EE Lecture 2: Electronic Devices and Circuits-Part A

Makerspace 101

2022-23/II (Spring)

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Analog Electronic Sub-systems

- Two-terminal devices
  - diodes (and special types of diodes)
- Three-terminal 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

Syllabi for Lect 2 and Lect 3

- **Lect 2 – Electronic Devices**
  - Electronic Sub systems: Two-terminal electronic devices (diodes); Two-port networks: 3-pin devices (BJT, MOSFET), Filters, Amplifiers
  - *pn* junction diode
  - Zener diode,
  - LED,
  - Photodiode, and
  - Solar Cell
- **Lect 3 – Rectifier and Regulator Circuits**
  - Rectifier circuits: Half-wave rectifier, Full-wave rectifier, Bridge rectifier
  - Unregulated DC Power Supply
  - Voltage Regulator: IC based DC Power Supply

1. The *pn* Junction Diode

- 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.
- **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.

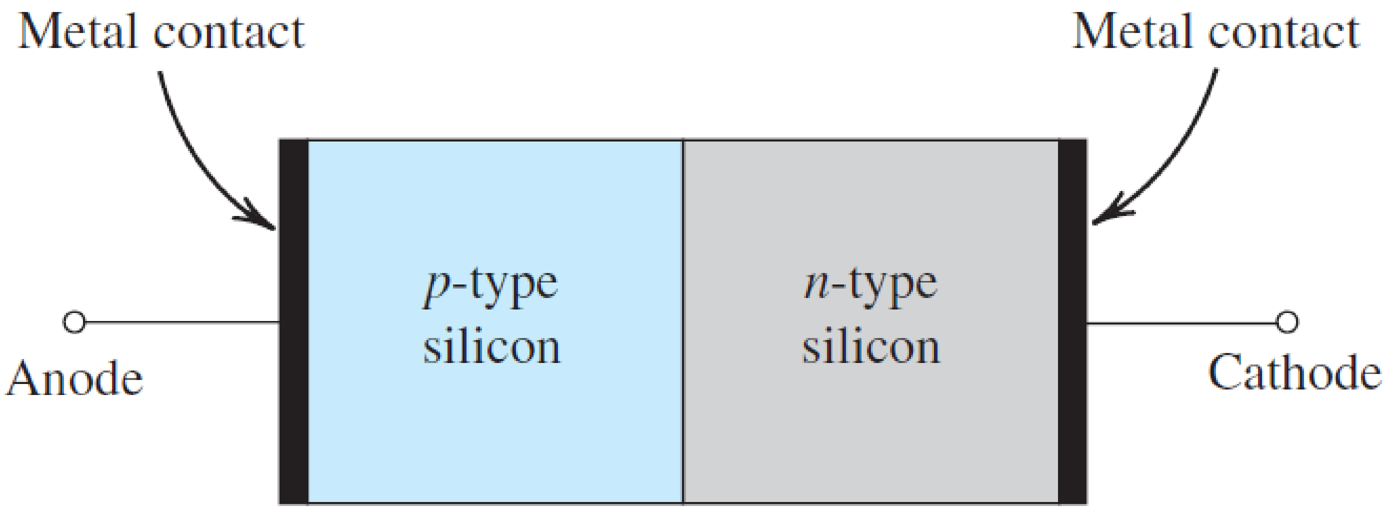

Fig. 1 Simplified physical structure of the *pn* junction.

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Since the *pn* junction is used as a diode, the diode terminals are therefore labeled “anode” and “cathode” in keeping with diode terminology.

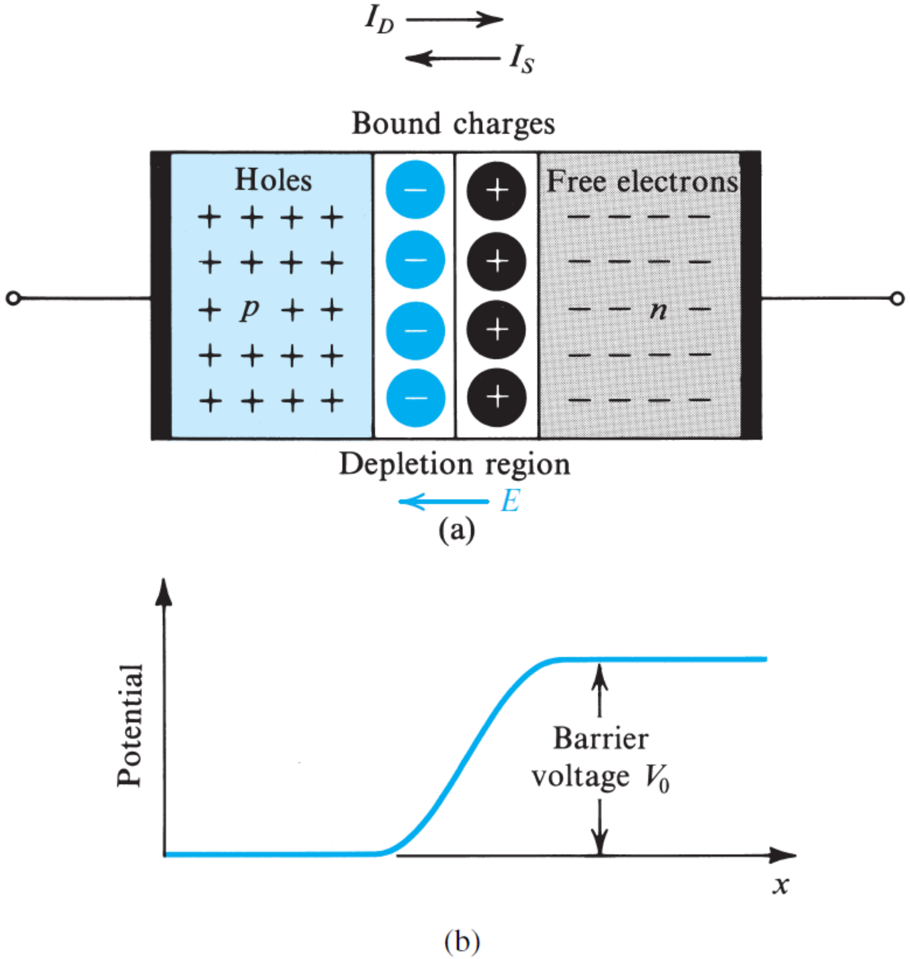


Fig 2 (a) The *pn* junction with no applied voltage (open-circuited terminals).

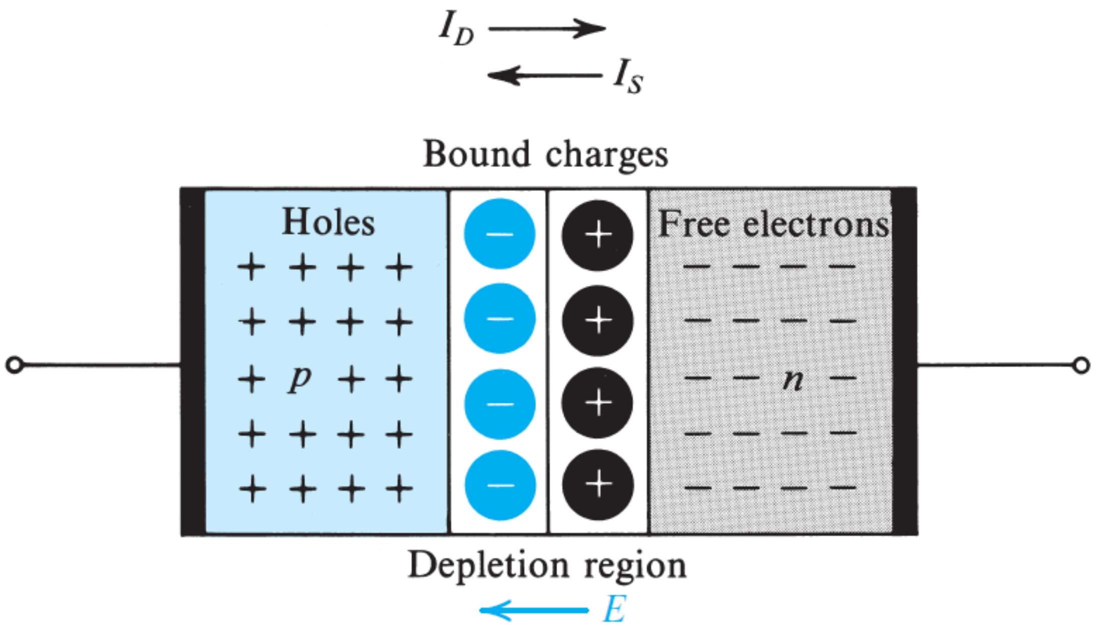
(b) The potential distribution along an axis perpendicular to the junction.

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

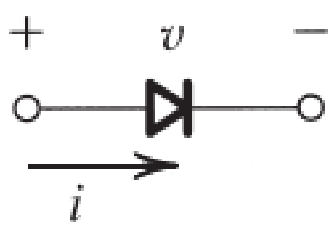
- Holes diffuse across the junction from the *p* side to the *n* side.
- Similarly, electrons diffuse across the junction from the *n* side to the *p* side.
- Recombination takes place close to the junction.
- There will be a region close to the junction that is *depleted of free electrons and holes*.
  - 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:

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

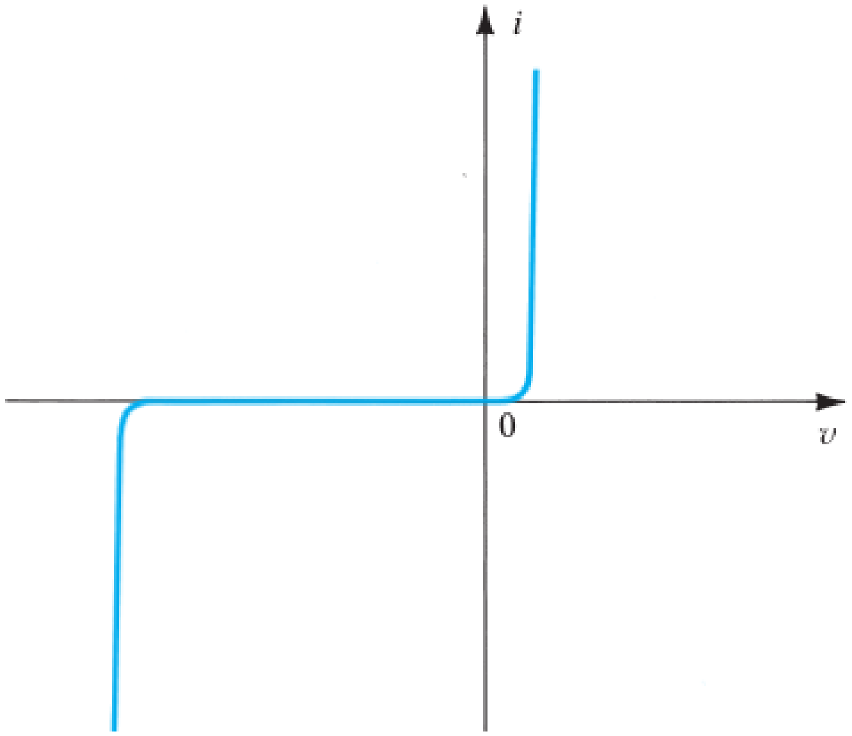
where I_S = reverse saturation current (typ of the order of 10^{-15} A)

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

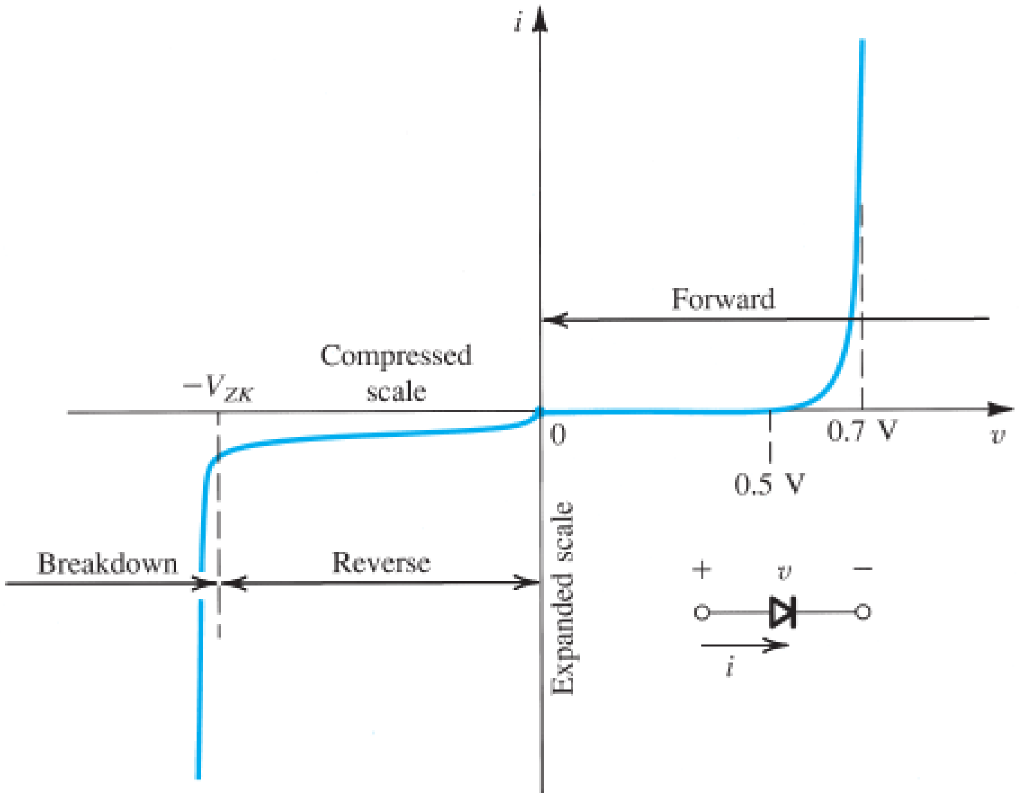
k = Boltzmann's constant = 8.62×10^{-5} eV/K = 1.38×10^{-23} joules/kelvin

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

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



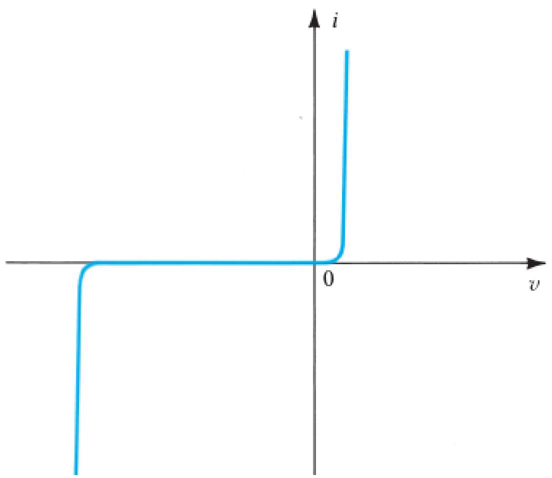
To scale

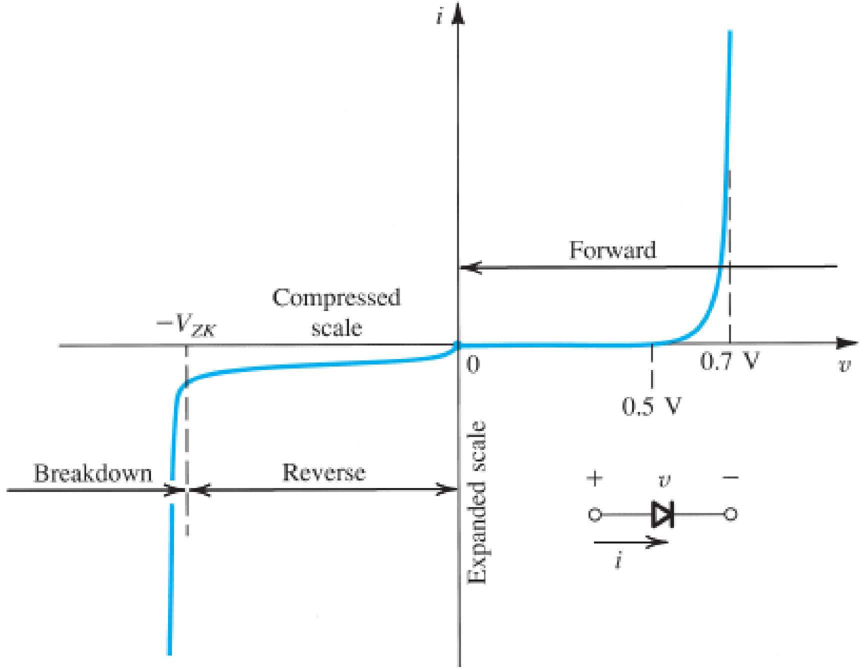


The *i*-*v* characteristic with expanded and compressed scales to reveal details

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

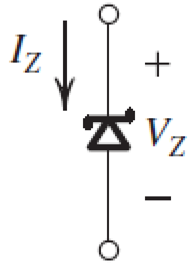
Applications of Diodes

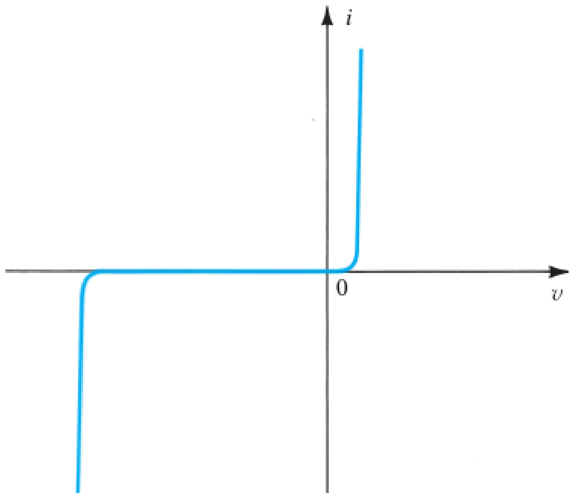
- The most important application is in rectifier circuits, for converting ac voltages to dc
  - Half-wave rectifier, full-wave rectifier and bridge rectifier circuits

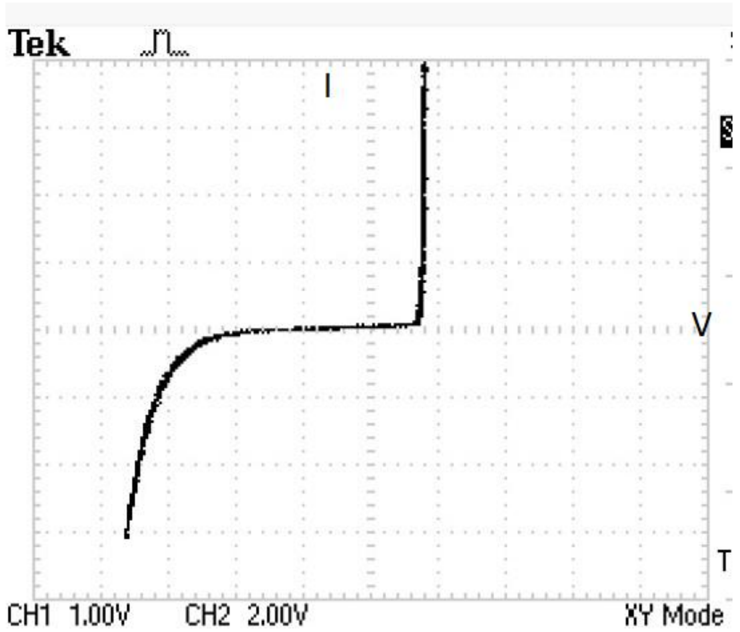
- **Other Applications**
  - In general circuit applications to allow current flow only in one direction
  - As a protection device in relay circuits
  - In waveshaping circuits, such as diode clipper circuits
  - In switching and clamping circuits

2. 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 system power-supply 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.







Measured zener characteristic

Fig. 4

Applications of Zener diodes

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

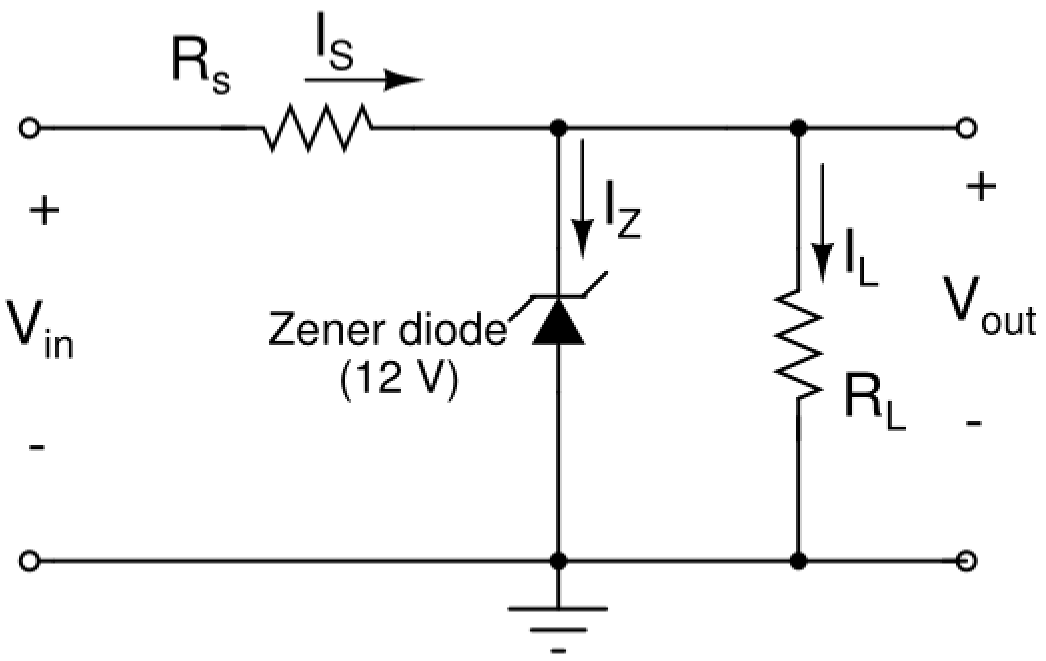
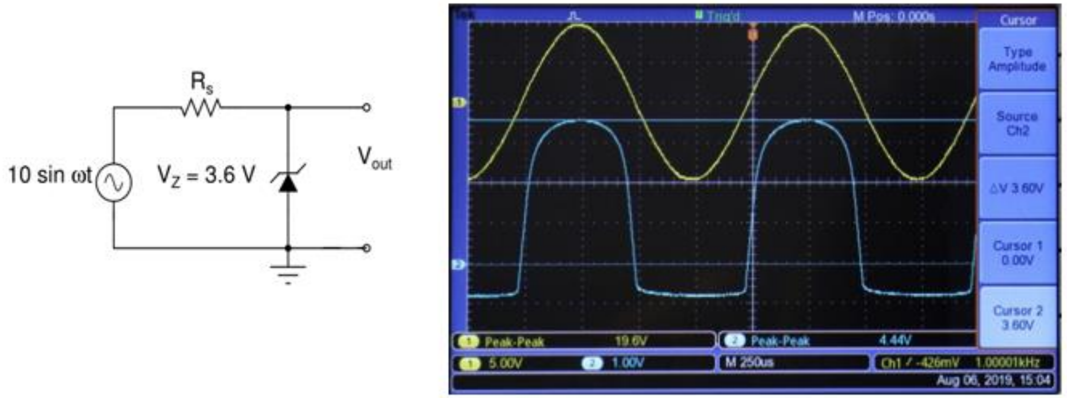
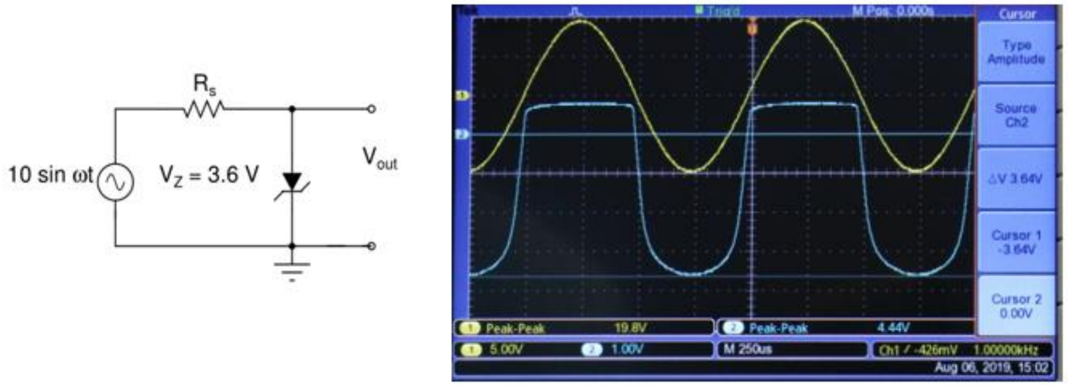


Fig. 5 Zener regulator circuit

B) Waveshaping (Clipping) Circuits



Zener diode clipping circuit 1 and the observed V_{out} waveform



Zener diode clipping circuit 2 and the observed V_{out} waveform

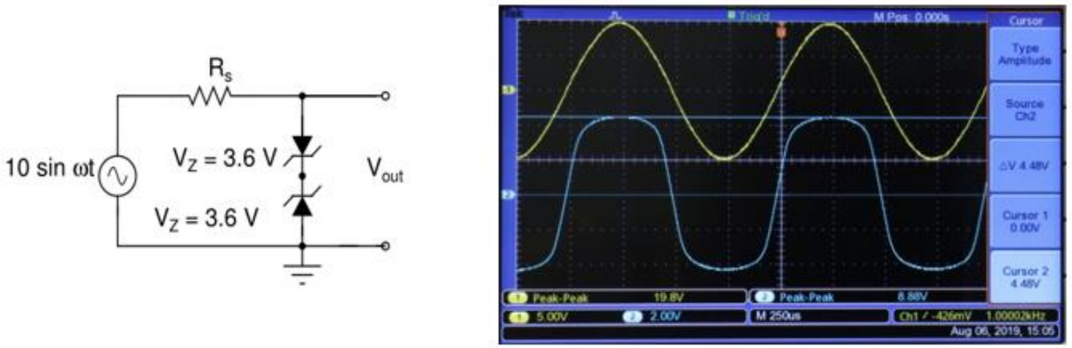
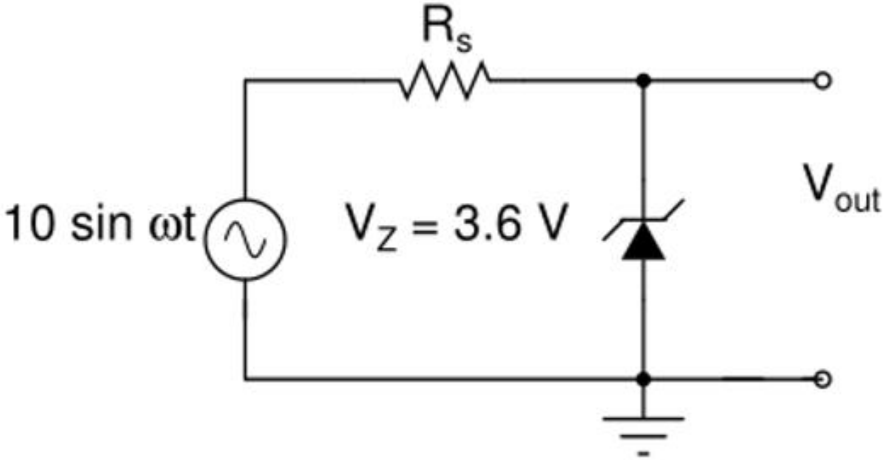


Fig. 6

Zener diode clipping circuit 3 and the observed V_{out} waveform



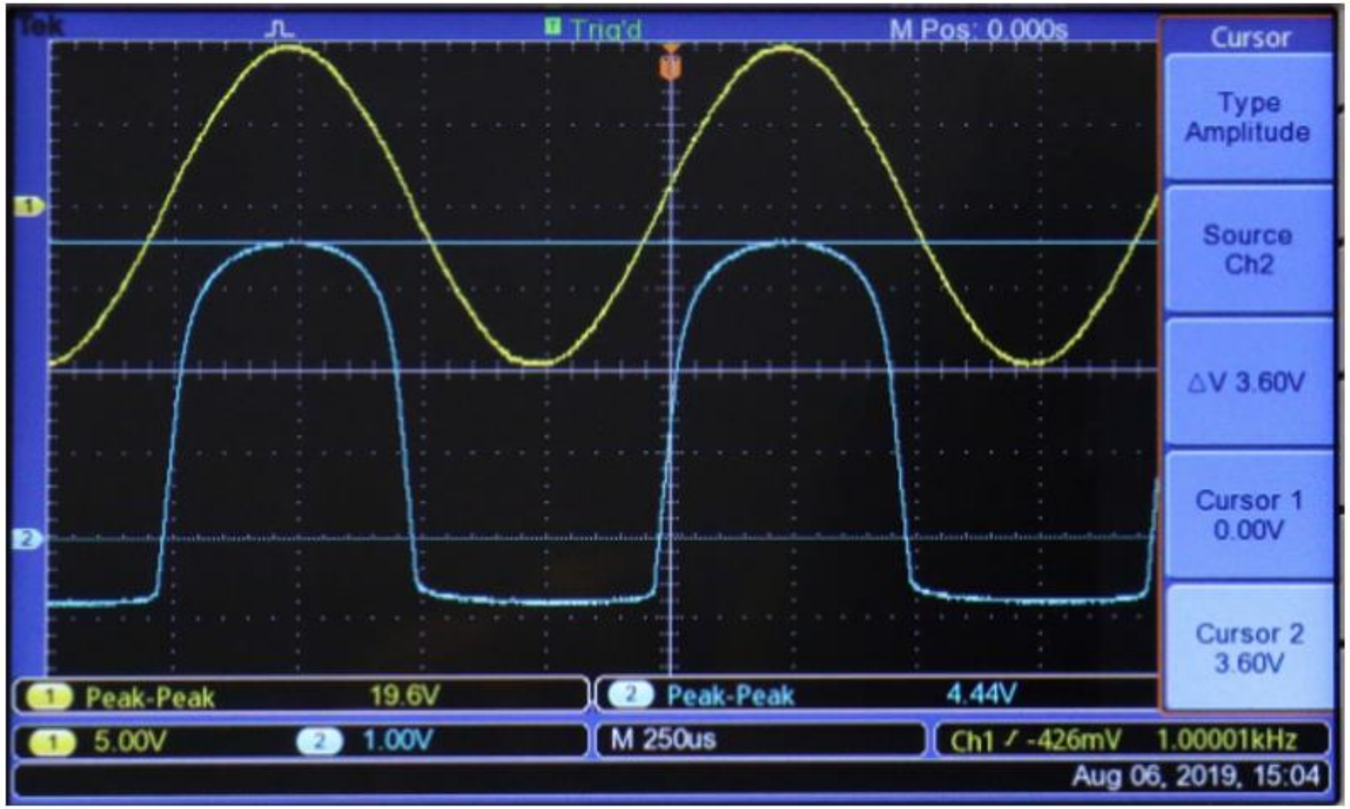


Fig. 7 Zener diode clipping circuit 1 and the observed V_{out} waveform

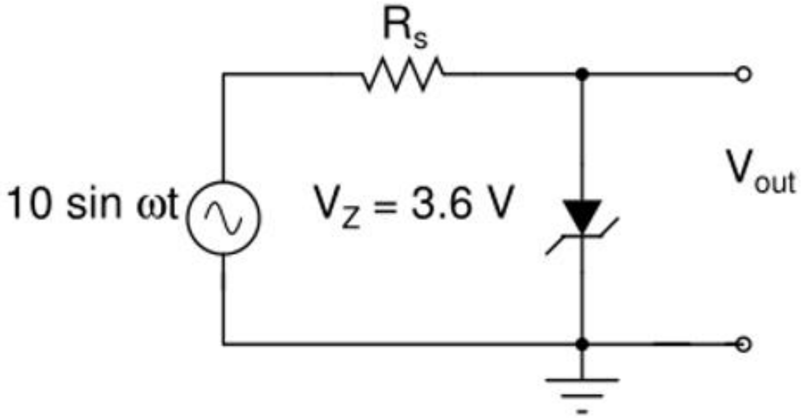
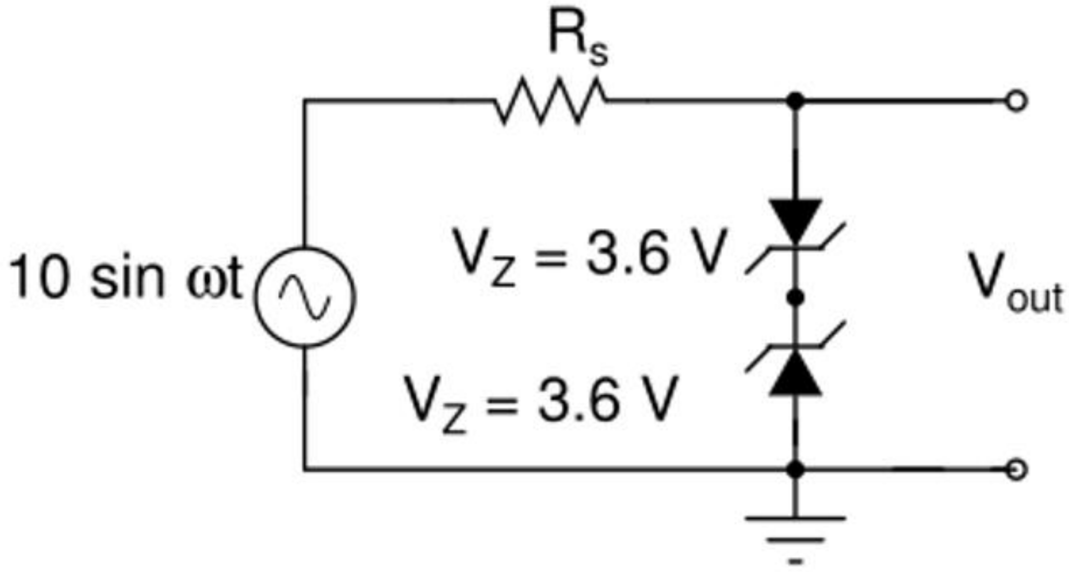


Fig. 8 Zener diode clipping circuit 2 and the observed V_{out} waveform



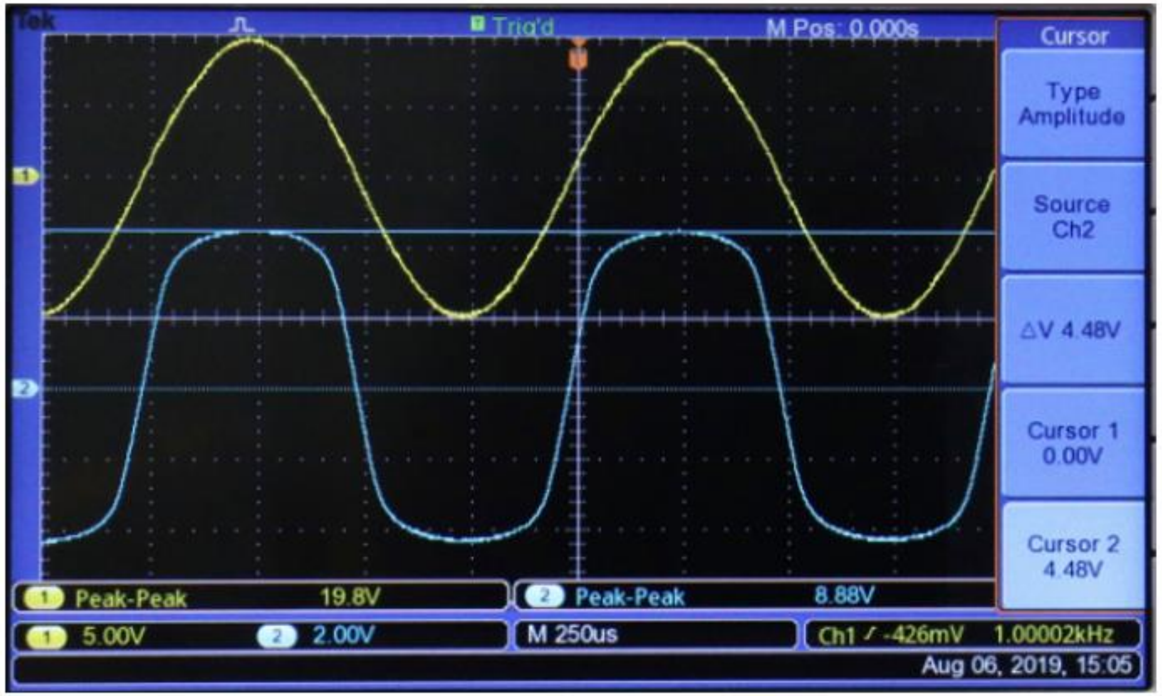


Fig. 9 Zener diode clipping circuit 3 and the observed V_{out} waveform

3. Light Emitting Diodes

- LEDs are special diodes which convert the forward current through them into light (i.e. electrical-to-optical converter).
- 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, 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

4. 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.

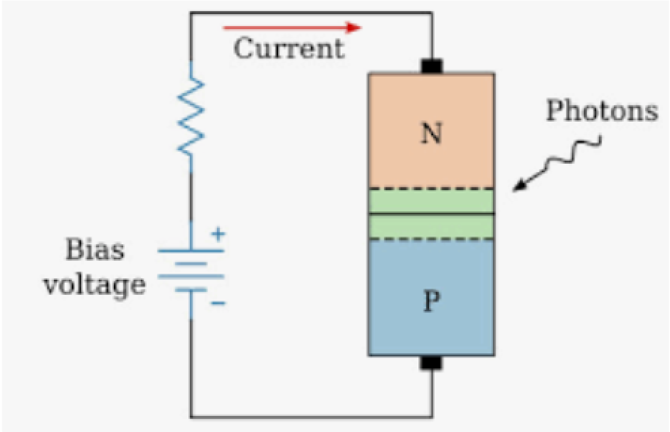
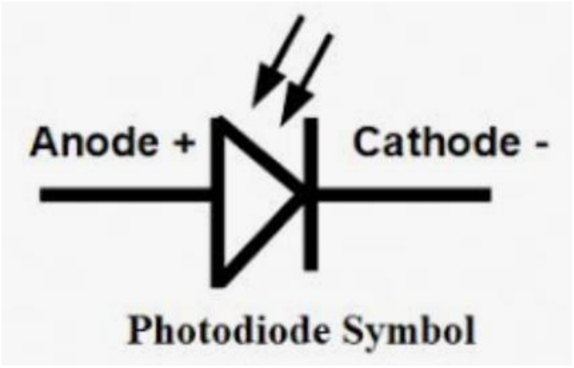
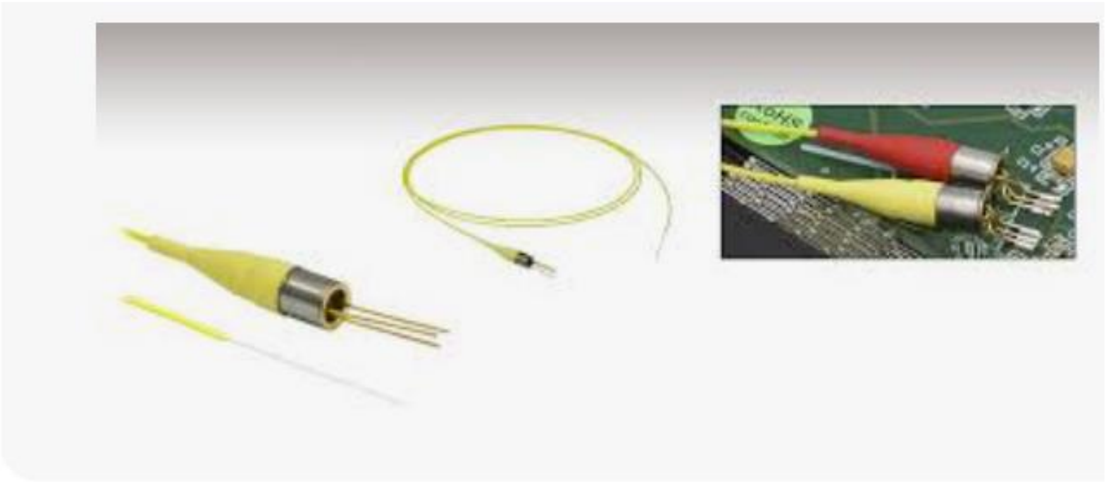


Fig. 11
Source: Electric Circuit Studio and OSI Optoelectronics

Applications of Photodiodes

- Electrical to optical conversion (EO conversion)
  - Remote control of electronic appliances
  - As a sensor for obstacle detection (eg. in a lift door)
  - 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.





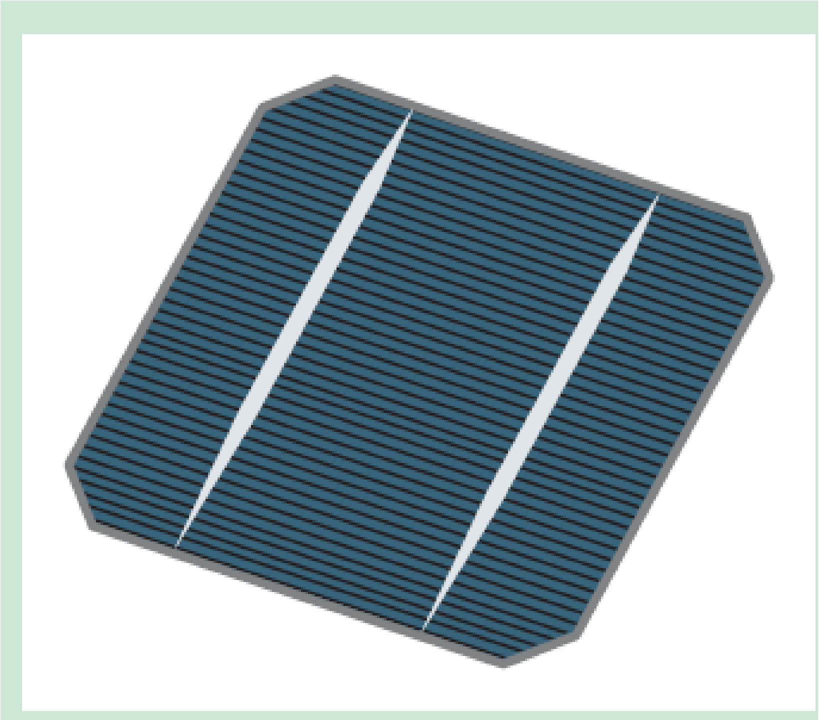
Thorlabs, Inc.

Pigtailed Photodiodes

Fig. 12

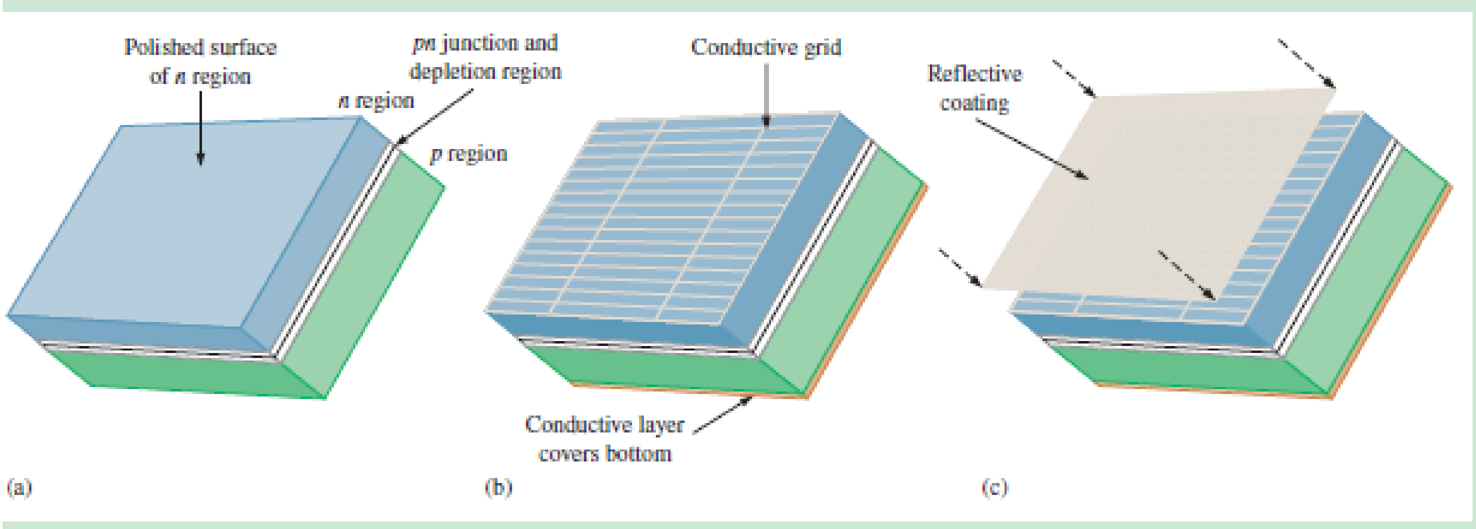
5. Solar Cells

- 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.

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

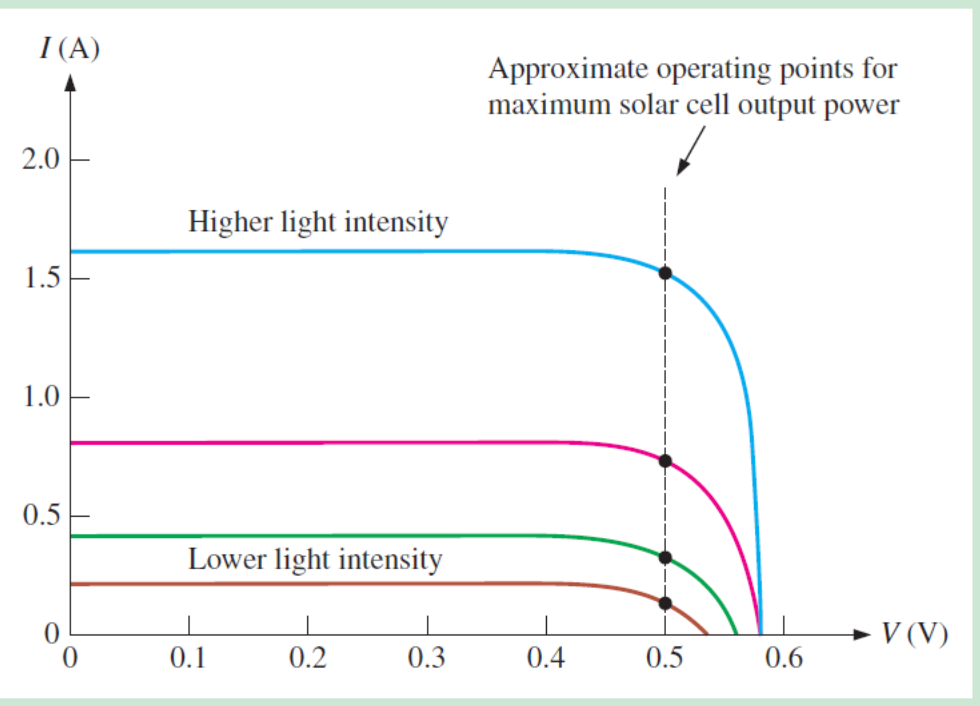


Fig. 15

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