EE Dept, IIT Bombay
Academic Year: 2025-2026, Semester I (Autumn)

Course: MS101 Makerspace

EE Lecture 2
Devices and Circuits II

Topics
1. Analog Circuits
2. PN Junction Diodes
3. Zener Diodes
4. Light Emitting Diodes
5. Photodiodes
6. Solar Cells

Reference: AS Sedra and KC Smith, Microelectronic Circuits, 7th ed., Oxford University Press, 2015. Ch. 4.

1. Analog Circuits

- *Two-terminal (single-port) devices*
  - two-terminal linear passive devices: R, L, C;
  - two-terminal active devices: independent voltage & current sources;
  - two-terminal nonlinear passive devices (to be studied later in this lecture): *pn* junction diodes, special types of diodes.

- *Two-port devices*
  - two port passive devices: transformers;
  - two-port active devices: dependent or controlled sources (VCVS, CCVS, VCCS, CCCS).

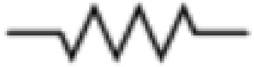
- *Three-terminal (two-port) active devices* (to be studied in lecture 10)
  - Bipolar junction transistor (BJT);
  - Metal-oxide-semiconductor field-effect transistor (MOSFET).

- *Circuit:* Connection of multiple devices.
- *Passive Circuit:* A circuit using only passive devices (R, L, C, diodes): attenuators, filters, rectifiers, etc.
- *Active Circuit:* A circuit using at least one active device. Examples: amplifiers, voltage regulators, sinusoidal oscillators, waveform generators, etc.
- *Electronic Device:* A device in which an electric field controls the flow of electrons (or other charge carriers). Examples: diode, BJT, MOSFET, etc.
- *Electronic Circuit:* Circuit with at least one electronic device.
- *Analog Circuit:* A circuit using a continuous range of currents and voltages that are functions of continuous time.
- *Digital Circuit:* A circuit using discrete values (usually binary (high/low)) of currents and voltages that are defined at discrete time instants. To be studied in lectures 6-7.

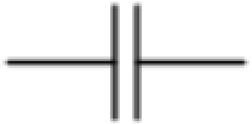
1.1 Single-Port (Two-Terminal) Devices

- Single-port (2-terminal) devices: Resistor (R), Capacitor (C), Inductor (L), Diode (D)

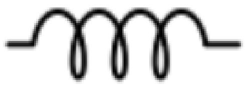
- Single-port devices are described by their i-v characteristic
  - Resistor: $\boldsymbol{v = iR}$



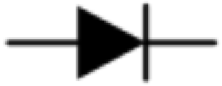
  - Capacitor: $\boldsymbol{v = 1/C \int i\, dt}$



  - Inductor: $\boldsymbol{v = L \frac{di}{dt}}$



  - Diode: $\boldsymbol{i = I_s \left[\exp\left(\frac{v}{V_T}\right) - 1\right]}$,



  where $\boldsymbol{I_s}$ = reverse saturation current,

  $\boldsymbol{V_T = \frac{kt}{q_e}}$ (thermal voltage ≈ 25 mV at 20 °C).

1.2 Impedance

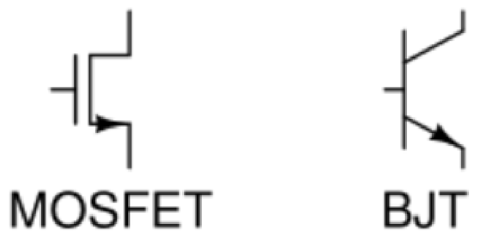
When the voltage input to a resistor, an inductor, or a capacitor is sinusoidal, we can define a voltage-to-current ratio called impedance.

- Impedance of a resistor = R.
- Impedance of an inductor = $j\omega L$.
- Impedance of a capacitor = $1/(j\omega C)$.
  where j = sqrt(-1), $\omega = 2\pi f$, 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).

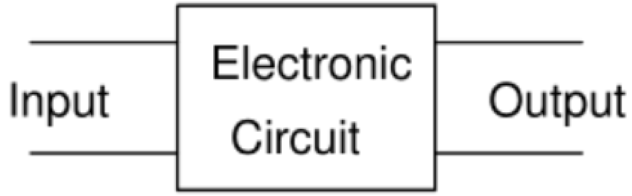
1.3 Two-Port Devices & Circuits

- One port may be input port, and the other may be output port.
- A four-terminal device has two terminals for each port. In a three-terminal device, one terminal is common to the two ports.
- Three-terminal device examples: bipolar junction transistor (BJT), metal-oxide-semiconductor field-effect transistor (MOSFET).
- Two-port electronic circuit examples: Amplifiers, Oscillators, Filters, etc.

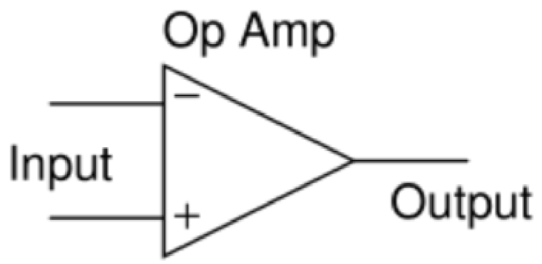
3-terminal active devices.



Circuit with an input port & an output port.

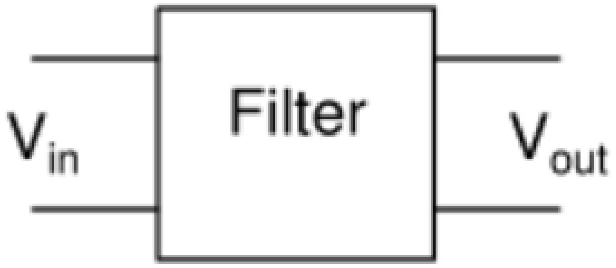


Op amp: A device with two input ports and an output port, with one common terminal for all ports (usually not shown).

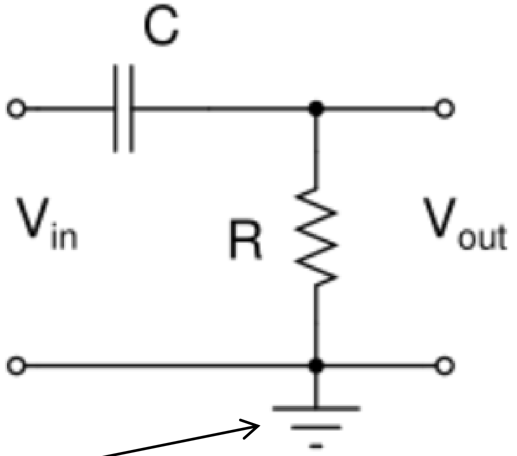


1.4 Frequency-Selective Circuits or Filters

- A circuit whose output response to sinusoidal input varies as a function of frequency of the input is called a frequency-selective circuit or filter.
- Examples: low-pass, high-pass, band-pass, band-stop filters. Gain of a practical filter varies smoothly with frequency.
- Passive filters can be made using R, L, and C.
- A simple low-pass or high-pass filter can be built using just one R and one C.



RC high-pass filter (passive circuit)



Circuit ground, common terminal of the input & output ports

1.5 RC Filters

- RC filters are passive frequency-selective circuits using resistors and capacitors.
- A low-pass filter offers low attenuation for the sinusoidal input of frequency f below a cut-off frequency f_c and high attenuation for higher frequency, i.e. it passes lower range of frequencies and stops higher range of frequencies.

$$|V_{out}/V_{in}| \approx 1 \text{ for } f \ll f_c \quad \text{and} \quad |V_{out}/V_{in}| \ll 1 \text{ for } f \gg f_c$$

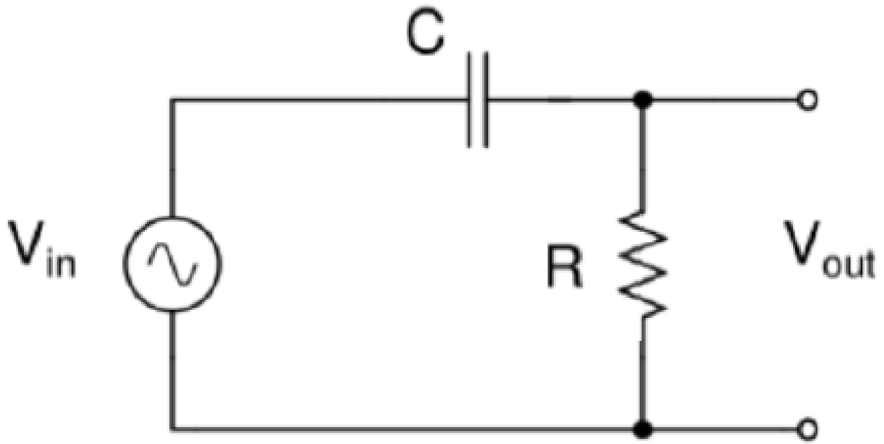
- A high-pass filter passes higher range of frequencies and stops lower range of frequencies.

$$|V_{out}/V_{in}| \approx 1 \text{ for } f \gg f_c \quad \text{and} \quad |V_{out}/V_{in}| \ll 1 \text{ for } f \ll f_c$$

- Cut-off frequency f_c depends on the R and C values.

- A band-pass filter passes frequencies in a band marked by lower and upper cut-off frequencies, and it stops the frequencies outside it.
- A band-stop filter passes frequencies outside a band and stops those inside it.
- $\left| V_{out} / V_{in} \right|$ = filter gain. Maximum gain in an RC filter is one.
- A filter may have multiple pass and stop bands or may have more complex gain variation.

1.6 RC High-Pass Filter



- Circuit: High-pass RC filter with one R and one C.
- V_{out}/V_{in} in terms of R & C impedances:

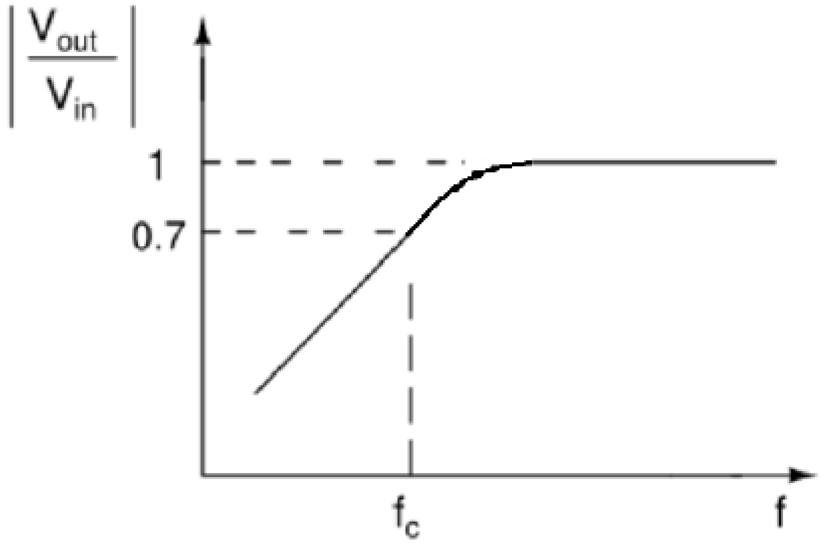
  $V_{out}/V_{in} = R/[R + (1/(j\omega C))] = 1/[1+1/(j\omega CR)]$

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

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

  where $\omega_c = 1/(RC)$ and $f_c = 1/(2\pi RC)$.
- Sketch: $|V_{out}/V_{in}|$ as a function of f.

  At $f = f_c$, $A = \frac{1}{[2]^{1/2}} = 0.707$

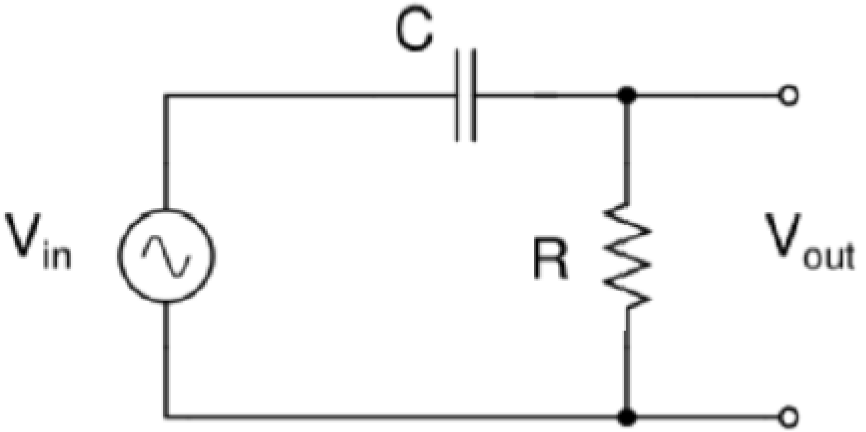


- ***High-Pass RC Filter: Gain vs frequency***

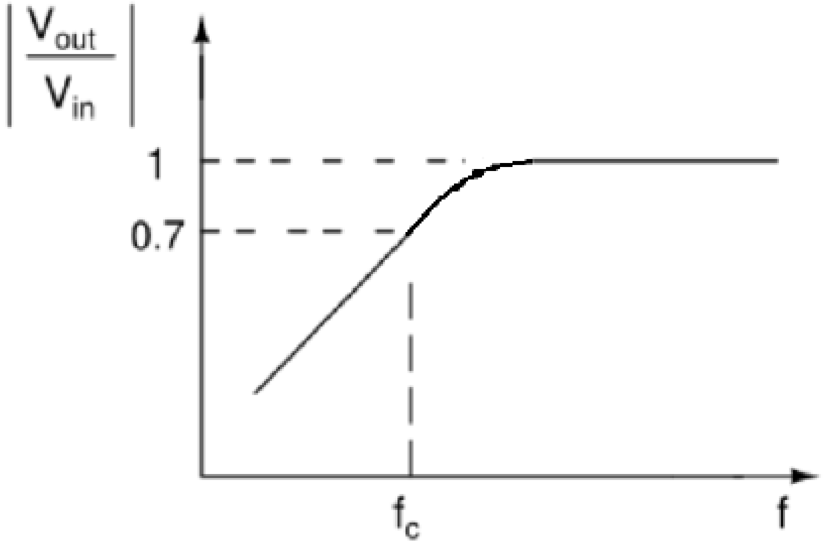
Let $R = 20$ kΩ and $C = 0.01$ μF.

Gain: $A = \left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\left(1+(f_c/f)^2\right)^{1/2}}$

$f_c = 1/(2\pi RC) = 795.7747$ Hz.



RC High-Pass Filter Gain values	
f (Hz)	A
10	0.0126
100	0.1246
795.7747	0.7071
2000	0.9292
20000	0.9992



1.7 RC Low-Pass Filter

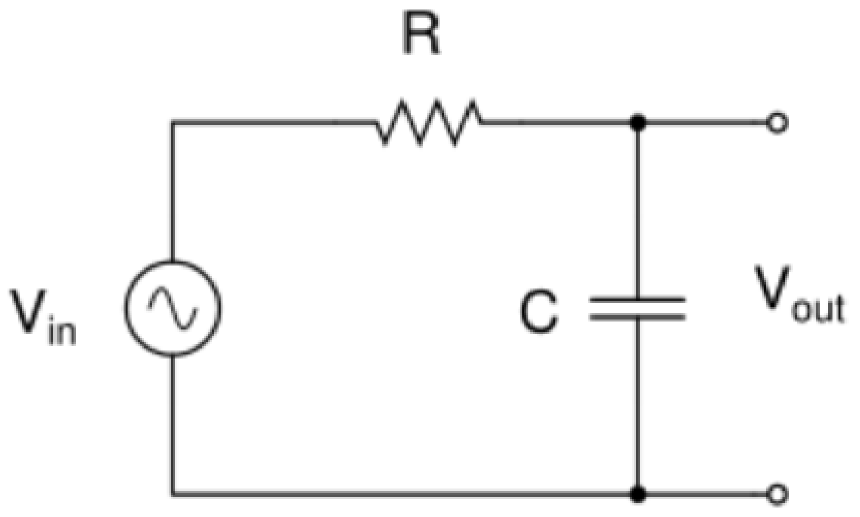
- Circuit: Low-pass RC filter with one R and one C.
- V_{out}/V_{in} in terms of R & C impedances:
  $V_{out}/V_{in} = (1/j\omega C)/[R + (1/j\omega C)] = 1/[1+j\omega CR]$,
  where $\omega = 2\pi f$
- Gain: $A = \left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\left[1+(\omega CR)^2\right]^{1/2}}$

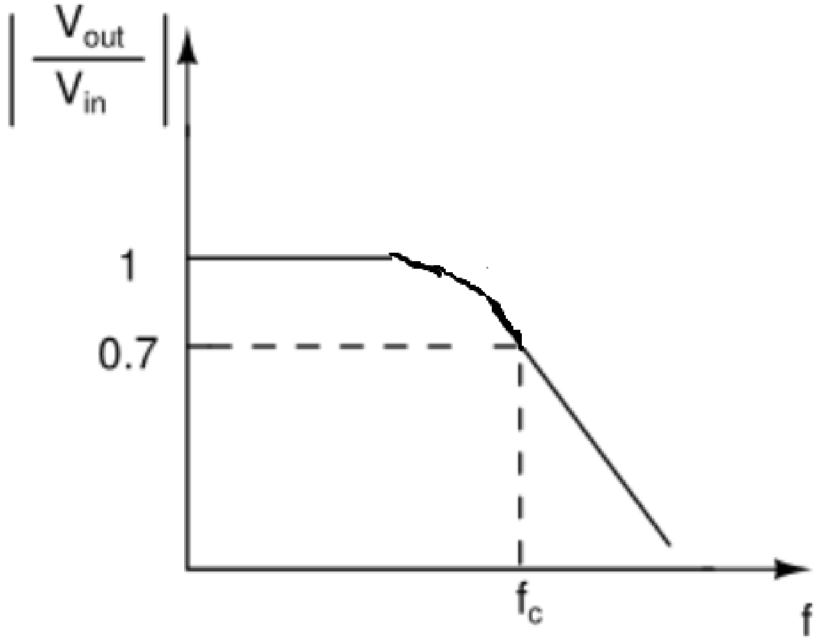
$$= \frac{1}{[1 + (\omega/\omega_c)^2]^{1/2}} = \frac{1}{[1 + (f/f_c)^2]^{1/2}}$$

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

- Sketch: $|V_{out}/V_{in}|$ as a function of f.

At $f = f_c$, $A = \frac{1}{[2]^{1/2}} = 0.707$



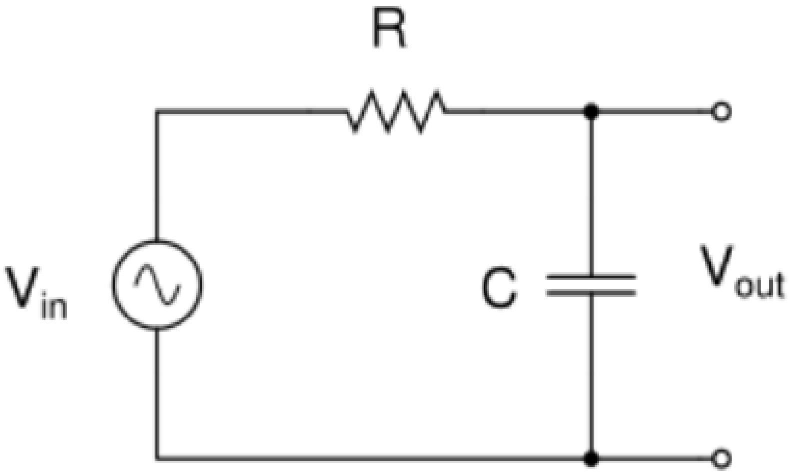


- ***Low-Pass RC Filter: Gain vs frequency***

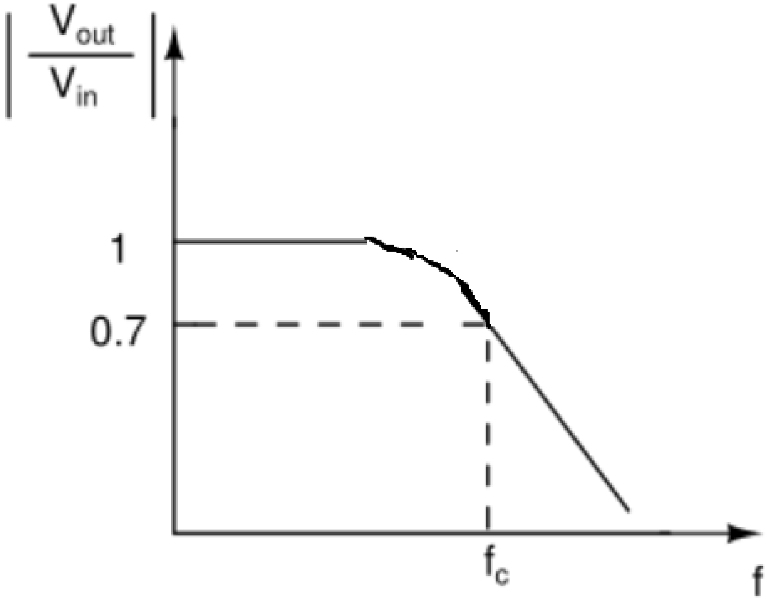
  Let R = 20 kΩ and C = 0.01 μF

  Gain: $A = \left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\left[1+(f/f_c)^2\right]^{1/2}}$

  $f_c = 1/(2\pi RC) = 795.7747$ Hz.



RC Low-Pass Filter Gain values	
f (Hz)	A
10	0.9999
100	0.9922
795.7747	0.7071
2000	0.3697
20000	0.0398



2. PN Junction Diode

2.1 Semiconductors

- Semiconductor: Material having conductivity between that of conductors (e.g. copper) and insulators (e.g. glass).

  - Single-element semiconductors: germanium (Ge) and silicon (Si), which are in group IV of the periodic table;

  - Compound semiconductors formed by elements in groups III & V or groups II and VI, e.g. gallium-arsenide. They are useful in special electronic circuit applications and in applications that involve light, such as light-emitting diodes (LEDs).

- Two elemental semiconductors: Ge, Si. Ge was used in the fabrication of very early transistors (late 1940s, early 1950s), but today's integrated-circuit technology is almost entirely Si-based.

2.2 Current Flow in Semiconductors

- Free electrons are responsible for current flow in metals, and ions (+ve and −ve) in ionic solutions.
- Free electrons and holes are responsible for current flow in a semiconductor. A hole is the absence of an electron. As a charge carrier, it has a positive charge equal in magnitude to the electron charge.
- Free electron and hole concentrations are referred to as n and p, associated with their respective charge polarities.
- A semiconductor in its pure form is known as intrinsic semiconductor. It has the same concentration of free electrons and holes. An intrinsic semiconductor is not useful for device fabrication, instead it is doped with impurities.

2.3 Doped Semiconductors

- Doping involves introducing impurity atoms into the 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.

- To increase the concentration of free electrons, n, Si (group IV) is doped with an element from group V, such as phosphorus (P). Each P atom contributes a free electron. This doping results in an n-type semiconductor, with electrons as the majority charge carriers and holes as the minority charge carriers.

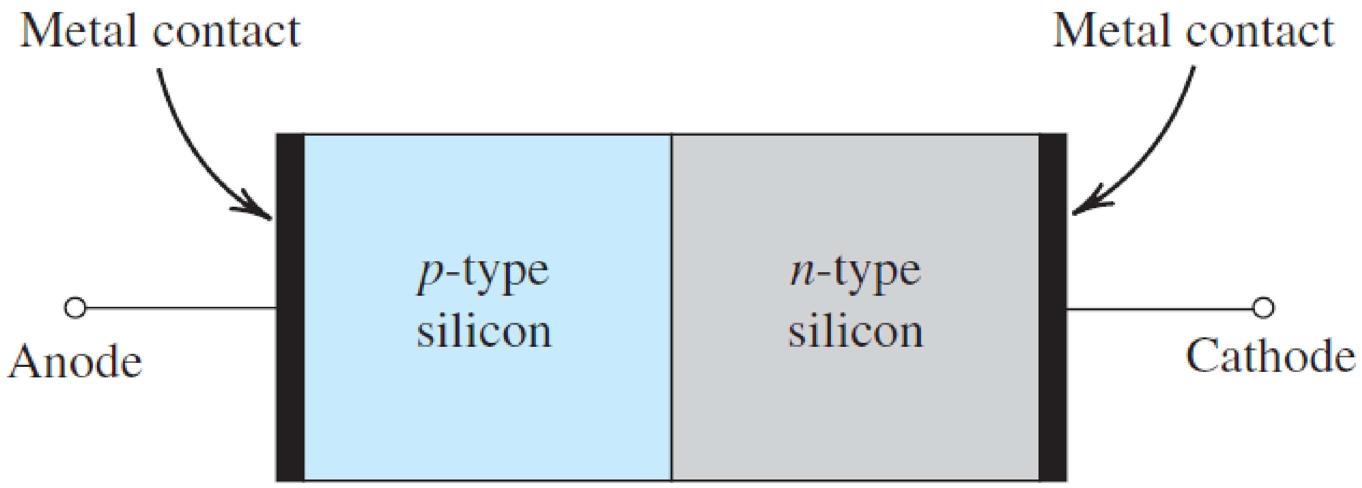
- To increase the concentration of holes, p, Si is doped with an element from group III, such as boron (B). Each B atom causes the absence of a free electron. This doping results in a p-type semiconductor, with holes as the majority charge carriers and electrons as the minority charge carriers.

2.4 Junction Diode

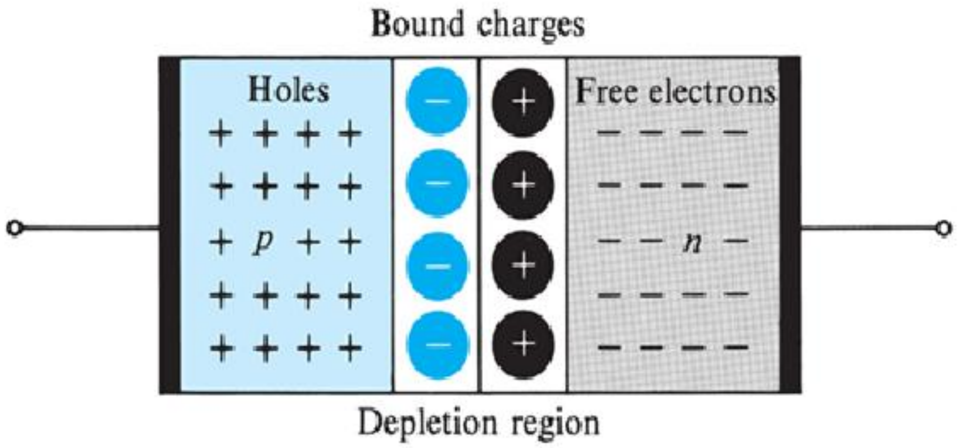
- A junction diode is made of a semiconductor crystal, with a *p*-type doped region on one side with high concentration of holes and an *n*-type doped region on the other side with high concentration of free electrons. The interface between the two regions is the *pn* junction.

- Terminals are attached to the two regions. The terminal connected to the *p*-type region is called anode and that to the *n*-type region is called cathode.

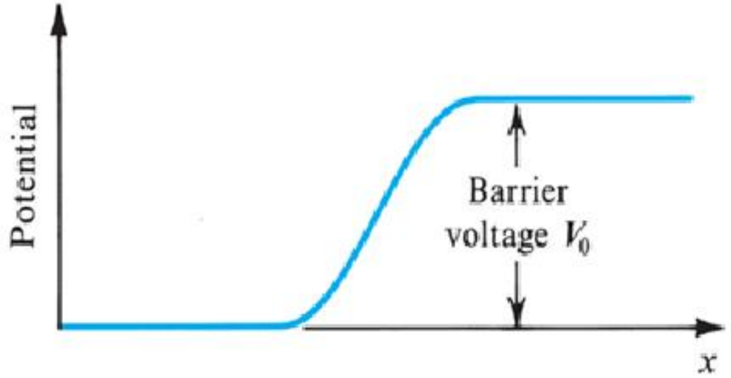
Simplified physical structure of a *pn* junction diode



2.5 Junction Diode with No Applied Voltage (open circuited terminals)



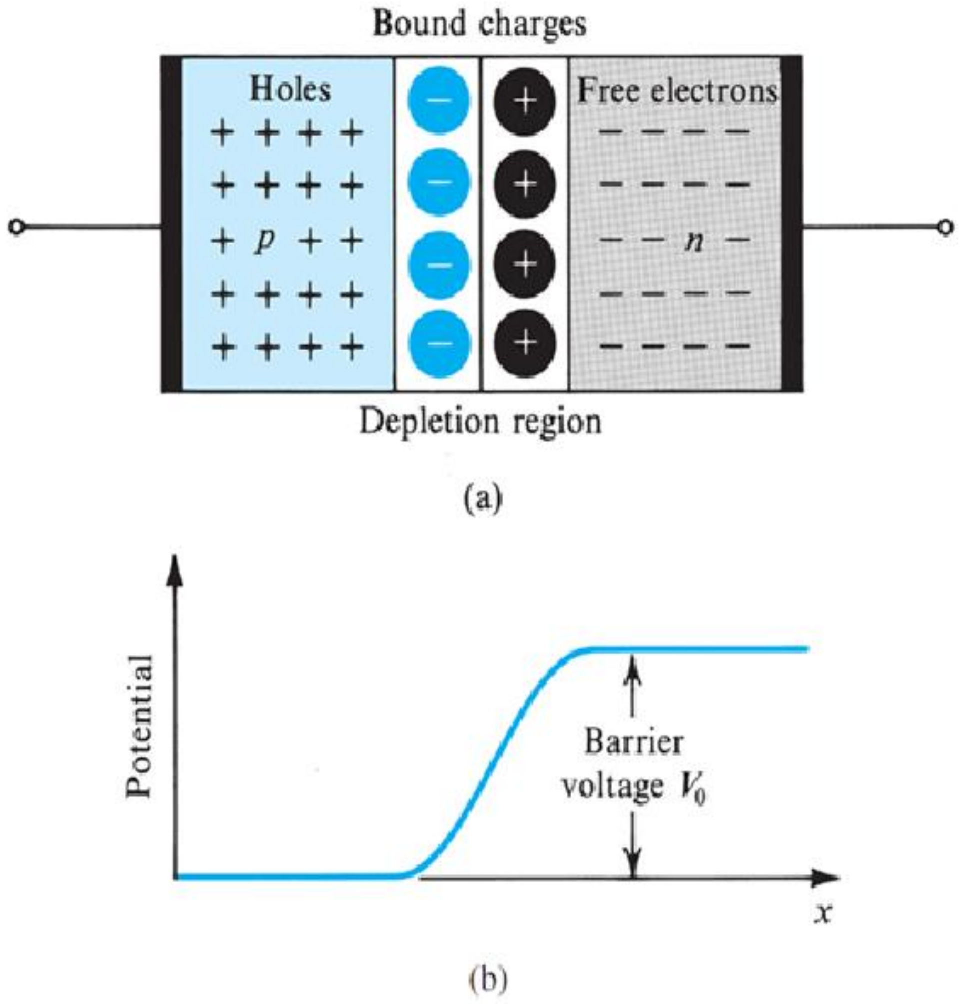
(a)



(b)

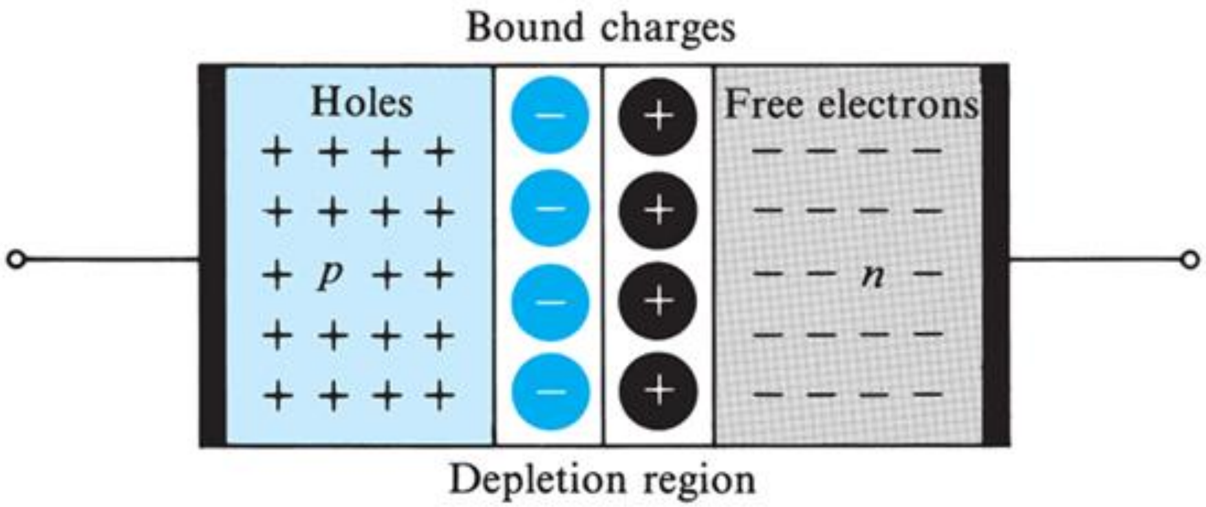
- The p region has high concentration of holes, and the *n* region has high concentration of free electrons.
- The concentration differences across the junction cause diffusion of the charge carriers: holes from the *p* side to the *n* side, electrons from the *n* side to the *p* side.
- Electron-hole recombination takes place close to the junction on both sides, resulting in a region depleted of free electrons and holes. This region is called the *depletion* or *space-charge* region.

- The depletion region has bound charges: negative charges on the *p* side and positive charges on the *n* side.
- 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 potential difference 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.
- Typical *barrier voltage* (or junction built-in potential) for Si at room temperature is 0.6– 0.9 V. This voltage is across the depletion region and cannot be measured across the diode terminals.



2.6 Junction Diode with an Applied Voltage

- If the applied voltage on the *p* side is positive with respect to the *n* side, the junction is said to be forward biased.
- If the applied voltage on the *p* side is negative with respect to the *n* side, the junction is said to be reverse biased.
- The *pn* junction exhibits different conduction properties in the forward and reverse directions.



2.7 Junction Diode Terminal Characteristic

The terminal characteristic (i.e. i vs v) can be approximated as

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

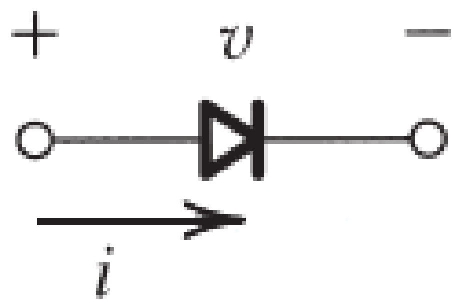
where I_S = reverse saturation current of the device (changes with temperature, typically of the order of 10^{-15} A);

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

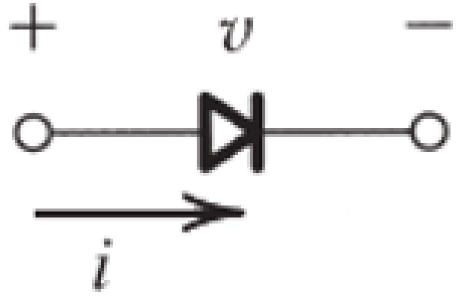
k = Boltzmann's constant = 8.62×10^{-5} eV/K = 1.38×10^{-23} J/K;

T = absolute temperature in K = 273 + temperature in °C;

q = magnitude of electronic charge = 1.60×10^{-19} C.



Example

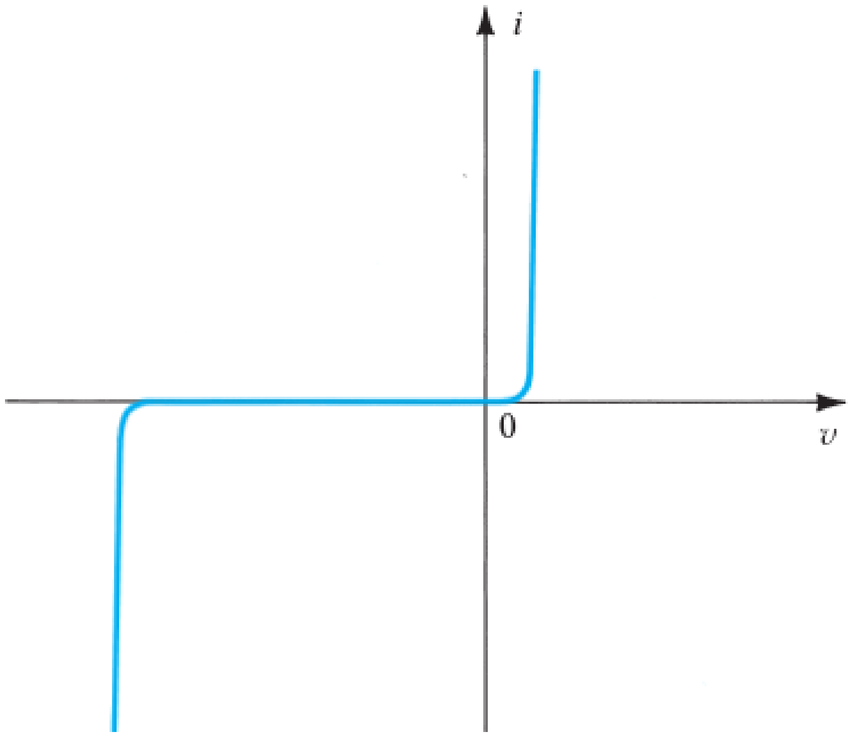


Diode current: $i = I_S[\exp(v/V_T) - 1]$
Let $I_S = 10^{-15}$ A & $V_T = 25$ mV.

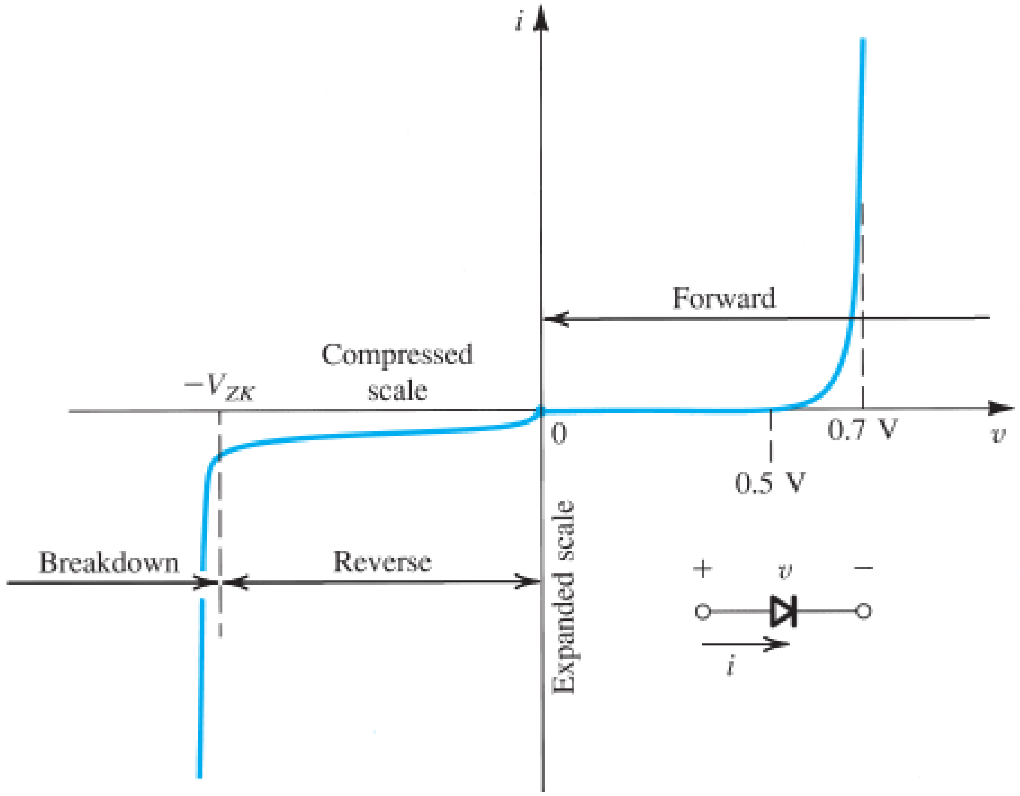
Forward bias condition	
v (mV)	i (mA)
400	0.0089 x10^{-3}
500	0.4852 x10^{-3}
600	26.4891 x10^{-3}
700	1.4463
800	78.963
850	583.46
875	1586
900	4311
1000	235385

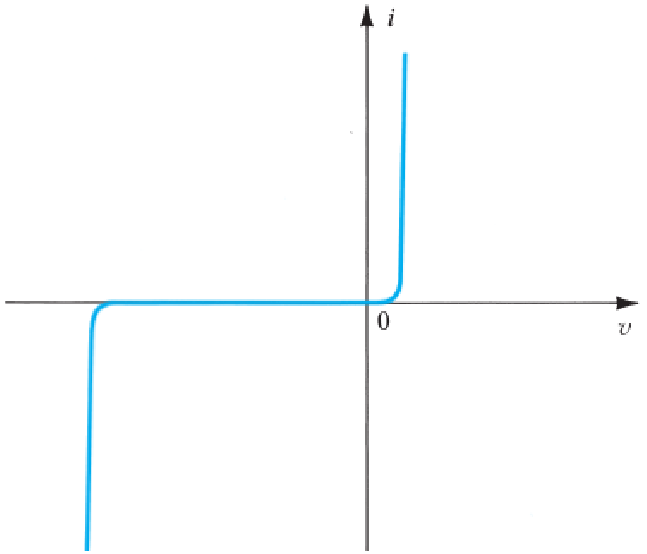
Reverse bias condition	
v (V)	i (A)
0	0
−1	10^{-15}
−2	10^{-15}
−3	10^{-15}
−4	10^{-15}
−5	10^{-15}
−10	10^{-15}
−20	10^{-15}
−30	10^{-15}

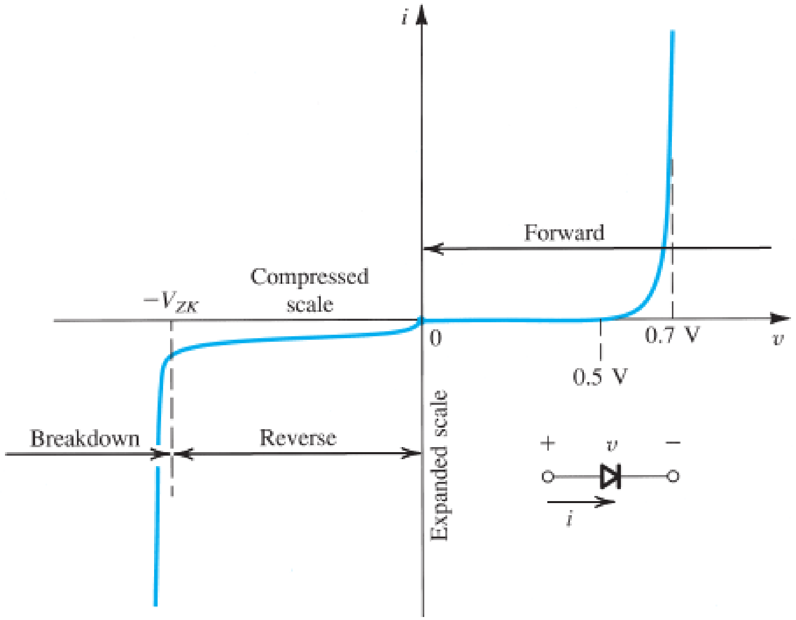
I-V characteristic of a Si diode.



I-V characteristic with expanded and compressed scales to reveal details.







- Forward-bias region: $v > 0$; Reverse-bias region: $v < 0$; Breakdown region: $v < -V_{ZK}$.
- Forward-bias characteristic
  - Very small current for $v <$ 0.5 V (called *cut-in voltage*);
  - Forward voltage drop for a "fully conducting" diode is 0.6–0.8 V.
- Reverse-bias characteristic
  - When v is negative but above the "breakdown voltage ($-V_{ZK}$)", current is negligible, $I \approx -I_S$.
- Reverse breakdown region
  - As the negative voltage approaches $-V_{ZK}$, the reverse current increases rapidly.
  - Diode breakdown is normally not destructive.

2.8 Diode Applications

- Rectifier circuits for converting AC voltages to DC voltage

  - Half-wave rectifier, full-wave rectifier, and bridge rectifier circuits.

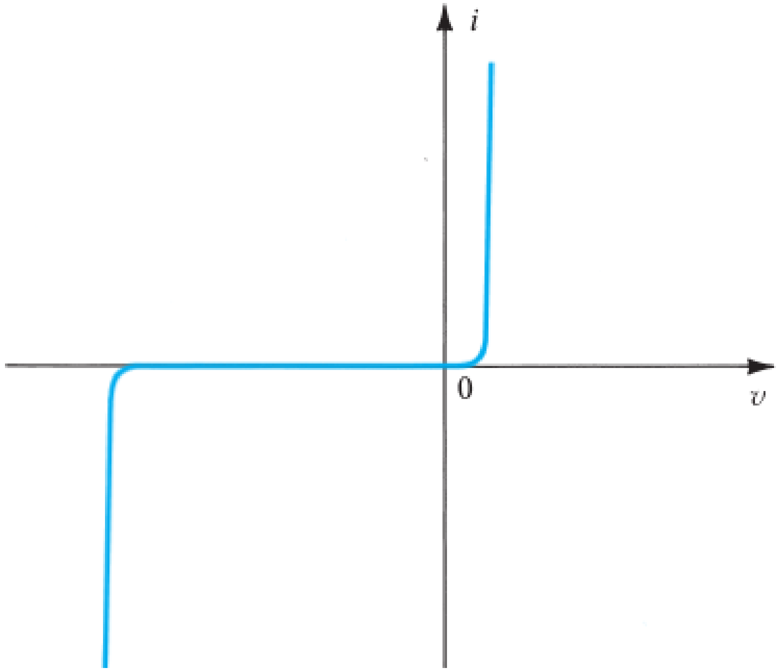
- As a protection device in circuits for switching inductive loads (relay coil, motor winding).
- In waveshaping circuits, such as clipping circuits, clamping circuits.
- In signal processing circuits, modulators, demodulators.
- Specific diode types are used for different applications.
- Some important diode specifications: reverse saturation current, maximum current, reverse breakdown voltage, switching speed.

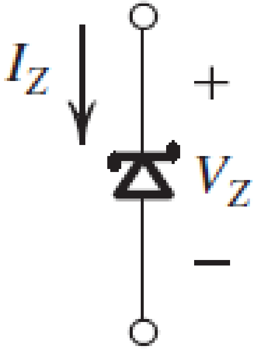
3. Zener Diodes

- *PN* junction diodes have steep $i - v$ curve in the breakdown region with a nearly constant voltage drop.

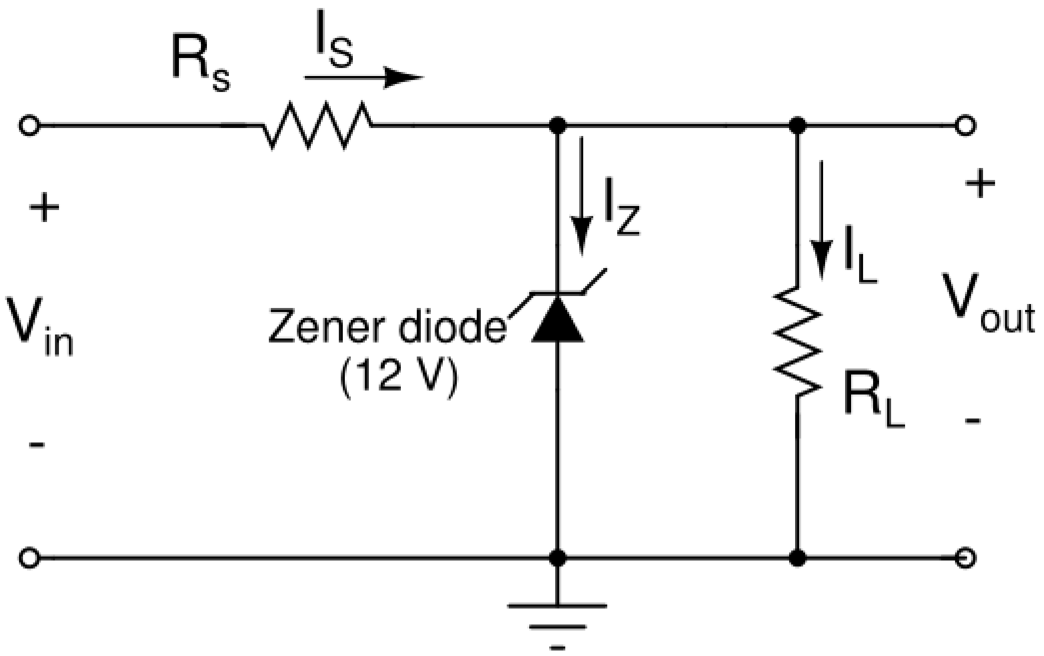
- Zener diodes (or breakdown diodes) are diodes manufactured to operate specifically in the breakdown region with an almost constant voltage drop.

- 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. The current in the Zener diode is to be limited by the external circuit.





Zener Regulator Circuit



- Zener diode is in the reverse breakdown region for $V_{in} > V_Z$. $V_{out} = V_Z$.
- V_{out} will be reasonably constant against variations in V_{in} and I_L.
- Voltage-current relations

$$I_s = (V_{in} - V_{out}) / R_s$$

$$I_L = V_{out} / R_s$$

$$I_Z = I_s - I_L$$

- $I_Z > (I_Z)_{\min}$ for V_Z to be constant. $I_Z < (I_Z)_{\max}$ to avoid the Zener diode overheating.

Zener Diode Applications

- For providing reference voltage in voltage regulators, the circuits that provide constant DC output voltage for varying load current and input voltage.

- For input voltage limiting in amplifiers.

4. Light Emitting Diodes (LEDs)

- LEDs are special diodes with transparent packaging that emit light when forward biased (i.e. they convert electrical energy into light). They are used as electrical-to-optical converters.

- Light is produced due to *radiative recombination* of electrons and holes in the region around the *pn* junction.

- For radiative recombination, the diode should be made using a semiconductor of the type known as *direct-bandgap* materials, such as Gallium arsenide (GaAs), AlGaAs, GaN, InP.

- Wavelength of the emitted light depends on the electronic bandgap of the material used.

- The intensity of light emitted is proportional to the recombination rate, i.e. *proportional to the forward current* in the diode.

LED Applications

- Indicators and displays

  - Single LED indicators of various colors;

  - Seven-segment LED numeric displays and alphanumeric displays in laboratory instruments and equipment.

- White LEDs for lighting

  - Light conversion efficiency: 60%. (incandescent bulbs: 5–12 %, compact fluorescent lamps: 27 %).

- Video displays (backlighting in LCD screens of laptops and PCs).

- Large LED screens.

Electronics Hub
Light Emitting Diode Basics | LED Types ...

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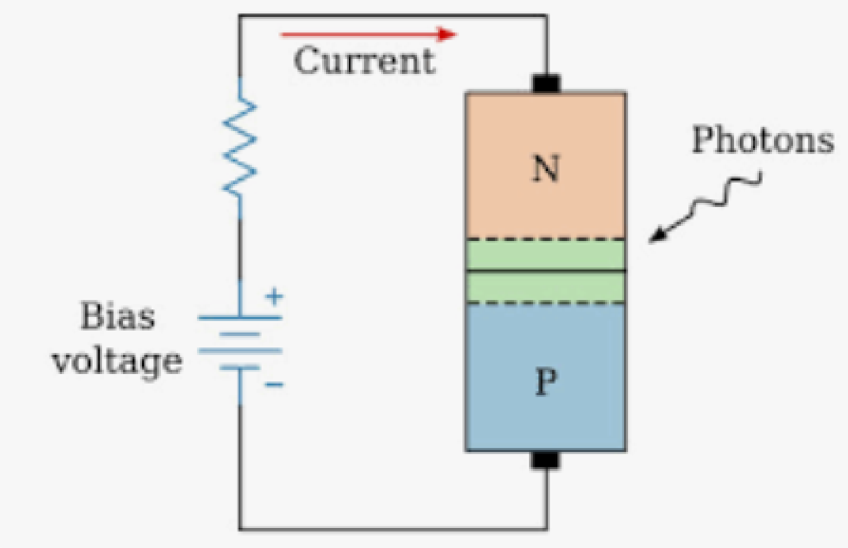
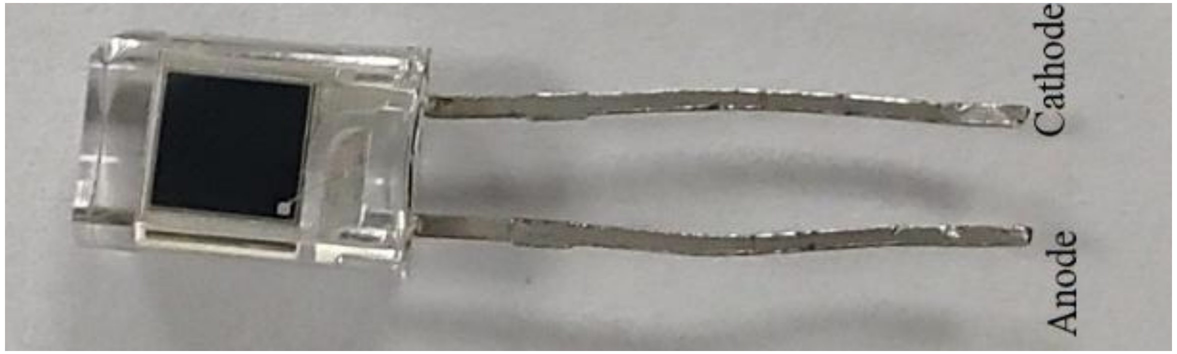
Arrow Electronics

5. Photodiodes



- Photodiodes are special diodes with transparent packaging in which the diode current responds to the light incident on the *pn* junction. They are used as light sensors.
- 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.
- If the reverse-biased *pn* junction is exposed to light, the photons impacting the junction cause covalent bonds to break, and electron-hole pairs are generated in the depletion region. It gives rise to a reverse current across the junction. This current is known as photocurrent, and is proportional to the intensity of the incident light.

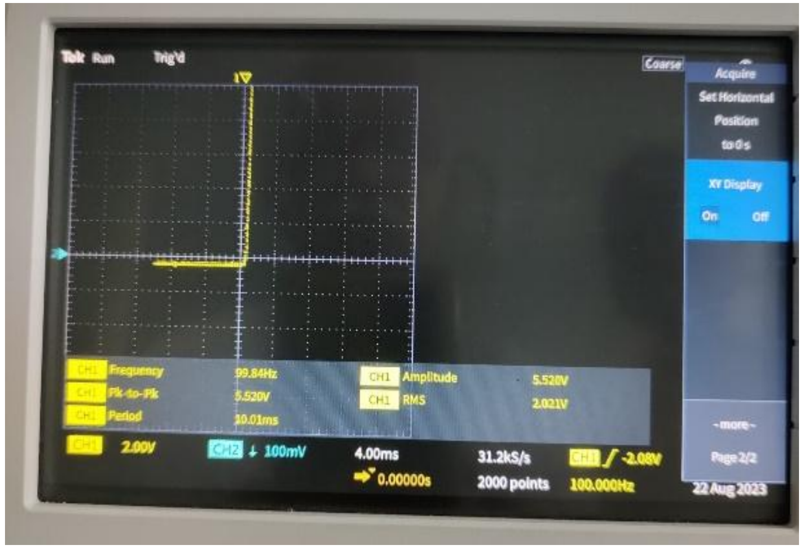
Typical Photodiode Characteristics (experimentally observed)



A. Ambient light conditions

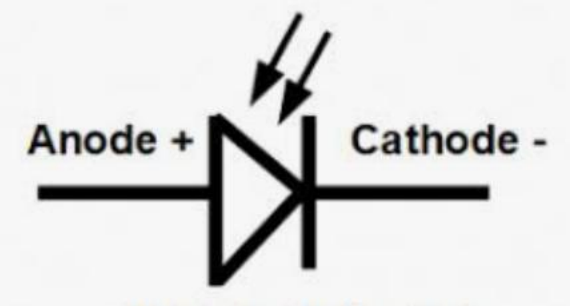
B. Medium light conditions

C. Higher light conditions



Photodiode Applications

- Electrical-to-optical conversion in optical fiber communication at the receiver side for detecting optical signals. Optical fiber communication is employed for high-speed telecommunication and internet data applications.



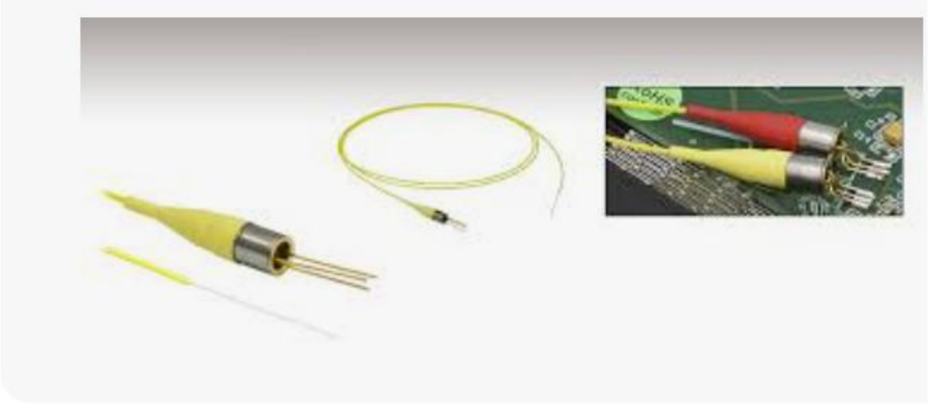
Photodiode Symbol

- LED-Photodiode combination

  - Remote control of electronic appliances;

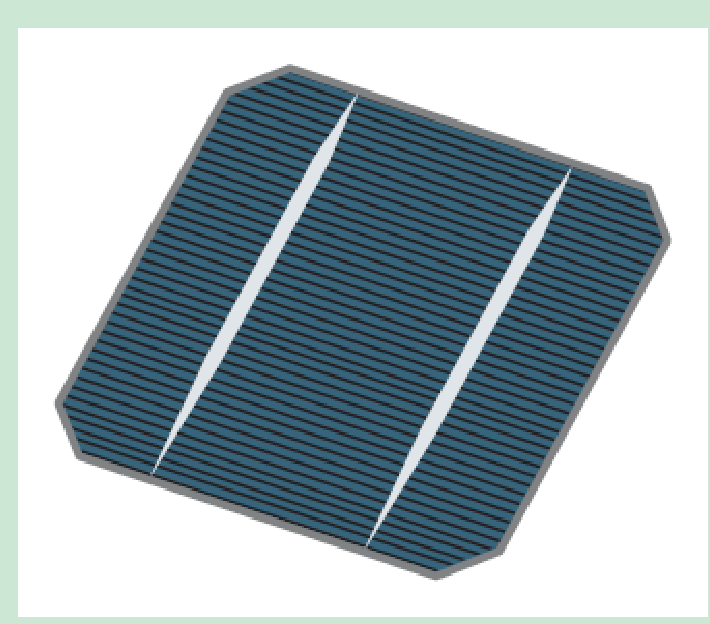
  - Obstacle detection (eg. in a lift door);

  - Optocoupler for coupling signals between electrically isolated circuits.



Thorlabs, Inc.
Pigtailed Photodiodes

6. Solar Cells



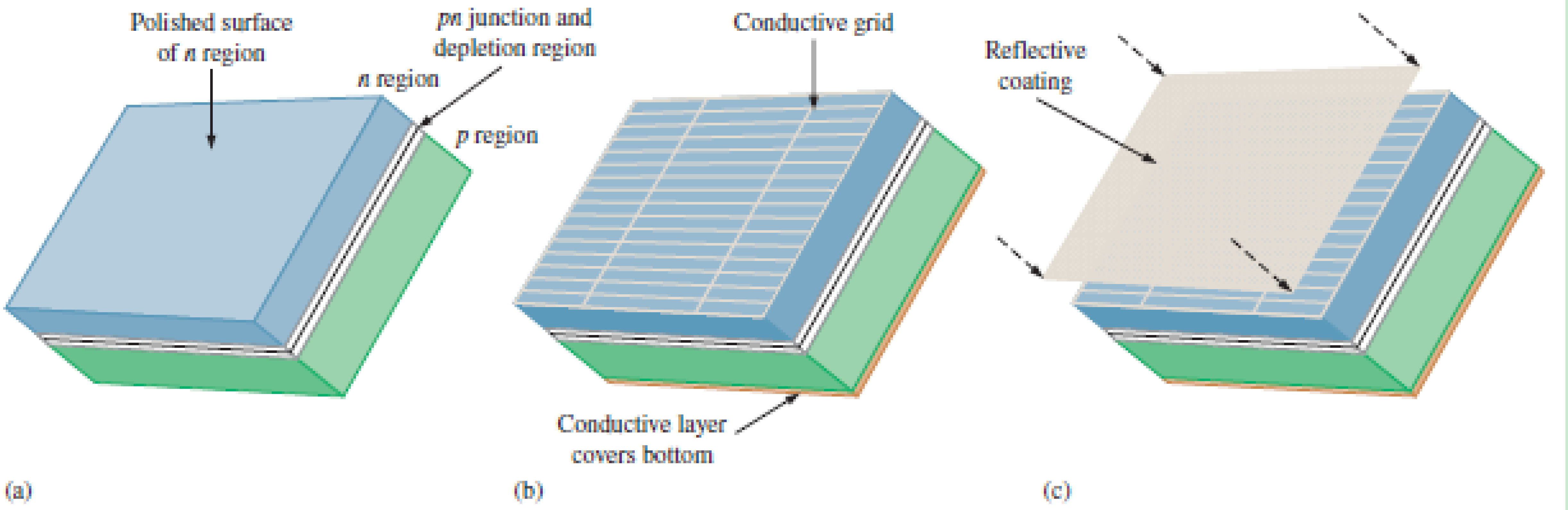
- Solar cells are illuminated photodiodes *without reverse bias.* They convert incident light energy into electrical energy based on the photovoltaic effect.

- They have large junction areas and are fabricated using low-cost Si.

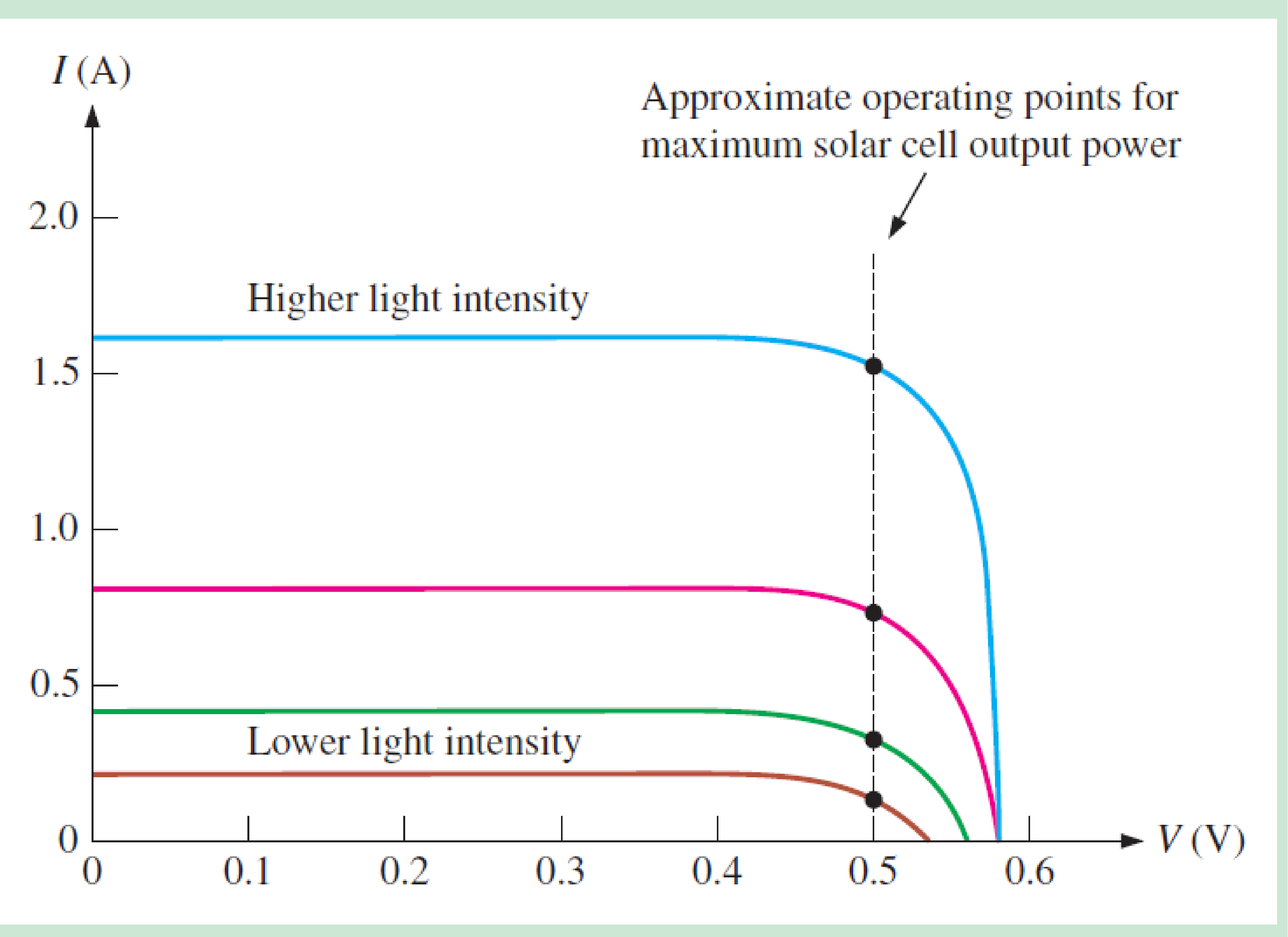
- In a solar cell, the photon energy creates electron-hole pairs in the *n* and *p* regions. Electrons accumulate in the *n*-region and holes in the *p* region, generating a potential difference (voltage) across the cell.

- The potential difference across the cell causes current in an external load.

Basic Construction of a Photovoltaic (PV) Solar Cell



V-I characteristics of a typical solar cell for increasing light intensities



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