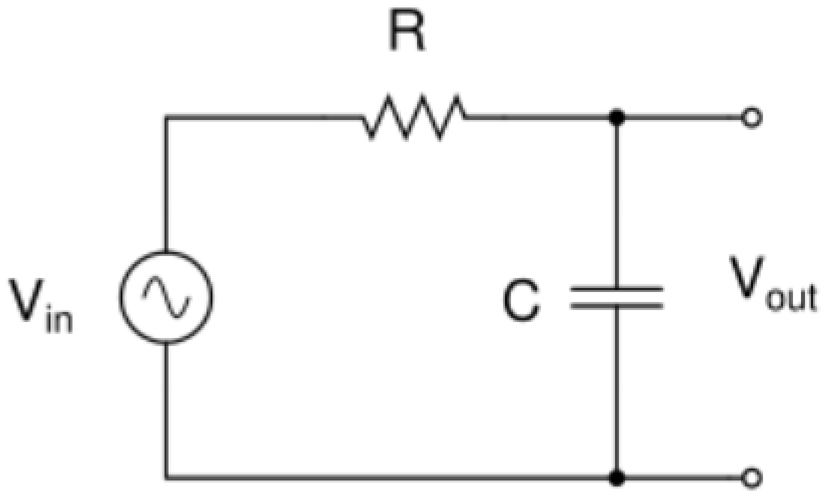
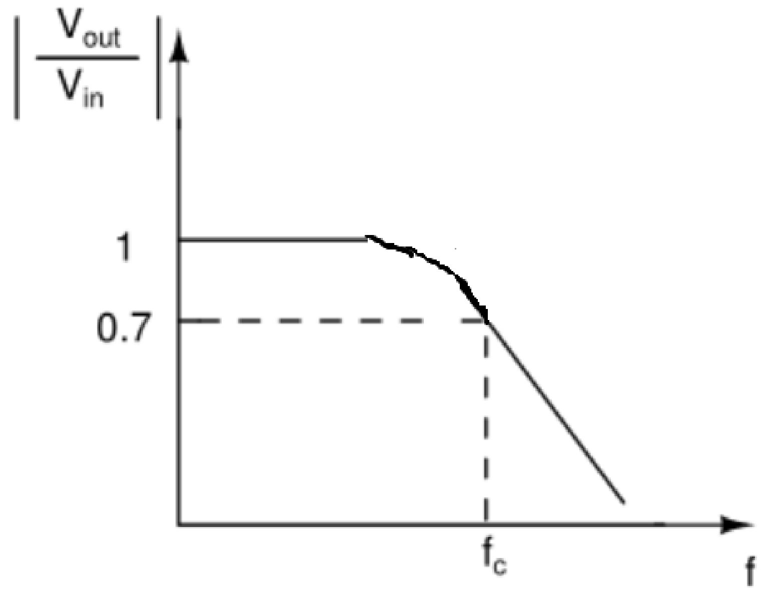




B. The *pn* Junction Diode

Semiconductors (Intrinsic Semiconductors)

- Semiconductors are materials whose conductivity lies between that of conductors, such as copper, and insulators, such as glass.
- There are two kinds of semiconductors:
  - **Single-element semiconductors**, such as germanium and silicon, which are in group IV in the periodic table; and
  - **Compound semiconductors**, such as gallium-arsenide, which are formed by combining elements from groups III and V or groups II and VI.
  - Compound semiconductors are useful in special electronic circuit applications as well as in applications that involve light, such as light-emitting diodes (LEDs).
- Two elemental semiconductors - Germanium (Ge) and Silicon (Si)
  - Ge was used in the fabrication of very early transistors (late 1940s, early 1950s).
  - Si became soon popular. Today's integrated-circuit technology is almost entirely based on silicon.

- Silicon (Si) is the most commonly used material used in *pn* junction diodes.
- Si in its intrinsic (or pure) form is not useful for fabricating devices, instead it is doped with impurities.
- **Free Electrons** and **holes** are responsible for current flow in a semiconductor. A hole may be thought of as the absence of an electron with a positive charge equal in magnitude to the electron charge.
- **Doping** involves introducing impurity atoms into the silicon crystal in sufficient numbers to substantially increase the concentration of either free electrons or holes but with little or no change in the crystal properties of silicon.
- To increase the concentration of free electrons, *n*, silicon is doped with an element with a valence of 5, such as phosphorus.
  - This results in an ***n* type** silicon.
- To increase the concentration of holes, *p*, silicon is doped with an element having a valence of 3, such as boron
  - This results in ***p* type** silicon.

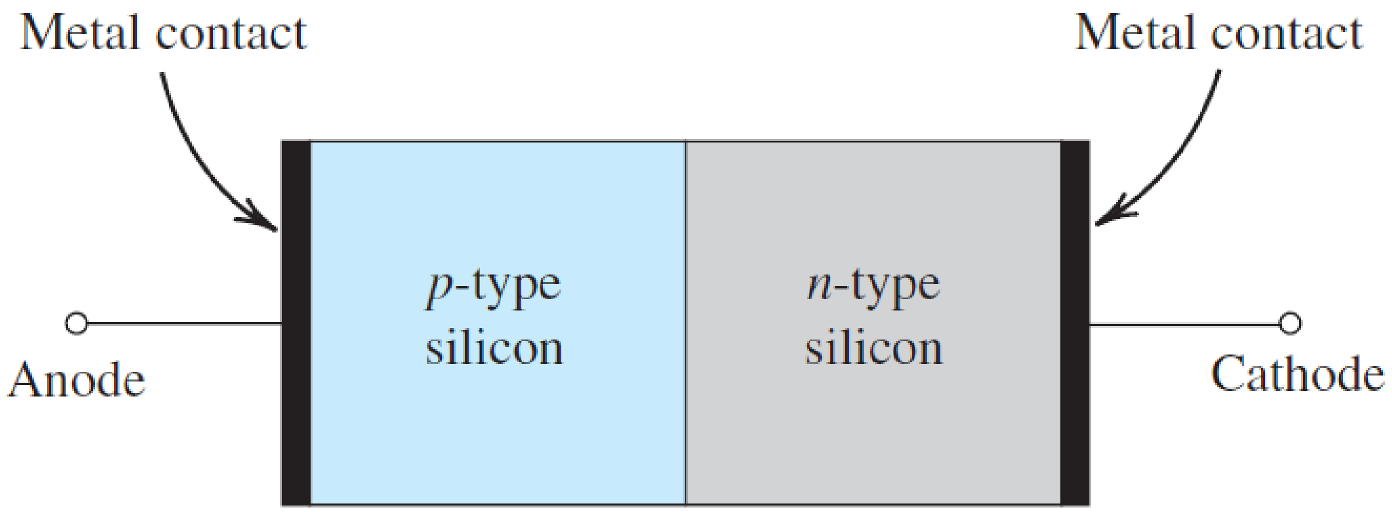


Fig. 1 Simplified physical structure of the *pn* junction.

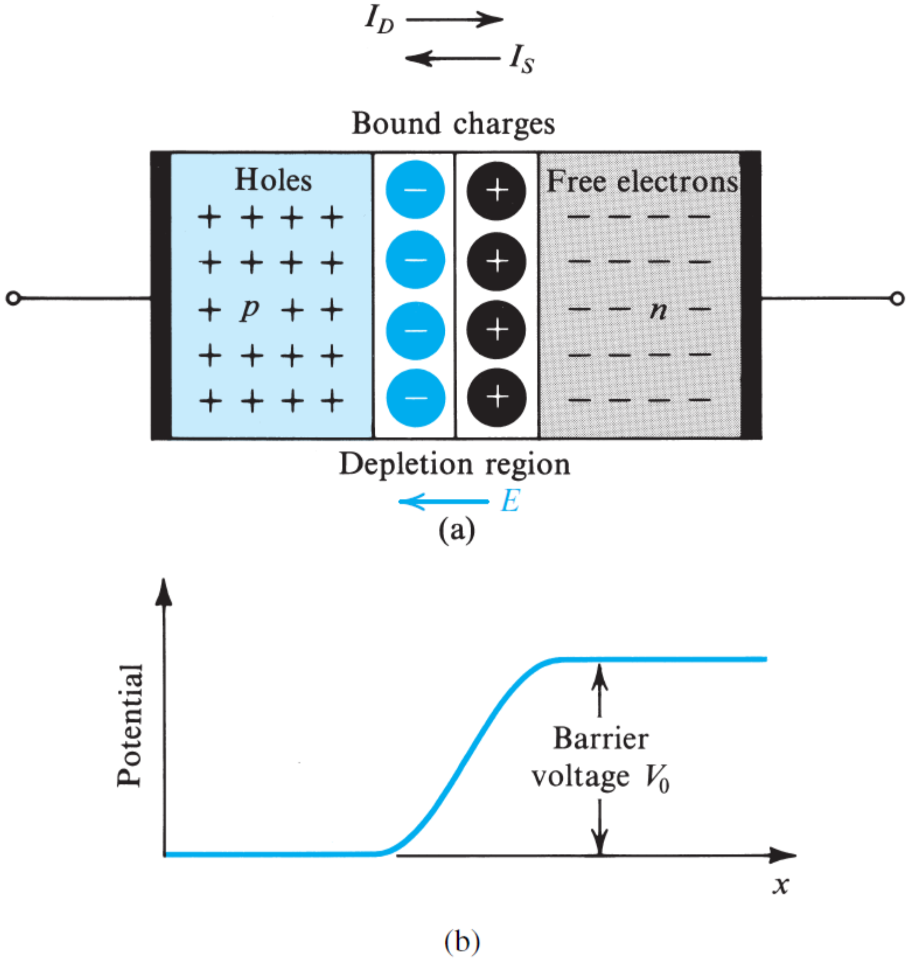


Fig 2 (a) The *pn* junction with no applied voltage (open-circuited terminals).

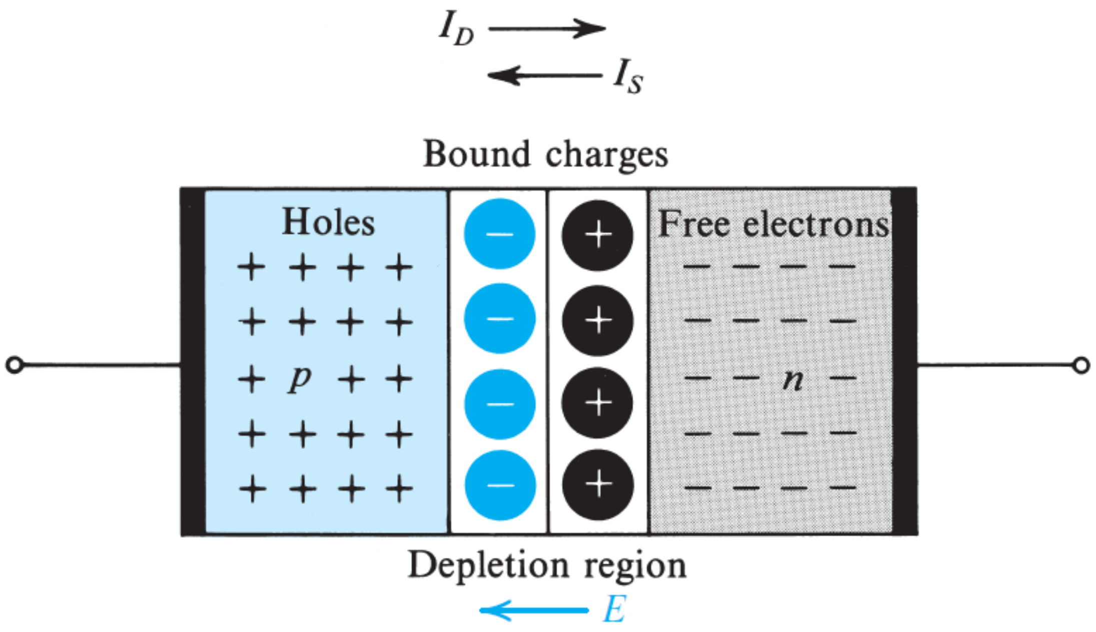
(b) The potential distribution along an axis perpendicular to the junction.

Source: Chap 3, Microelectronic Circuits, 7th ed., AS Sedra and KC Smith, Oxford University Press

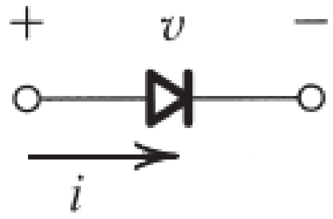
- Holes diffuse across the junction from the *p* side to the *n* side.
- Similarly, electrons diffuse across the junction from the *n* side to the *p* side.
- Recombination takes place close to the junction.
- There will be a region close to the junction that is *depleted of free electrons and holes*.
  - This region is called the **depletion region, or** the **space-charge region**.
- A potential difference results across the depletion region, with the *n* side at a positive voltage relative to the *p* side, as shown in (b).
- The resulting electric field acts as a **barrier** that has to be overcome for holes to diffuse into the *n* region and electrons to diffuse into the *p* region.
- Typically, for silicon at room temperature, the barrier voltage (or the **junction built-in potential**) V_0 is in the range of 0.6 V to 0.9 V.

The *pn* Junction with an Applied Bias

- Behaviour of the *pn* junction with an applied bias:
  - If the voltage is applied so that the *p* side is made more positive than the *n* side, it is referred to as a **forward-bias voltage**.
  - If our applied dc voltage is such that it makes the *n* side more positive than the *p* side, it is said to be a **reverse-bias voltage**.
- The *pn* junction exhibits vastly different conduction properties in its forward and reverse directions.



The *pn* junction Terminal Characteristic



- The terminal characteristic of a *pn* junction diode (i.e. *i* vs *v*) can be written as:

$$i = I_S\,[exp(v/V_T)\ \text{-}1],$$

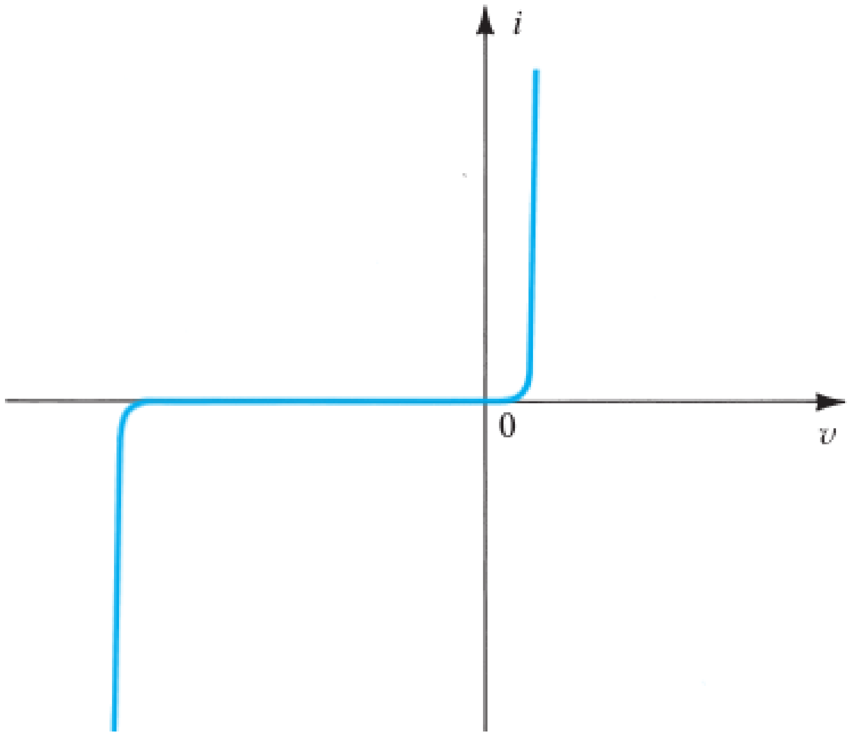
where I_S = reverse saturation current (typ of the order of 10^{-15} A)

$V_T = (kT/q)$ is the thermal voltage ($V_T \approx 25$ mV at 20 °C)

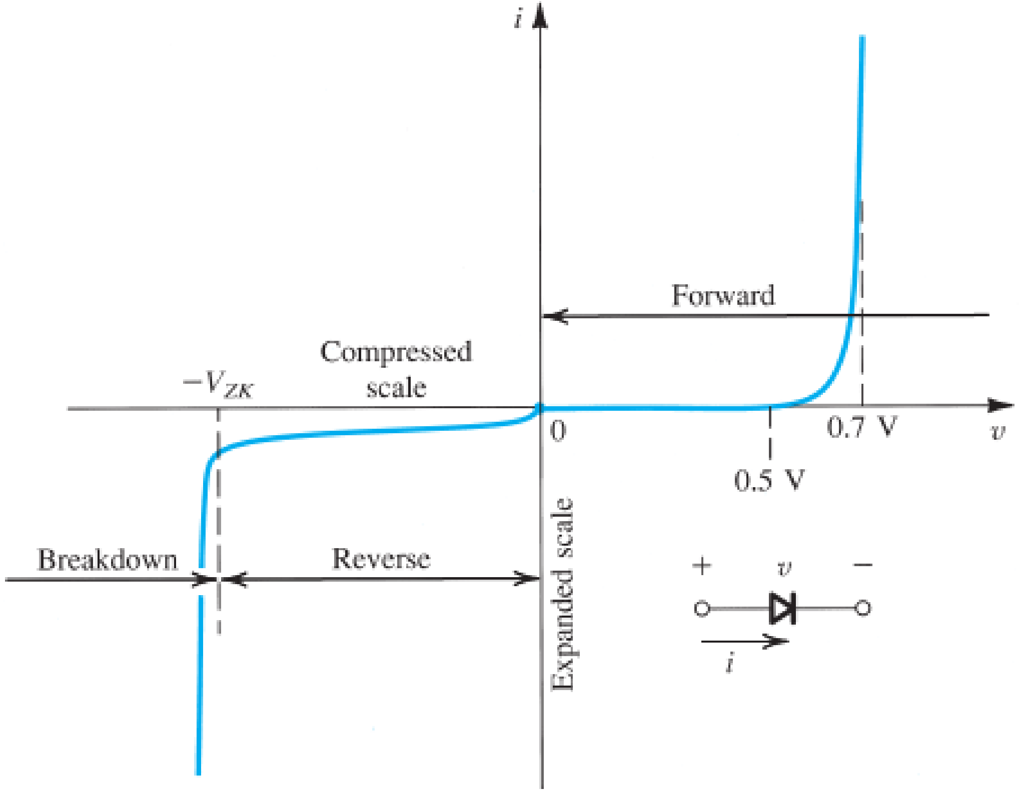
k = Boltzmann's constant = 8.62×10^{-5} eV/K = 1.38×10^{-23} joules/kelvin

T = the absolute temperature in kelvins = 273 + temperature in °C

q = the magnitude of electronic charge = 1.60×10^{-19} coulomb



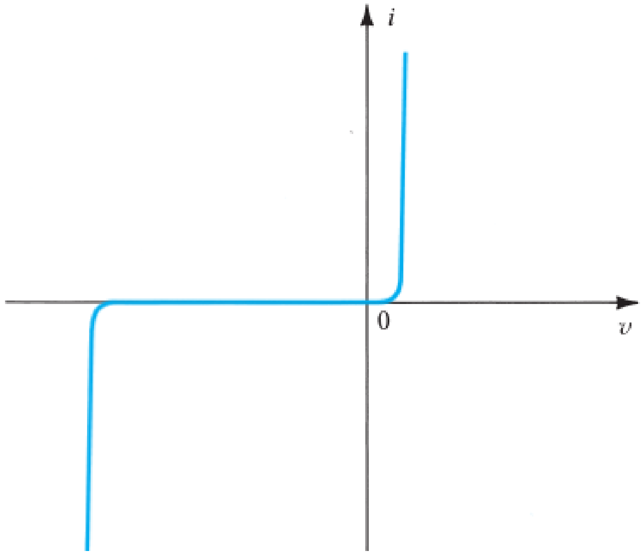
To scale

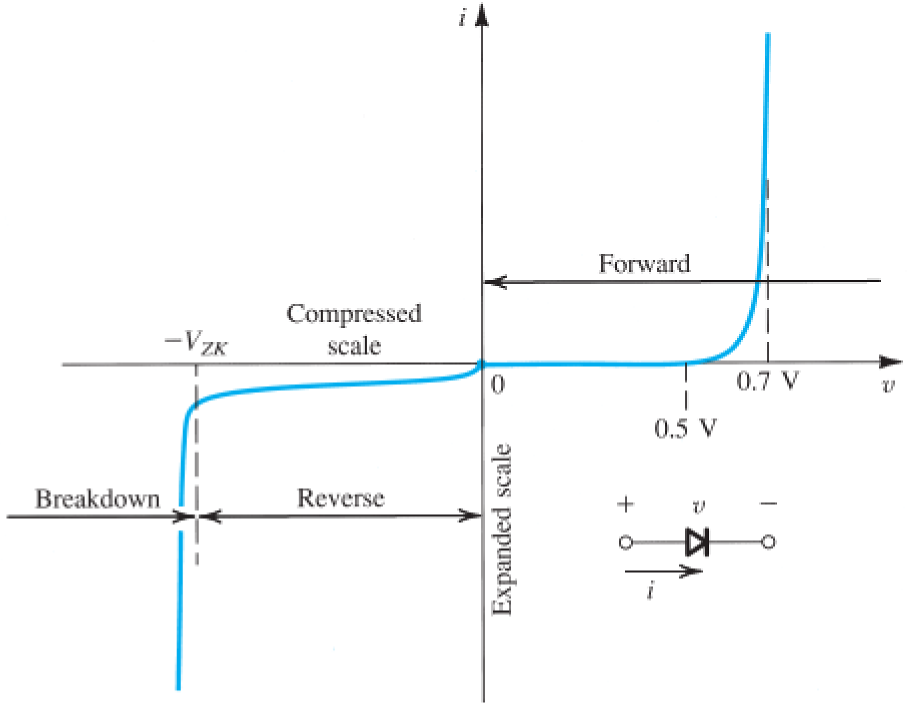


The *i*-*v* characteristic with expanded and compressed scales to reveal details

Fig. 3 The *i*-*v* characteristic of a silicon junction diode

Source: Chap4, Sec. 4.26, Microelectronic Circuits, 7th ed., AS Sedra and KC Smith, Oxford University Press





- The forward-bias region, determined by $v > 0$
- The reverse-bias region, determined by $v < 0$
- The breakdown region, determined by $v < -V_{ZK}$
- **Forward region**
  - Negligible current for $v < 0.5$ V (called *Cut-in voltage*)
  - Voltage drop for a "fully conducting" diode lies in a narrow range, approximately 0.6 V to 0.8 V.
- **Reverse region**
  - When v is made negative, current i will be negligible, and $I \approx -I_S$
- **Breakdown region**
  - When v is large and negative, the reverse current increases rapidly
  - Diode breakdown is normally not destructive

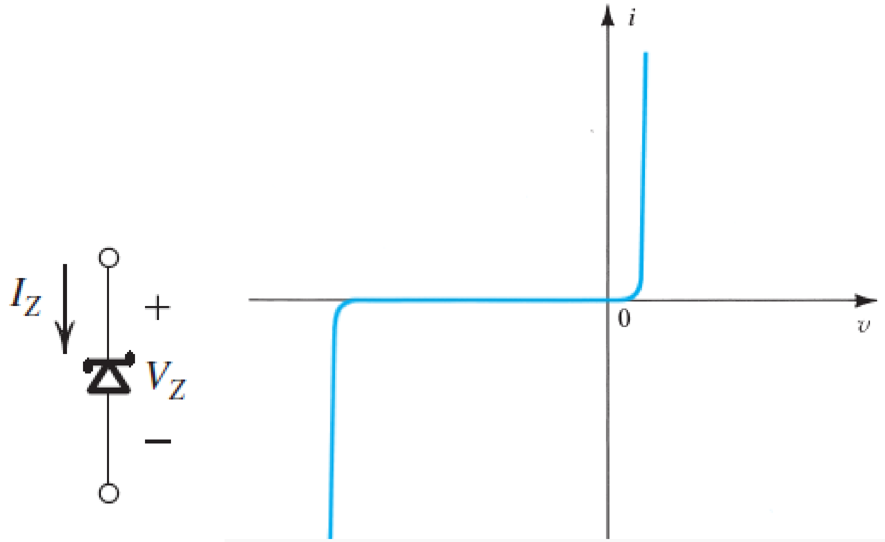
Applications of Diodes

- The most important application is in rectifier circuits, for converting ac voltages to dc
  - Half-wave rectifier, full-wave rectifier and bridge rectifier circuits

- **Other Applications**
  - As a protection device in relay circuits
  - In waveshaping circuits, such as diode clipper circuits
  - In switching and clamping circuits

C. Zener Diodes

- *pn* junction diodes have very steep *i–v* curve in the breakdown region, and have almost constant voltage drop in that region
- Zener diodes (or breakdown diodes) are diodes operating in the reverse breakdown region, and are manufactured to operate specifically in the breakdown region.
- Can be used in the design of voltage regulators
    - Voltage regulators are circuits that provide a constant dc output voltage for varying load currents and input voltages.
- In normal applications of Zener diodes, current flows into the cathode, and the cathode is positive with respect to the anode.
    - Thus I_Z and V_Z in the figure have positive values.



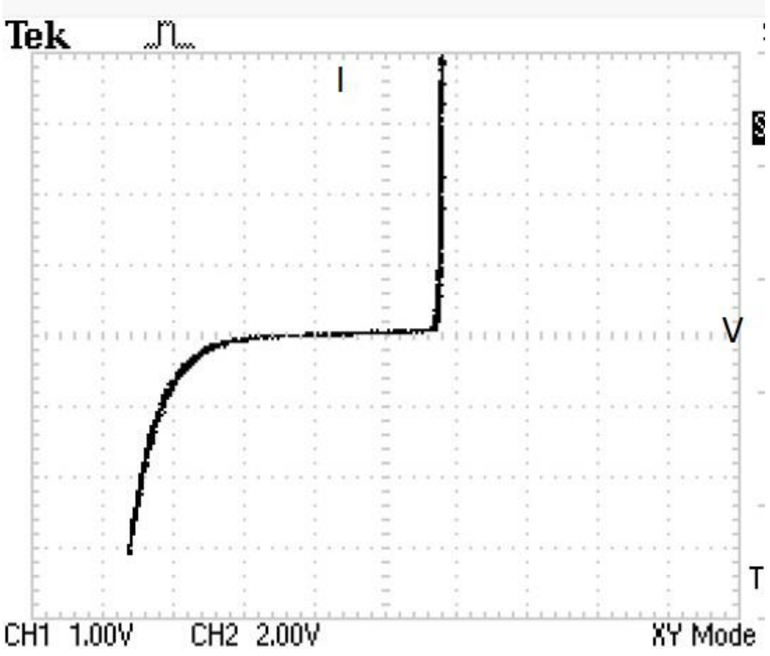


Fig. 4

Measured Zener characteristic

Main Application of Zener diodes

- Zener regulator circuit
  - Output voltage V_{out} will be reasonably constant for
    - Variations in V_{in}, and
    - Variations in I_L

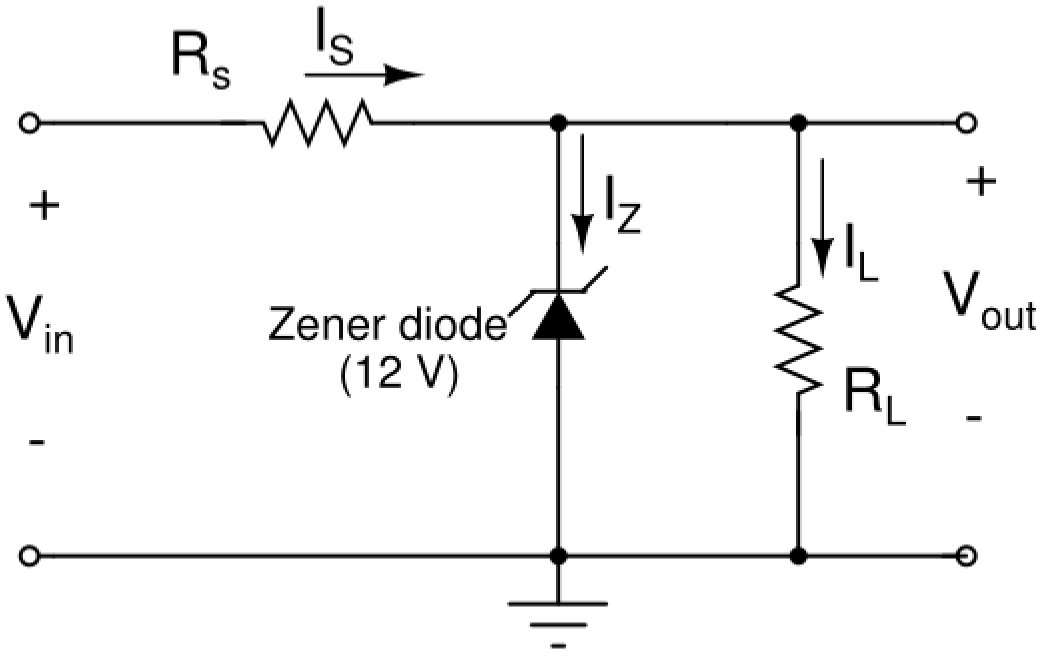


Fig. 5 Zener regulator circuit

D. Light Emitting Diodes

- LEDs are special diodes that emit light when forward biased (i.e. they convert electrical energy into light). They are called electrical-to-optical converters.
- Light is produced due to *radiative recombination* of injected minority carriers with the majority carriers.
- For radiative recombination, the *pn* junction should be made using a semiconductor of the type known as *direct-bandgap materials*.
- Examples of direct-bandgap material
  - Gallium arsenide (GaAs), AlGaAs, GaN, InP, ..
  - Wavelength of an LED's light depends on the electronic bandgap of the material used
- The light emitted by an LED is proportional to the number of recombinations that take place, i.e. *proportional to the forward current* in the diode.

Applications of LEDs

- As display devices
  - Single LED indicators of various colours
  - Seven-segment LED numeric displays and alphanumeric displays in laboratory instruments and equipment
- White LEDs for lighting
  - Light conversion efficiency: 60%. (Incandescent bulbs: 5 to 12 %, Compact Fluorescent bulbs: 27 %)
- Other Modern applications
  - Video displays (Laptop and PC)
  - Large LED display screens

Electronics Hub

Light Emitting Diode Basics | LED Types ...

IndiaMART

Arrow Electronics

Fig. 10

E. Photodiodes

- When a *pn* junction is reverse-biased, a depletion region is formed around the *pn* junction.
  - Only the reverse saturation current flows, which is very small and is primarily due to the minority carriers.
- If the reverse-biased *pn* junction is exposed to incident light
  - the photons impacting the junction cause covalent bonds to break, and thus electron-hole pairs are generated in the depletion layer.
  - The electric field in the depletion region then sweeps the liberated electrons to the *n* side and the holes to the *p* side, giving rise to a reverse current across the junction.
  - This current is known as **photocurrent**, and is proportional to the intensity of the incident light.
  - Such a diode is called a *photodiode*
  - It can be used to convert light signals into electrical signals.

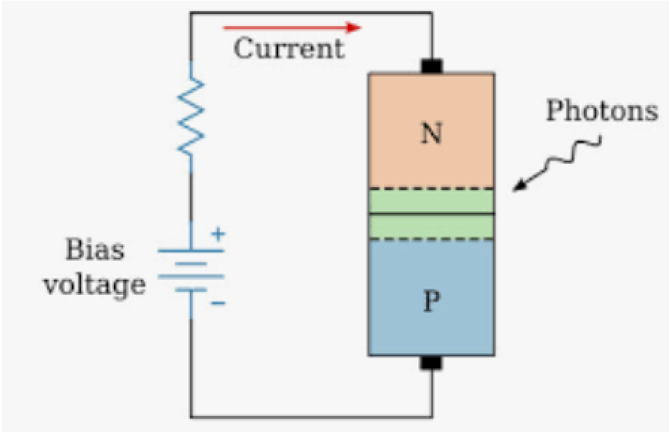


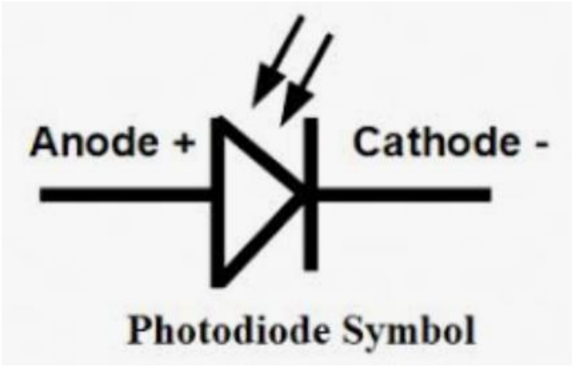
Fig. 11
Source: Electric Circuit Studio and OSI Optoelectronics

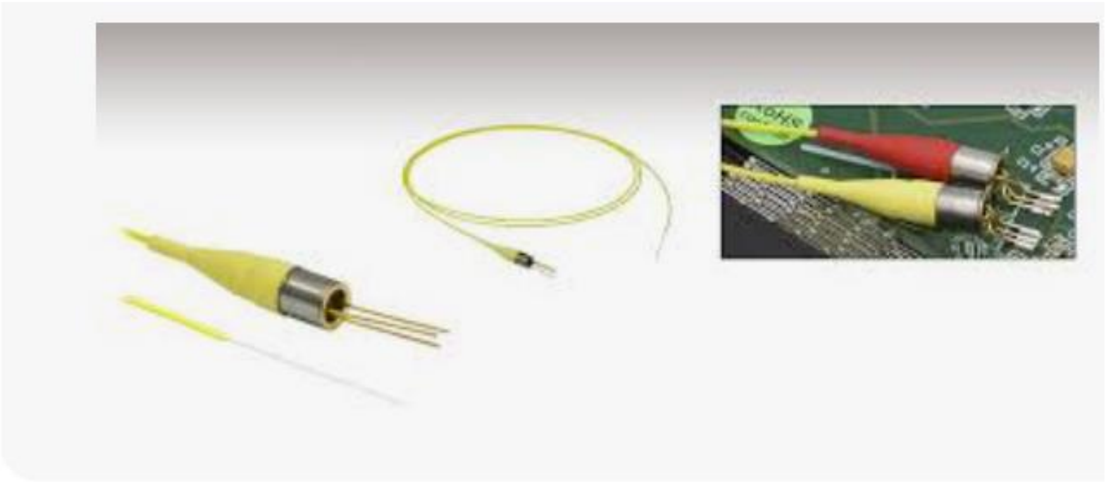
Applications of Photodiodes

- Electrical-to-optical conversion (EO conversion)

  Extensively used in optical fiber communications at the receiver side for detecting the optical signals sent. (Optical fiber communications is employed for telecommunication and internet data applications).

- LED (OE) - Photodiode (EO) combination
  - Remote control of electronic appliances.
  - For obstacle detection (eg. in a lift door).





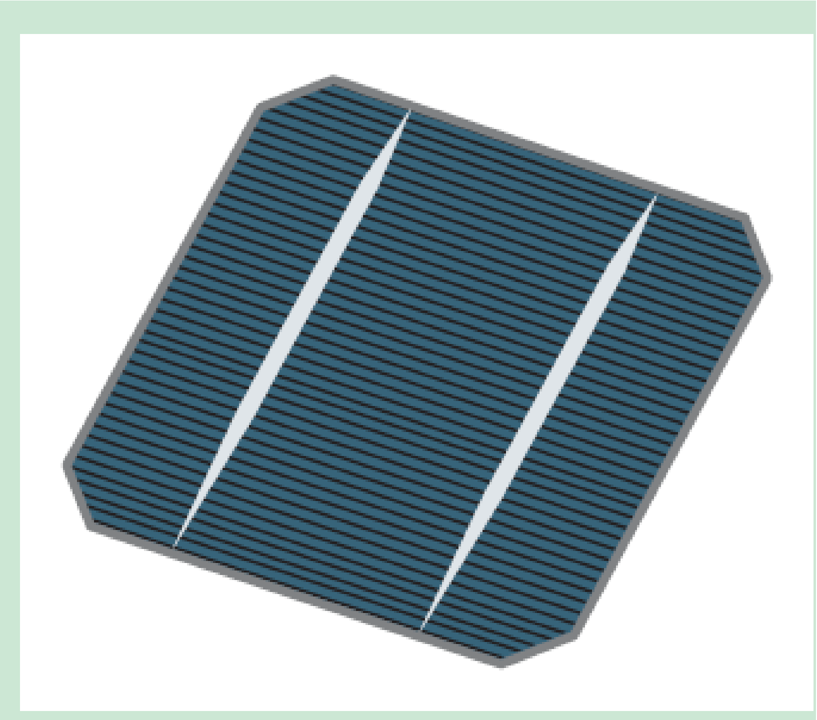
Thorlabs, Inc.

Pigtailed Photodiodes

Fig. 12

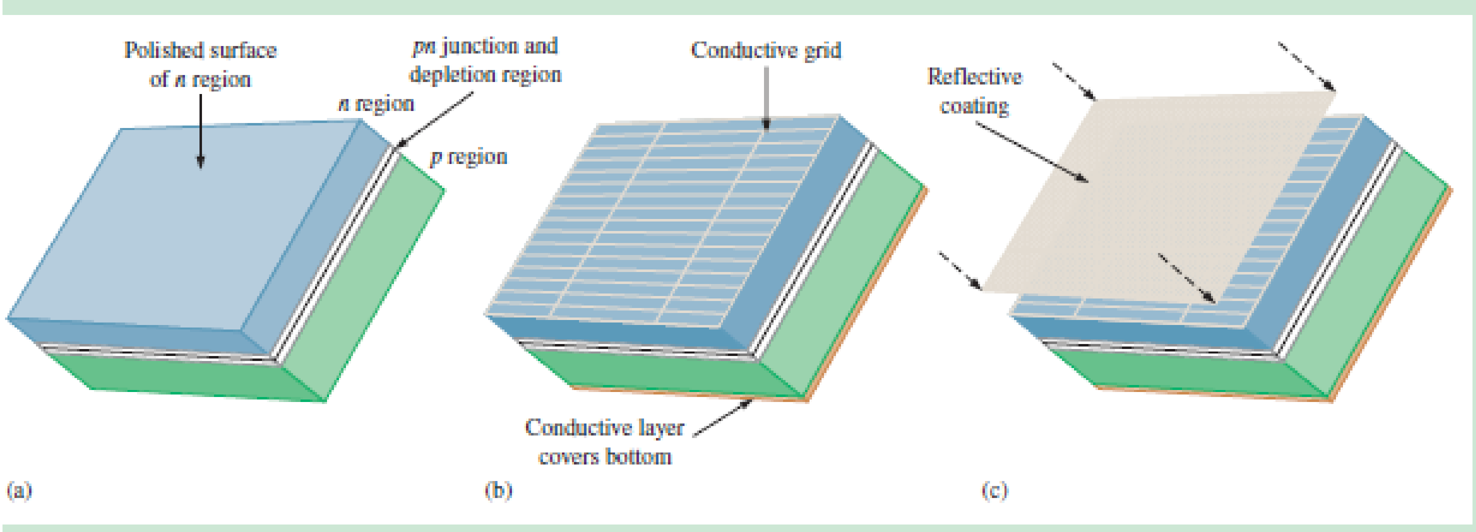
F. Solar Cells

- Solar cells are illuminated photodiodes *without reverse bias* (uses **photovoltaic effect).**
- Fabricated from low-cost silicon.
- A solar cell converts sunlight into electricity.
- Photon energy creates electron-hole pairs in the *n* and *p* regions.
- Electrons accumulate in the *n*-region and holes accumulate in the *p* region, producing a potential difference (voltage) across the cell.
- When an external load is connected, the electrons flow through the semiconductor material and provide current to the external load.



Source: Chap 1, Electronic Devices, 9th ed., Thomas L Flyod, Prentice Hall, 2012.

Fig. 14



Basic construction of a photovoltaic (PV) solar cell.

Fig. 15

Source: Chap 1, Electronic Devices, 9th ed., Thomas L Flyod, Prentice Hall, 2012.

V-I characteristic for a typical single solar cell for increasing light intensities.