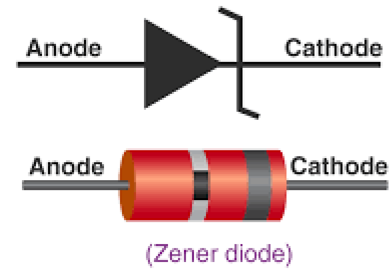
Chapter Five
Special Purpose Diodes

5.1: The Zener Diode

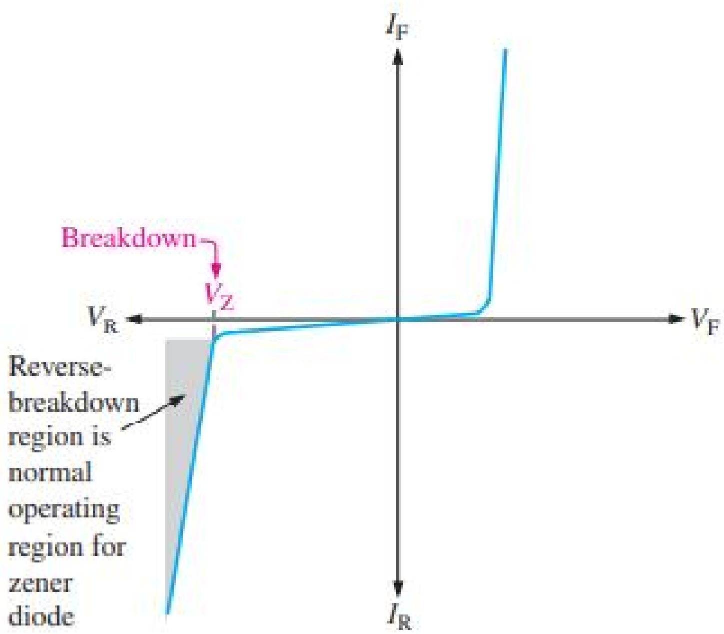


A **Zener diode is a particular type of diode that, unlike a normal one, allows current to flow not only from its anode to its cathode, but also in the reverse direction, when the *Zener voltage* is reached**.

A **major application for Zener diode** is as a type of voltage regulator for providing stable reference voltages for use in power supplies, voltmeters and other instruments.

The **breakdown voltage of a Zener diode** is set by carefully controlling the doping level during manufacture. When a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically.

The volt-ampere (VI) characteristic is shown in this Figure with normal operating regions for rectifier diodes and for Zener diodes shown as shaded areas. **If a Zener diode is forward-biased, it operates the same as a rectifier diode**.

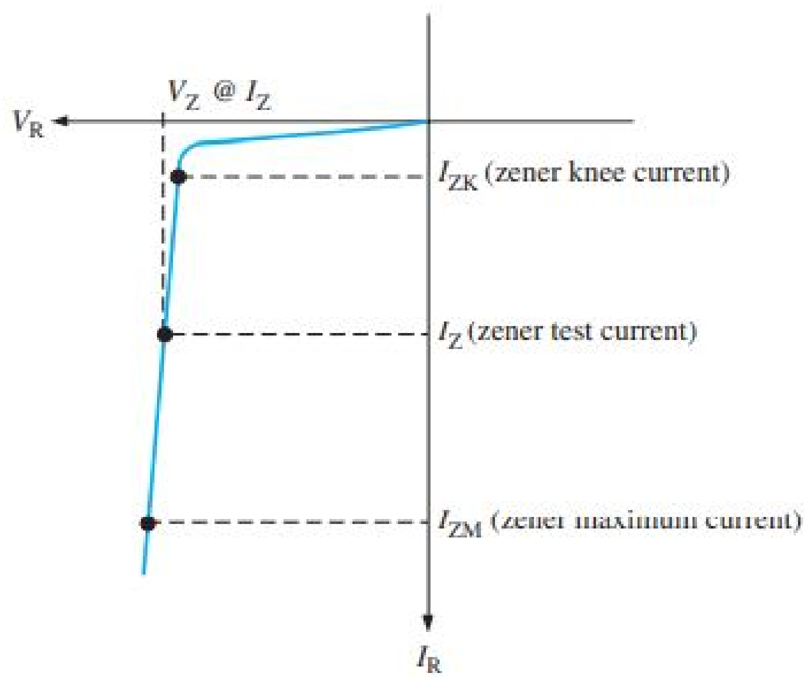


General zener diode *V-I* characteristic.

5.1.1: Zener Breakdown

As discussed before, **breakdown** occurs in both rectifier and Zener diodes at a sufficiently **high** reverse voltage.
Zener breakdown occurs in a Zener diode at **low** reverse voltages because is heavily doped to reduce the breakdown voltage. This causes a **very thin depletion region**. As a result, an intense electric field exists within the depletion region.

Near the Zener breakdown voltage (V_Z), the field is intense enough to pull electrons from their valence bands and create a current.
Zener diodes with **breakdown voltages** of less than approximately **5 V** operate predominately in **Zener breakdown**.
Those with **breakdown voltages** greater than approximately **5 V** operate predominately in **avalanche breakdown**.



Reverse characteristic of a zener diode. V_Z is usually specified at a value of the zener current known as the test current.

5.1.2: Zener Regulation

The ability to keep the reverse voltage across its terminals essentially constant is the key feature of the Zener diode.

When operating in breakdown acts as a voltage regulator because it maintains a nearly constant voltage across its terminals over a specified range of reverse-current values.

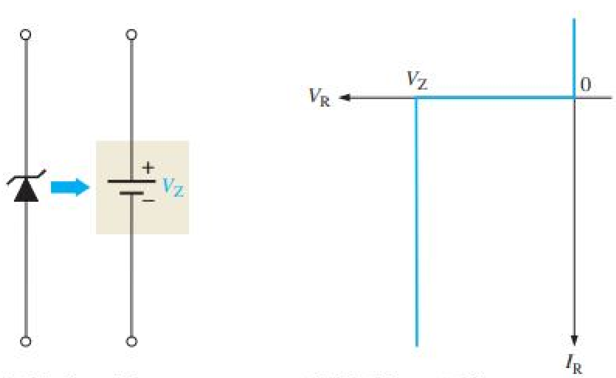
- A **minimum value of reverse current**, **I_{ZK}** must be maintained in order to keep the diode in breakdown for voltage regulation.
- Also, there is a **maximum current**, **I_{Zm}** above which the diode may be damaged due to excessive power dissipation.
- A **nominal Zener voltage**, **V_{ZT}** is usually specified on a data sheet at a value of reverse current called the **Zener test current**, **I_{ZT}**.

5.1.3: Zener Equivalent Circuit

Since the actual voltage curve is not ideally vertical, a change in Zener current (ΔI_z) produces a small change in Zener voltage (ΔV_z). as illustrated in Figure (d).

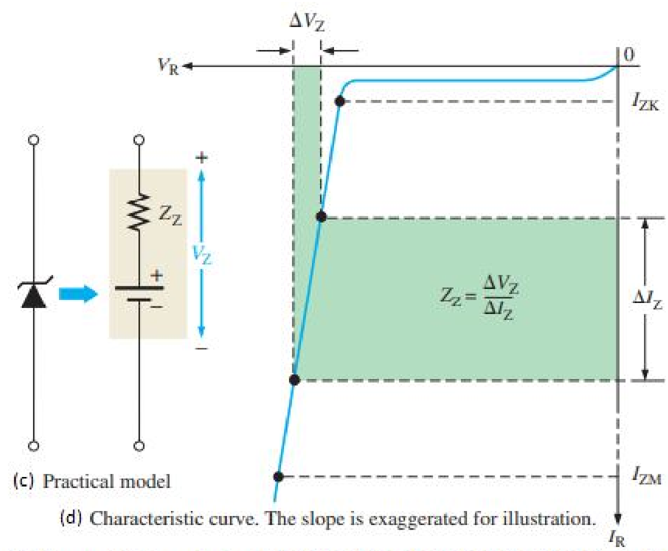
By Ohm's law, the ratio of ΔV_z to ΔI_z is the **impedance** as expressed in the following equation:

$$Z_z = \frac{\Delta V_z}{\Delta I_z} \quad \dots (1)$$



(a) Ideal model (b) Ideal characteristic curve

Ideal zener diode equivalent circuit model and the characteristic curve.

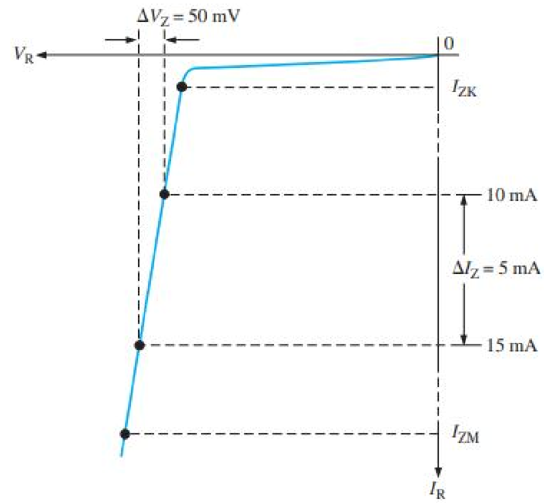


(c) Practical model

(d) Characteristic curve. The slope is exaggerated for illustration.

Practical zener diode equivalent circuit and the characteristic curve illustrating Z_Z.

Example 5.1: A Zener diode exhibits a certain change in V_Z for a certain change in I_Z on a portion of the linear characteristic curve between I_{ZK} and I_{ZM} as illustrated in this Figure. What is the Zener impedance?



Solution:

$$Z_z = \frac{\Delta V_z}{\Delta I_z} = \frac{50\,mV}{5\,mA} = 10\,\Omega$$

5.1.4: Temperature Coefficient (TC)

The temperature coefficient specifies the percent change in Zener voltage for each degree Celsius change in temperature.

The formula for calculating the **change in Zener voltage** for a given junction temperature change, for a specified temperature coefficient, is:

$$\boldsymbol{\Delta V_z = V_z \times TC \times \Delta T} \quad \dots (2)$$

where $\boldsymbol{V_z}$ is the **nominal Zener voltage** at the reference temperature of 25^{0}C, $\boldsymbol{TC}$ is the **temperature coefficient**, and $\boldsymbol{\Delta T}$ is the **change in temperature** from the reference temperature.

Example 5.2: An 8.2 V Zener diode (8.2 V at 25°C) has a positive temperature coefficient of 0.05%/°C. What is the Zener voltage at 60°C?

Solution:

$$\Delta V_z = V_z \times TC \times \Delta T = 8.2 \times \frac{0.05}{100} \times (60 - 25) = 144\,mV$$

The Zener voltage at 60°C is:

$$V_z = V_{zT} + \Delta V_z = 8.2 + 0.144 = 8.344\,V$$

5.1.5: Zener Power Dissipation and Derating

Zener diodes are specified to operate at a maximum power called the maximum dc power dissipation ($P_{D(max)}$). The dc power dissipation is determined by the formula;

$$\boldsymbol{P_D = I_z V_z} \quad \dots (3)$$

The **maximum derated power** can be determined with the following formula:

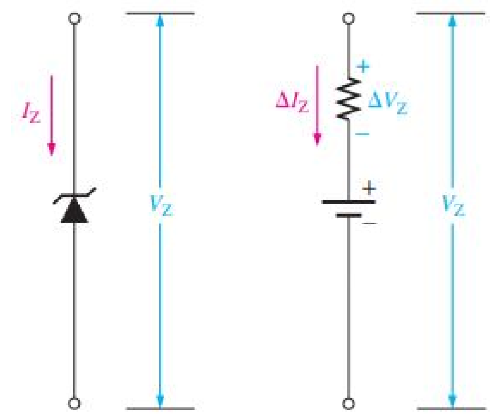
$$\boldsymbol{P_{D(\text{derated})} = P_{D(\max)}(mV) - \text{Derating Factor}\left(\frac{mV}{°C}\right) \Delta T\ (°C)} \quad \dots (4)$$

Example 5.3: A certain Zener diode has a maximum power rating of 400 mW at 50°C and a derating factor of 3.2 mW/°C. Determine the maximum power the Zener can dissipate at a temperature of 90°C.

Solution:

$$P_{D(\text{derated})} = P_{D(\max)} - \text{Derating Factor} \times \Delta T = 400 - 3.2 \times (90 - 50) = 400 - 128 = 272 mV$$

Example 5.4: A 1N4736 Zener diode has a Z_{ZT} of 3.5 Ω. The data sheet gives V_{ZT} = 6.8 V at I_{ZT} =37 mA and I_{ZK} = 1mA. What is the voltage across the Zener terminals when the current is 50 mA? When the current is 25 mA? This Figure represents the Zener diode.



Solution:

$\Delta I_Z = I_Z - I_{ZT} = 50 - 37 = 13\, mA,$

$\Delta V_Z = \Delta I_Z\, Z_{ZT} = 13 \times 3.5 = 45.5\, mV,$

The Zener voltage for $I_Z = 50\, mA$ is:

$$V_Z = V_{ZT} + \Delta V_Z = 6.8 + 0.0455 = 6.85\, V$$

For $I_Z = 25\, mA$:

$\Delta I_Z = I_Z - I_{ZT} = 25 - 37 = -12\, mA,$

$\Delta V_Z = \Delta I_Z\, Z_{ZT} = (-12) \times 3.5 = -42\, mV,$

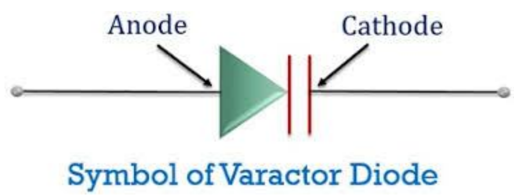
The Zener voltage for $I_Z = 50\, mA$ is:

$$V_Z = V_{ZT} + \Delta V_Z = 6.8 - 0.042 = 6.76\, V$$

5.1.6: Zener Diode Applications

The Zener diode can be used as a type of voltage regulator for providing stable reference voltages. Zeners can be used as regulators and as simple limiters or clippers.

5.2: The Varactor Diode



Varactor diodes are also known as **variable-capacitance diodes** because the junction capacitance varies with the amount of reverse-bias voltage.
They are specifically designed to take advantage of this variable-capacitance characteristic.
They are commonly used in electronic tuning circuits used in communications systems.

5.2.1: Varactor Basic Operation

A varactor **is a diode that always operates in reverse-bias and is doped to maximize the inherent capacitance of the depletion region.**
The depletion region widened by the reverse bias, acts as a capacitor dielectric because of its nonconductive characteristic. The p and n regions are conductive and act as the capacitor plates, as illustrated in this Figure.

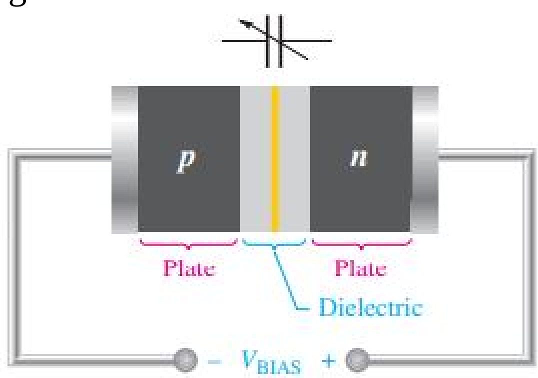


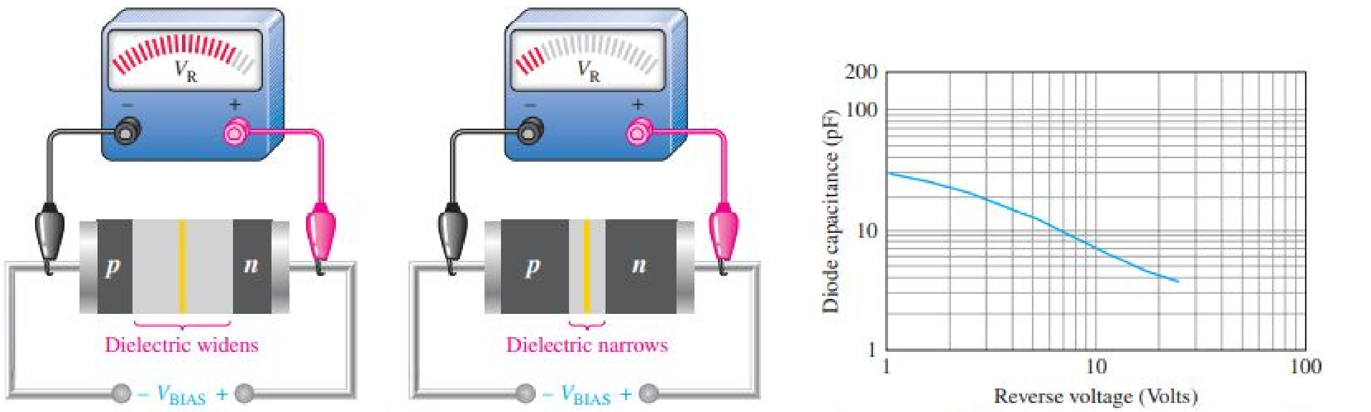
Figure: The reverse-biased Varactor diode acts as a variable capacitor.

As the reverse-bias voltage increases, the depletion region widens, effectively increasing the plate separation and the dielectric thickness and thus decreasing the capacitance. When the reverse-bias voltage decreases, the depletion region narrows, thus increasing the capacitance.

Recall that capacitance is determined by the parameters of plate area (A), dielectric constant (ε), and dielectric thickness (d), as expressed in the following formula:

$$C = \frac{\varepsilon A}{d}$$

A **varactor diode** is best explained as a variable capacitor. Think of the depletion region as a variable dielectric. The diode is placed in reverse bias. The dielectric is “adjusted” by reverse bias voltage changes.

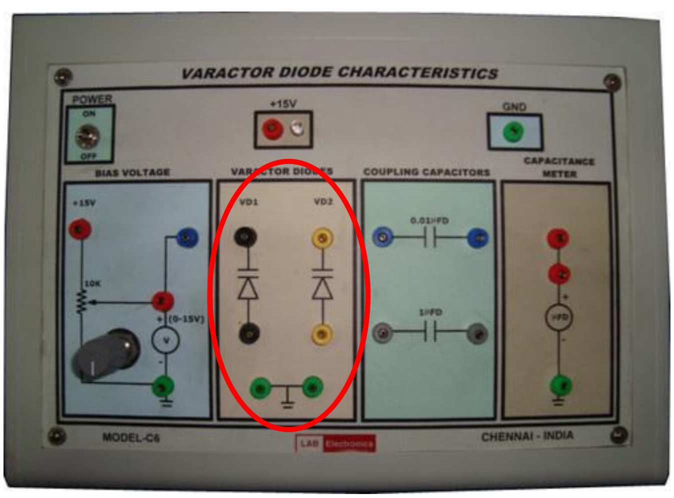


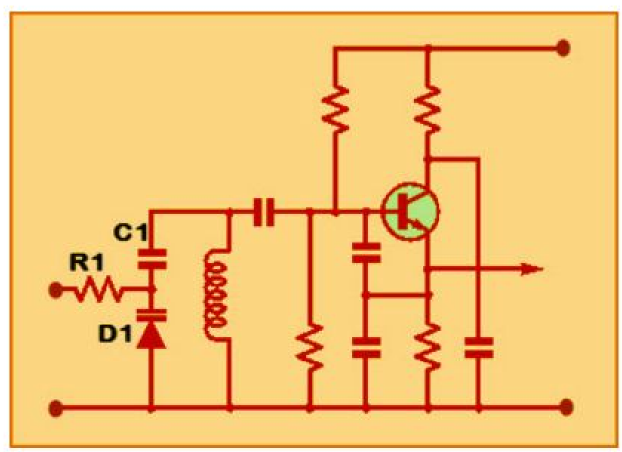
(a) Greater reverse bias, less capacitance (b) Less reverse bias, greater capacitance (c) Example of a diode capacitance versus reverse voltage graph

Figure: Varactor diode capacitance varies with reverse voltage.

5.2.2: Varactor Diode Applications

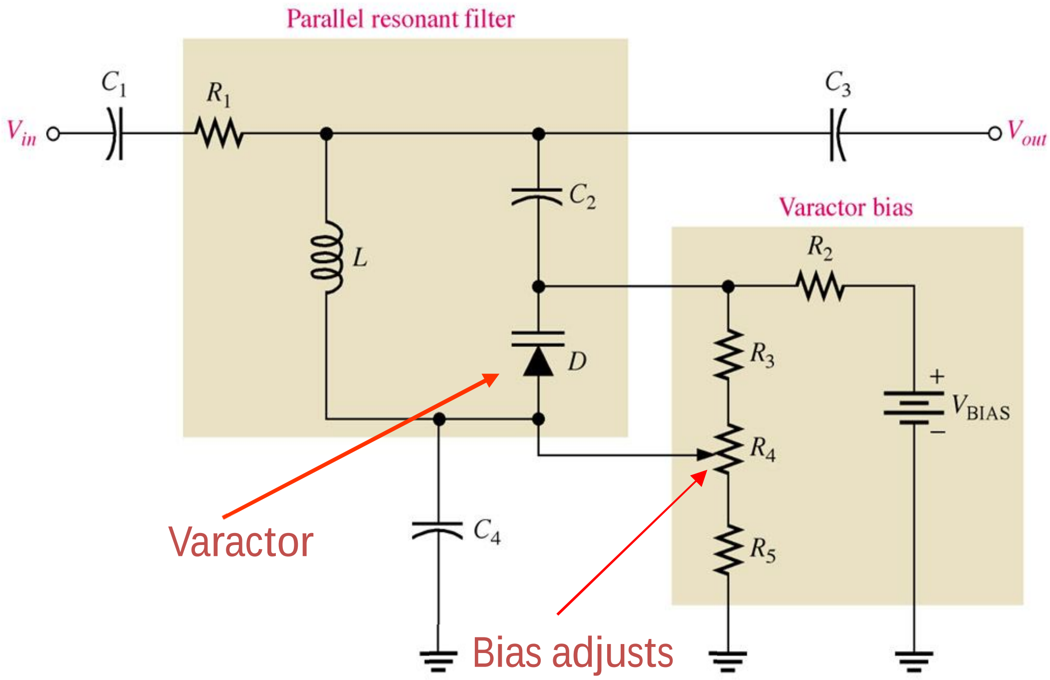
A major application of Varactor is in tuning circuits. For example, electronic tuners in TV and other commercial receivers utilize Varactor, allowing the resonant frequency to be adjusted by a variable voltage level.



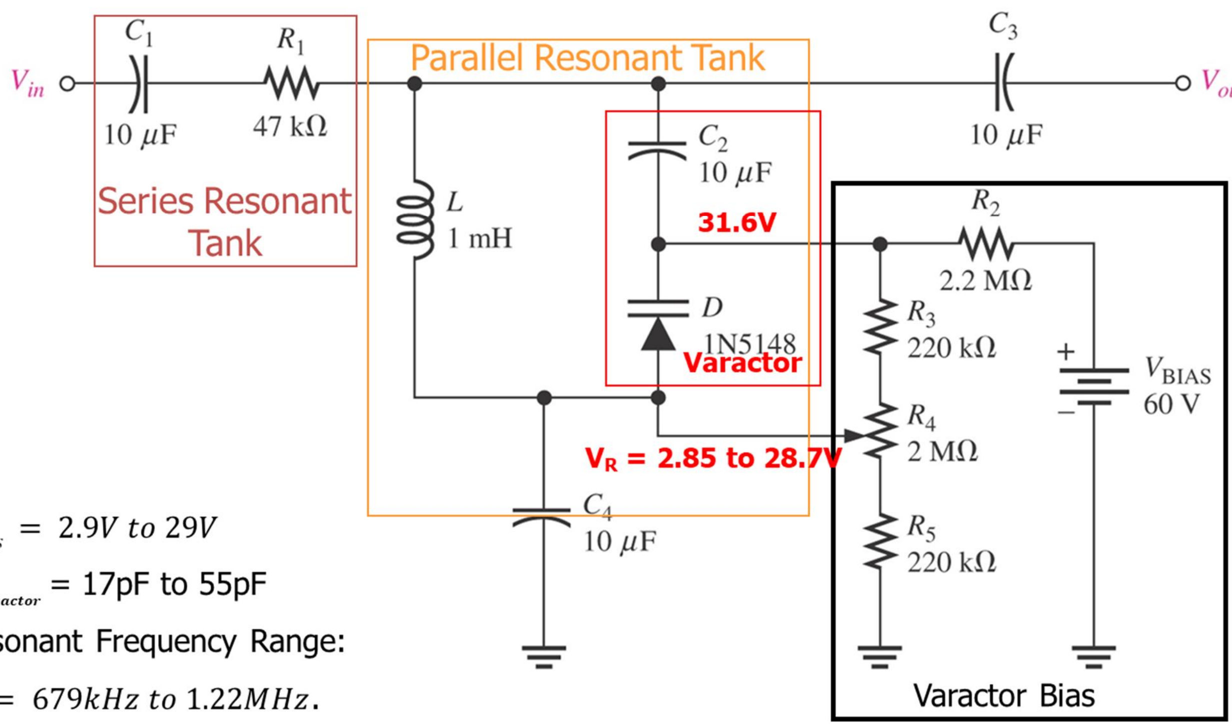


Model C6 Varactor Diode Characteristics **RF filter circuit with Varactor diodes**

Another application of varactor diode is useful in filter circuits as the adjustable component for resonance frequency selection.



Resonant Band-Pass Filter w/ Varactor Diode



$V_{BIAS} = 2.9V\ to\ 29V$

$C_{Varactor}$ = 17pF to 55pF

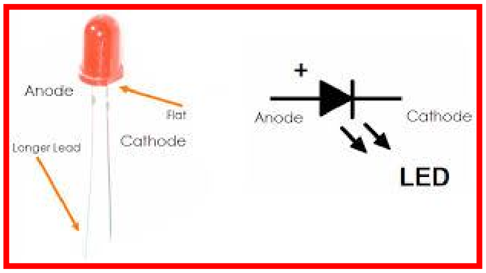
Resonant Frequency Range:

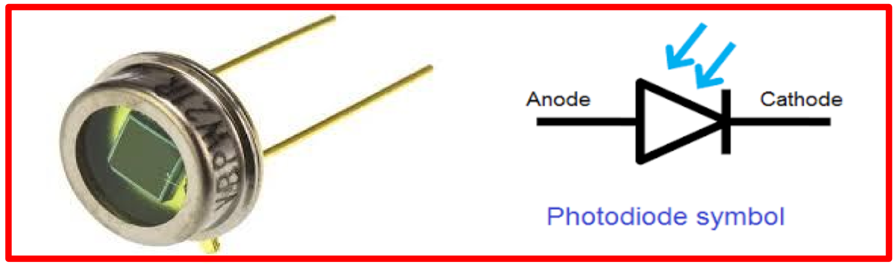
$f_r = 679kHz\ to\ 1.22MHz.$

5.3: Optical Diodes

Two types of optoelectronic devices:

- The light-emitting diode (LED), is a light emitter.
- The photodiode, is a light detector.

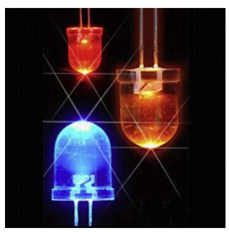




(a) The light-emitting diode **(b) The photodiode**

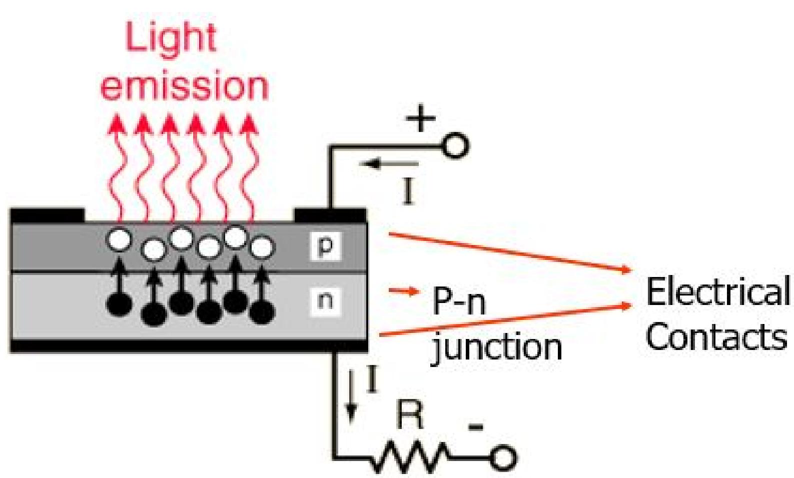
5.3.1: The Light-Emitting Diode (LED)

What is LED?



LED are semiconductor p-n junctions that under forward bias conditions can emit radiation by electroluminescence in the UV, visible or infrared regions of the electromagnetic spectrum.
~~The quanta of light energy released are approximately proportional to the band gap of the semiconductor (studied before !!!).~~

How does it work?



A typical LED needs a p-n junction

There are a lot of electrons and holes at the junction due to excitations

Electrons from n need to be injected to $\boldsymbol{p}$ to promote recombination

Junction is biased to produce even more $\boldsymbol{e-h}$ and to inject electrons from $\boldsymbol{n\ to\ p}$ for recombination to happen

Recombination produces light!!

Electroluminescence, the process of emitting photons from a parent material (substrate), is the basis for LEDs.

Colors result from the choice of substrate material and the resulting ***wavelength***;

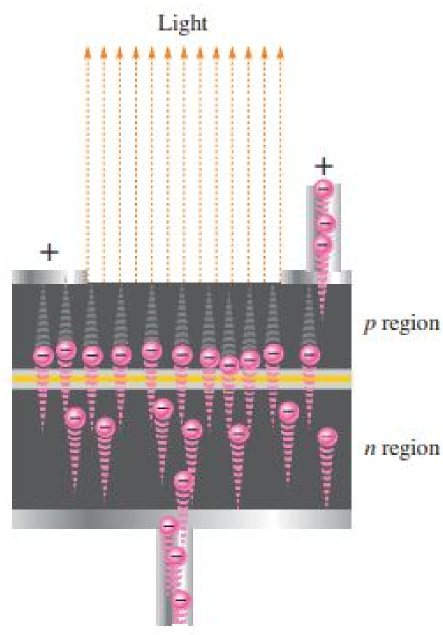
Today's LEDs (**green**, **red**, **yellow**) are based on *indium gallium aluminum phosphide*.

Blue uses *silicon carbide or gallium nitride*.

IR (infrared) – GaAs (gallium arsenide).

LED Biasing: 1.2V to 3.2V is typical.

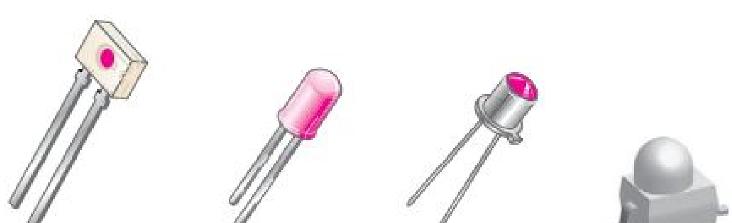
Note: Some newer LED's run at higher voltages and emit immense light energy.



Electroluminescence in a forward- biased LED.

A strong +bias encourages conduction-band electrons in the N-material to leap the junction and recombine with available holes releasing light and heat.

Typical LEDs:



(a) Typical small LEDs for indicators

(b) Typical LEDs for lighting applications

LED Diode Applications:

Standard LEDs are used for **indicator lamps** and **readout displays** on a wide variety of instruments, ranging from consumer appliances to scientific apparatus. A common type of display device using LEDs is the **seven-segment display**. Combinations of the segments form the ten decimal digits as illustrated in this Figure. Also, it has applications in **traffic signals**, Outdoor video screens, and Runway markers

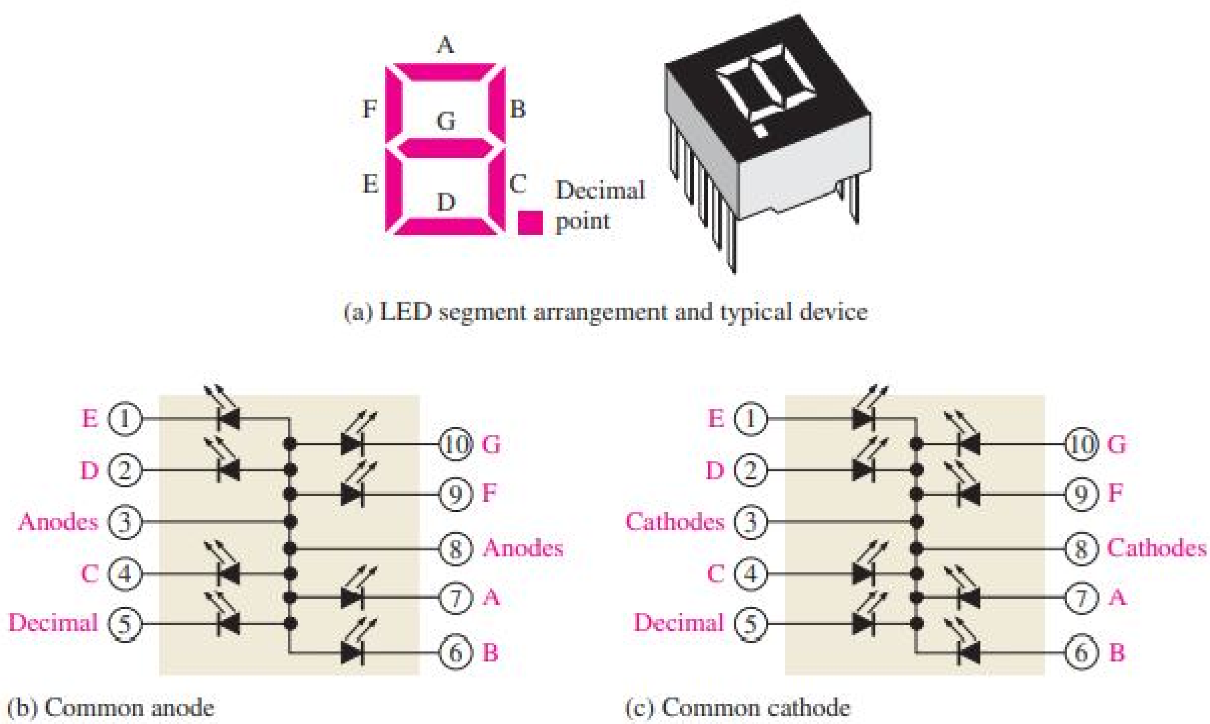


Figure: The 7-segment LED display.

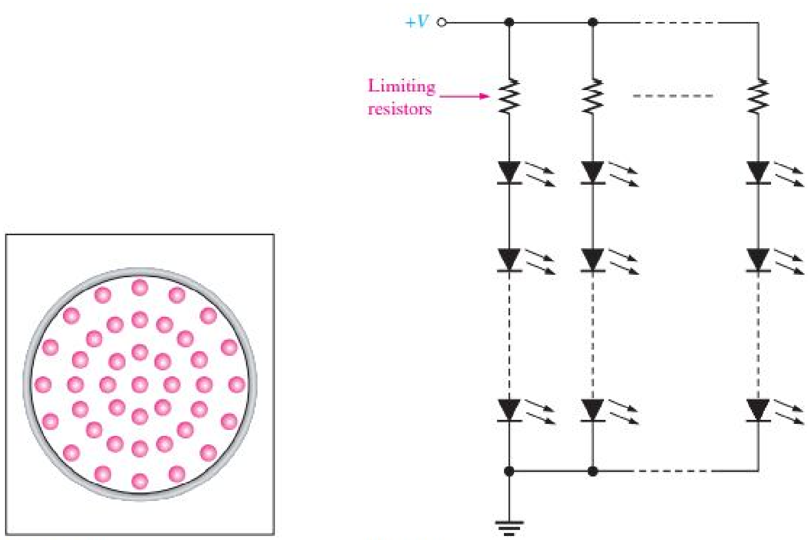
Each segment in the display is an LED. By forward-biasing selected combinations of segments, any decimal digit and a decimal point can be formed. Two types of LED circuit arrangements are the common anode and common cathode as shown.

Traffic Lights:

LEDs are quickly replacing the traditional incandescent **bulbs** in traffic signal applications.
Arrays of tiny LEDs form the **red**, **yellow**, and **green** lights in a traffic light unit.
An **LED** array has three major advantages over the incandescent bulb:

- **brighter light**,
- **longer lifetime** (years vs. months), and
- **less energy** consumption (about 90% less).

LED traffic lights are constructed in arrays with **lenses** that **optimize and direct the light output**.
Figure (a) illustrates the concept of a traffic light array using red LEDs. A **relatively low density** of LEDs is shown for illustration. The **actual number** and **spacing of the LEDs** in a traffic light unit depends on the **diameter of the unit**, the **type of lens**, the **color**, and the **required light intensity**.
With an appropriate LED density and a lens, an 8- or 12- inch traffic light will appear essentially as a **solid-color circle**.
LEDs in an array are usually connected either in a **series-parallel** or a **parallel** arrangement.
A **series connection is not practical** because if one LED fails open, then all the LEDs are disabled.
For a parallel connection, **each LED requires a limiting resistor**. To reduce the number of limiting resistors, a **series-parallel connection can be used**, as shown in Figure (b).

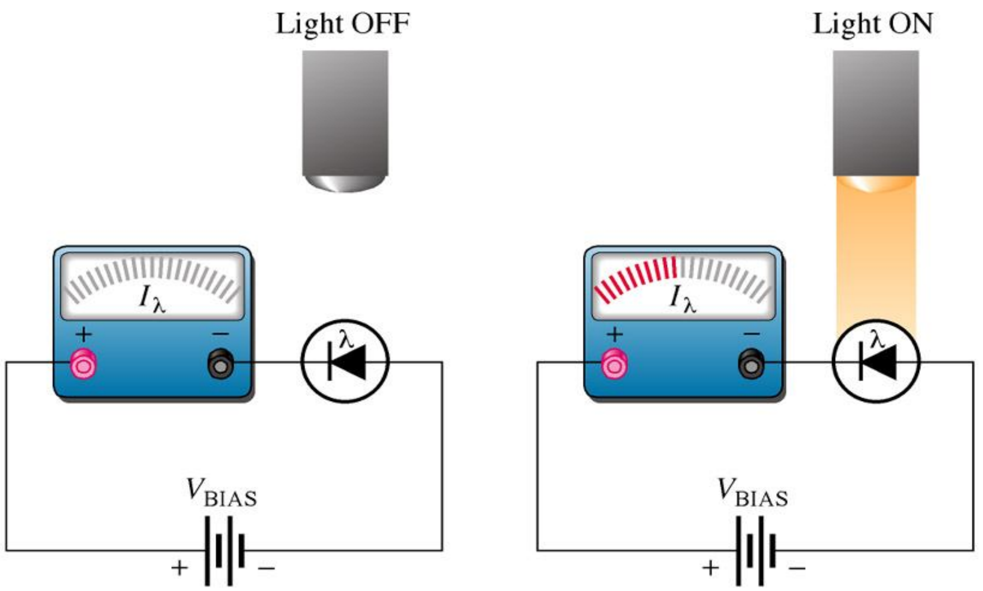


(a) LED array (b) Circuit

Figure: LED traffic light.

5.3.2: Photodiodes

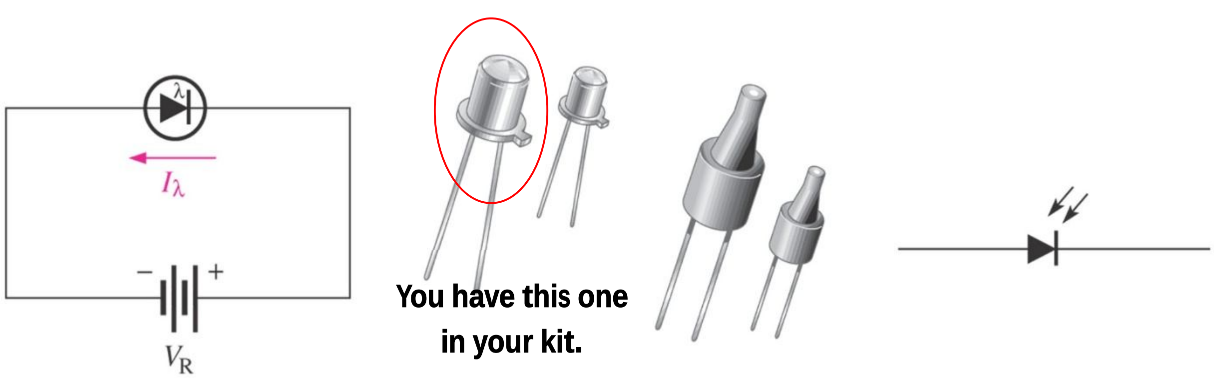
Unlike LED's, **photodiodes receive light rather than produce light**. The photodiode varies it's current in response to the amount of light that strikes it. It is placed in the circuit in **reverse bias**. As with most diodes, no current flows when in reverse bias, but when light strikes the exposed junction through a tiny window, **reverse current** increases proportional to **light intensity (irradiance)**.



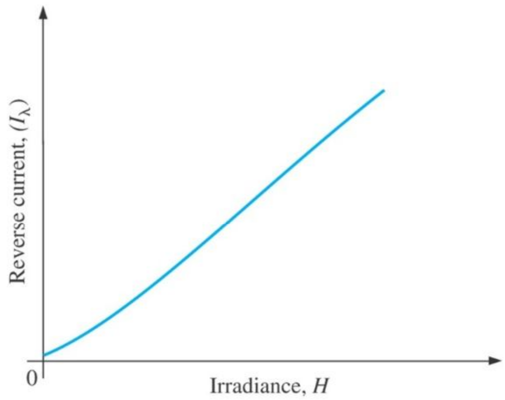
(a) No light, no current except negligible dark current

(b) Where there is incident light, resistance decreases and there is reverse current.

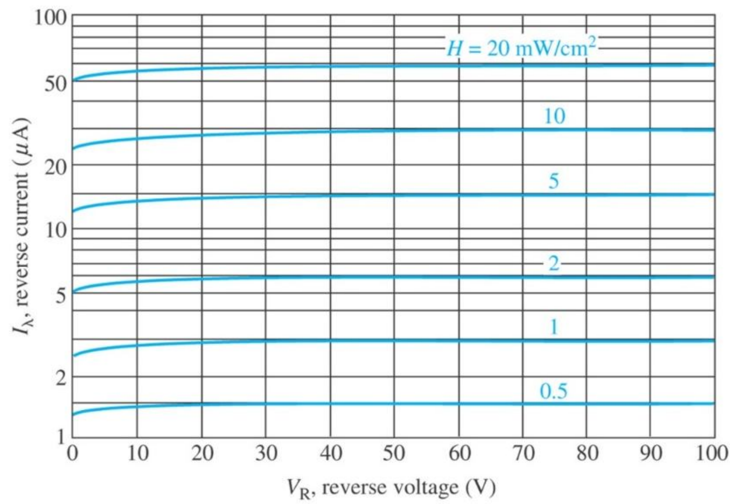
Note: Photodiodes all exhibit a "**reverse leakage current**" which appears as an inverse variable resistance. Irradiance causes the device to exhibit a reduction in the variable resistance characteristic.



(a) Reverse-bias operation (b) Typical devices (c) Alternate symbol



(a) General graph of reverse current versus irradiance

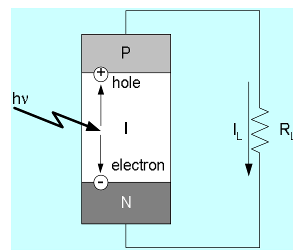


(b) Example of a graph of reverse current versus reverse voltage for several values of irradiance

Photodiode Fundamentals:

Based on PN or PIN junction diode

photon absorption in the depletion region induces current flow

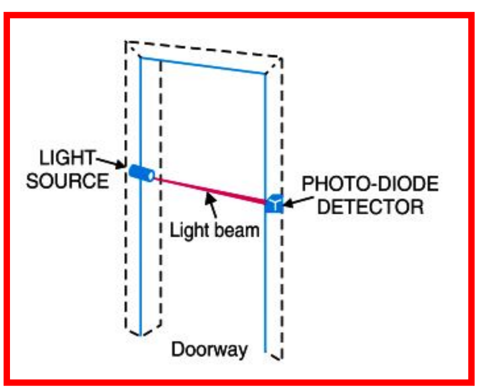


Spectral Sensitivity:

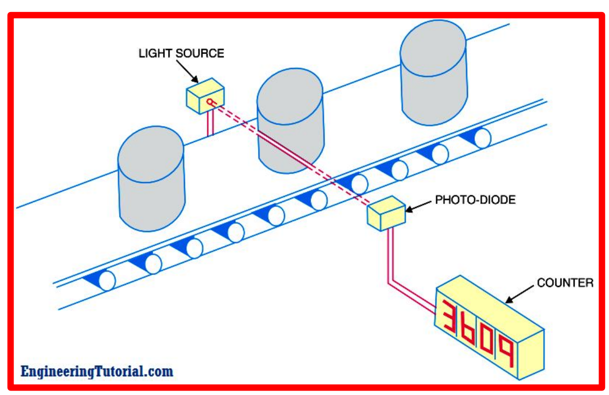
Material	Band gap (eV)	Spectral sensitivity
silicon (Si)	1.12	250 to 1100 nm
indium arsenide (InGaAs)	~0.35	1000 to 2200 nm
Germanium (Ge)	.67	900 to 1600 nm

Photodiode Applications:

- Alarm circuit
- Counter circuit



Alarm circuit using photodiode.



Counter circuit using photodiode.

5.4: Current Regulator Diode

The **current regulator diode** is often referred to as a constant-current diode Rather than maintaining a constant voltage, as the Zener diode does, this diode maintain a constant current. The symbol is shown in Figure below.

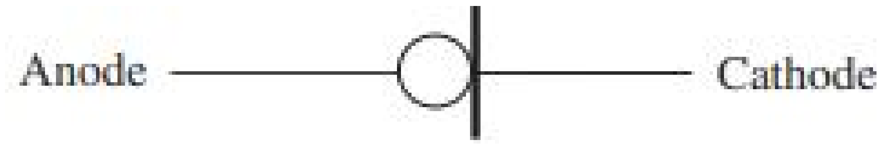
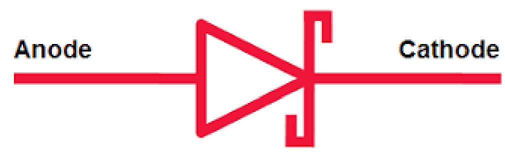


Figure: Symbol for a current regulator diode.

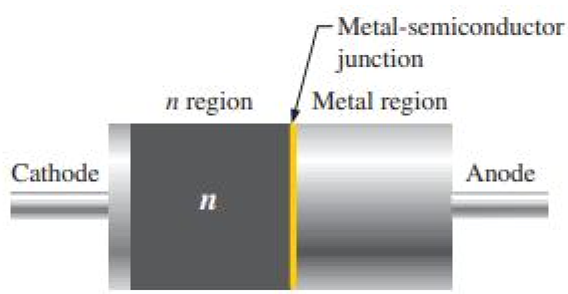
The **current regulator diode** operates in forward bias, and the forward current becomes a specified constant value at forward voltages ranging from about **1.5 V** to about 6 V depending on the diode type. The constant forward current is called the **regulator current** and is designated by **Ip**.

5.5: The Schottky Diode



Schottky diode symbol

Schottky diodes are used primarily in **high-frequency and fast-switching applications**. They are also known as hot-carrier diodes. It is formed by joining a doped semiconductor region (usually n-type) with a metal such as gold, silver, or platinum. Rather than a PN junction, there is a **metal-to-semiconductor junction**, as shown in the Figure. The forward voltage drop is typically around 0.3 V.



Lightly doped **Heavily doped (conduction-band electrons)**

Figure: Basic internal construction of a Schottky diode.

5.6: The PIN Diode

The pin diode consists of heavily doped **(*p*)** and **(*n*)** regions separated by an intrinsic region, as shown in the Figure. When reverse-biased, the PIN diode acts like a nearly constant capacitance. When forward-biased, it acts like a current-controlled variable resistance. This is shown in Figure (b) and (c). The low forward resistance of the intrinsic region decreases with increasing current.

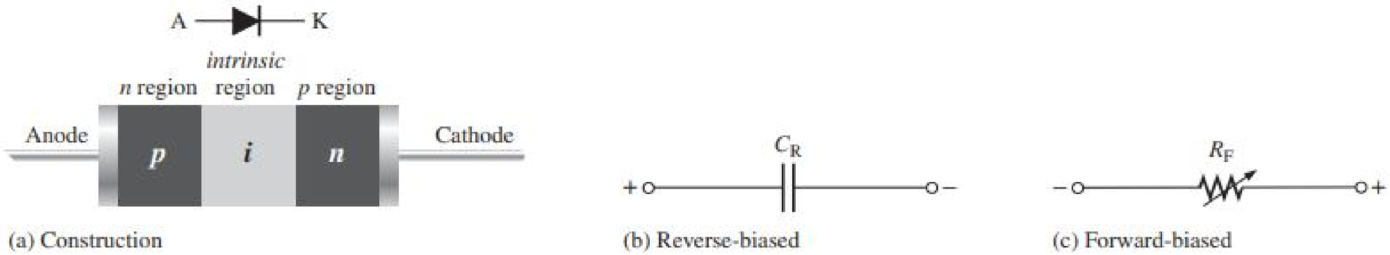


Figure: PIN diode.

The pin diode is used:

(i) As a **dc-controlled microwave switch** operated by rapid changes in bias that takes advantage of the **variable forward-resistance** characteristic.

(ii) It can also be used in attenuator applications because its resistance can be controlled by the amount of current.

(iii) **Photo detector** in fibre-optic systems.

5.7: The Tunnel Diode

The tunnel diode exhibits a special characteristic known as negative resistance. **This feature makes it useful in oscillator and microwave amplifier applications**. Two alternate symbols are shown in Figure below.

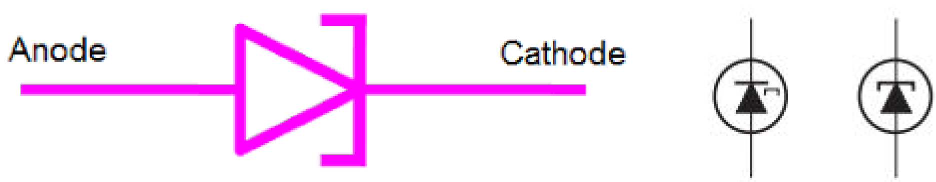


Figure: Tunnel diode symbols.

Tunnel diodes are constructed with germanium or gallium arsenide by doping the P and N regions much more heavily than in a conventional rectifier diode. This heavy doping results in an extremely narrow depletion region. The heavy doping allows conduction for all reverse voltages so that there is no breakdown effect as with the conventional rectifier diode. This is shown in this Figure.

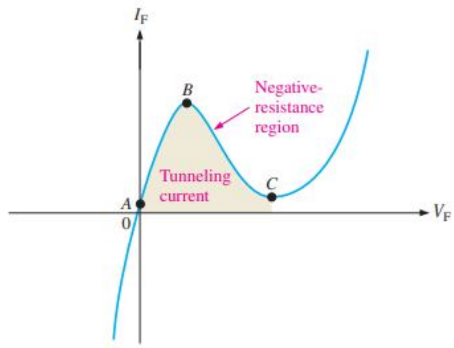


Figure: Tunnel diode characteristic curve.

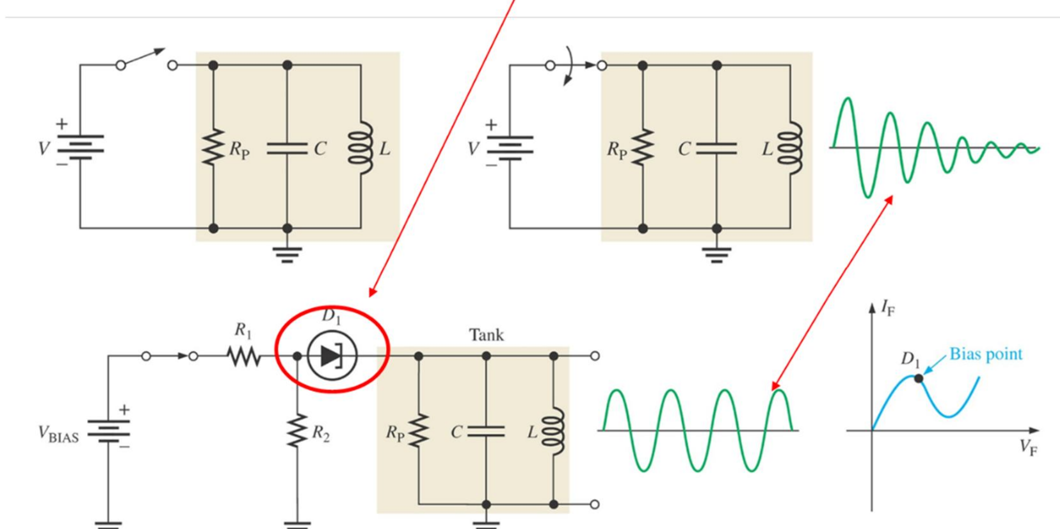
Also, the extremely narrow depletion region permits electrons to "tunnel" through the *pn* junction at very low forward-bias voltages, and the diode acts as a conductor. This is shown in this Figure between points A and B. At point B, the forward voltage begins to develop a barrier, and the current begins to decrease as the forward voltage continues to increase. This is the negative-resistance region.

$$R_f = \frac{\Delta V_f}{\Delta I_f}$$

This effect is opposite to that described in Ohm's law, where an increase in voltage results in an increase in current. At point C, the diode begins to act as a conventional forward biased diode.

An application:

Tank circuits oscillate but "die out" due to the internal resistance. A tunnel diode will provide "negative resistance" that overcomes the loses and maintains the oscillations.



5.8: The Laser Diode

- **Laser light** is **monochromatic**, which means that it consists of a **single colour** and not a mixture of colours. It is also called **coherent light**, a **single wavelength**, as compared to incoherent light, which consists of a wide band of wavelengths.
- The **laser diode** normally emits coherent light, whereas the **LED** emits incoherent light. The symbols are the same as shown in Figure (a).
- The **basic construction** of a laser diode is shown in Figure (b). A *pn* junction is formed by two layers of doped **gallium arsenide**. The **length** of the *pn* junction bears a precise relationship with the **wavelength** of the light to be emitted. There is a **highly reflective surface** at one end of the *pn* junction and **a partially reflective surface** at the other end produced by "**polishing**" the ends. External leads provide the anode and cathode connections.

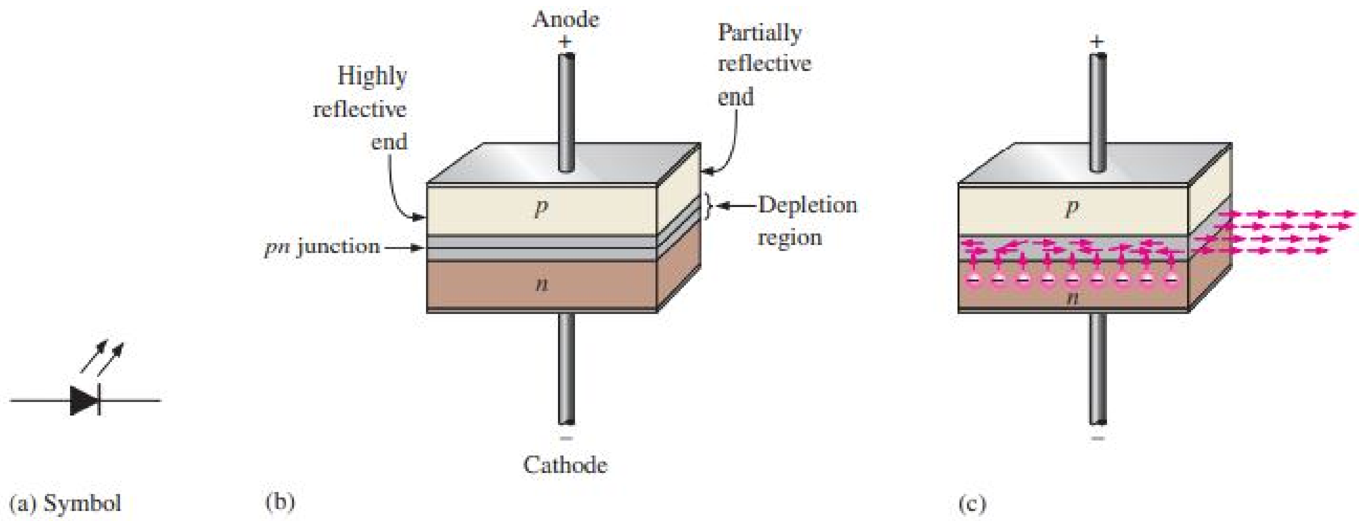


Figure: Basic laser diode construction and operation.

An application:

Laser diodes and photodiodes are used in the pick-up system of compact disk (CD) players. Audio information (sound) is digitally recorded in stereo on the surface of a compact disk in the form of microscopic "pits" and "flats." A lens arrangement focuses the laser beam from the diode onto the CD surface. As the CD rotates, the lens and beam follow the track under control of a servomotor. The laser light, which is altered by the pits and flats along the recorded track, is reflected back from the track through a lens and optical system to infrared photodiodes. The signal from the photodiodes is then used to reproduce the digitally recorded sound.

Summary:

- The Zener diode operates in reverse breakdown.
- A Zener diode maintains a nearly constant voltage across its terminals over a specified range of currents.
- Voltage regulation is the maintenance of a specific voltage with changing input voltages.
- Load regulation is the maintenance of a specific voltage for different loads.
- There are other diode types used for specific RF purposes such as varactor diodes (variable capacitance), Schottky diodes (high speed switching), and PIN diodes (microwave attenuation and switching).
- Photodiodes exhibit an increase in reverse current with light intensity.
- The laser diode emits a monochromatic light.

H.W: Q1: **Answers can be found at** https://quizlet.com/519379031/chapte-3-electronic-devices-flash-cards/

1. The cathode of a Zener diode in a voltage regulator is normally
   (a) more positive than the anode (b) more negative than the anode
   (c) at +0.7 V (d) grounded
2. If a certain Zener diode has a Zener voltage of 3.6 V, it operates in
   (a) regulated breakdown (b) Zener breakdown
   (c) forward conduction (d) avalanche breakdown
3. For a certain 12 V Zener diode, a 10-mA change in Zener current produces a 0.1 V change in Zener voltage. The Zener impedance for this current range is
   (a) 10 (b) 1000 (c) 100 (d) 0.01
4. The datasheet for a particular Zener gives V_Z 10 V at I_Z 500 mA. Z_Z for these conditions is
   (a) 500 (b) 200 (c) 100 (d) unknown
5. A no-load condition means that
   (a) the load has infinite resistance (b) the load has zero resistance
   (c) the output terminals are open (d) answers (a) and (c)
6. A varactor diode exhibits
   (a) a variable capacitance that depends on reverse voltage
   (b) a variable resistance that depends on reverse voltage
   (c) a variable capacitance that depends on forward current
   (d) a constant capacitance over a range of reverse voltages
7. An LED
   (a) emits light when reverse-biased (b) senses light when reverse-biased
   (c) emits light when forward-biased (d) acts as a variable resistance
8. Compared to a visible red LED, an infrared LED
   (a) produces light with shorter wavelengths
   (b) produces light of all wavelengths
   (c) produces only one color of light
   (d) produces light with longer wavelengths
9. Compared to incandescent bulbs, high-intensity LEDs
   (a) are brighter (b) have a much longer life
   (c) use less power (d) all of the above

10. An OLED differs from a conventional LED in that it
    (a) requires no bias voltage
    (b) has layers of organic material in the place of a pn junction
    (c) can be implemented using an inkjet printing process
    (d) both (b) and (c)

11. An infrared LED is optically coupled to a photodiode. When the LED is turned off, the reading on an ammeter in series with the reverse-biased photodiode will
    (a) not change (b) decrease (c) increase (d) fluctuate

12. The internal resistance of a photodiode
    (a) increases with light intensity when reverse-biased
    (b) decreases with light intensity when reverse-biased
    (c) increases with light intensity when forward-biased
    (d) decreases with light intensity when forward-biased

13. A laser diode produces
    (a) incoherent light (b) coherent light
    (c) monochromatic light (d) both (b) and (c)

14. A diode that has a negative resistance characteristic is the
    (a) Schottky diode (b) tunnel diode (c) laser diode (d) hot-carrier diode

15. In order for a system to function properly, the various types of circuits that make up the system must be
    (a) properly biased (b) properly connected
    (c) properly interfaced (d) all of the above (e) answers (a) and (b)

Answering:

1. a 2. b 3. c 4. b 5. d 6. a 7. c 8. d 9. d 10. d 11. b 12. b 13. d 14. b 15. d.