Unit 3: Special Purpose Diodes and Transistors

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1.1 Introduction

- Rectifier diodes are the most common type of diode. They are used in power supplies to convert ac voltage to dc voltage. But rectification is not all that a diode can do.
- Now we will discuss diodes used in other applications. The chapter begins with the Zener diode, which is optimized for its breakdown properties.
- Zener diodes are very important because they are the key to voltage regulation. The chapter also covers optoelectronic diodes, including light-emitting diodes (LEDs), Schottky diodes, Varactors, and other diodes.

1.2 The Zener Diode

- Small-signal and rectifier diodes are never intentionally operated in the breakdown region because this may damage them. A Zener diode is different; it is a silicon diode that the manufacturer has optimized for operation in the breakdown region.
- The Zener diode is the backbone of voltage regulators, circuits that hold the load voltage almost constant despite large changes in line voltage and load resistance.

1.2.1 I-V Graph

- Figure-1a shows the schematic symbol of a Zener diode; Figure-1b is an alternative symbol. In either symbol, the lines resemble a ***Z***, which stands for "Zener."
- By varying the doping level of silicon diodes, a manufacturer can produce Zener diodes with breakdown voltages from about ***2 to over 1000 V***. These diodes can operate in any of three regions: forward, leakage, and breakdown.
- Figure-1c shows the ***I-V*** graph of a Zener diode. In the forward region, it starts conducting around 0.7 V, just like an ordinary silicon diode. In the leakage region (between zero and breakdown), it has only a small reverse current.
- In a Zener diode, the breakdown has a very sharp knee, followed by an almost vertical increase in current. Note that the voltage is almost constant, approximately equal to V_Z over most of the breakdown region.
- Data sheets usually specify the value of V_Z at a particular test current I_{ZT}.
- Figure-1c also shows the maximum reverse current I_{ZM}. As long as the reverse current is less than I_{ZM}, the diode is operating within its safe range.
- If the current is greater than I_{ZM}, the diode will be destroyed. To prevent excessive reverse current, a current-limiting resistor must be used (discussed later).

1.2.2 Zener Resistance

- In the third approximation of a silicon diode, the forward voltage across a diode equals the knee voltage plus the additional voltage across the bulk resistance.
- Similarly, in the breakdown region, the reverse voltage across a diode equals the breakdown voltage plus the additional voltage across the bulk resistance.
- In the reverse region, the bulk resistance is referred to as the Zener resistance. This resistance equals the inverse of the slope in the breakdown region.
- In other words, the more vertical the breakdown region, the smaller the Zener resistance.

- In Figure-1c, the Zener resistance means that an increase in reverse current produces a slight increase in reverse voltage. The increase in voltage is very small, typically only a few tenths of a volt.
- This slight increase may be important in design work, but not in troubleshooting and preliminary analysis. Unless otherwise indicated, our discussions will ignore the Zener resistance. Figure-1d shows typical Zener diodes.

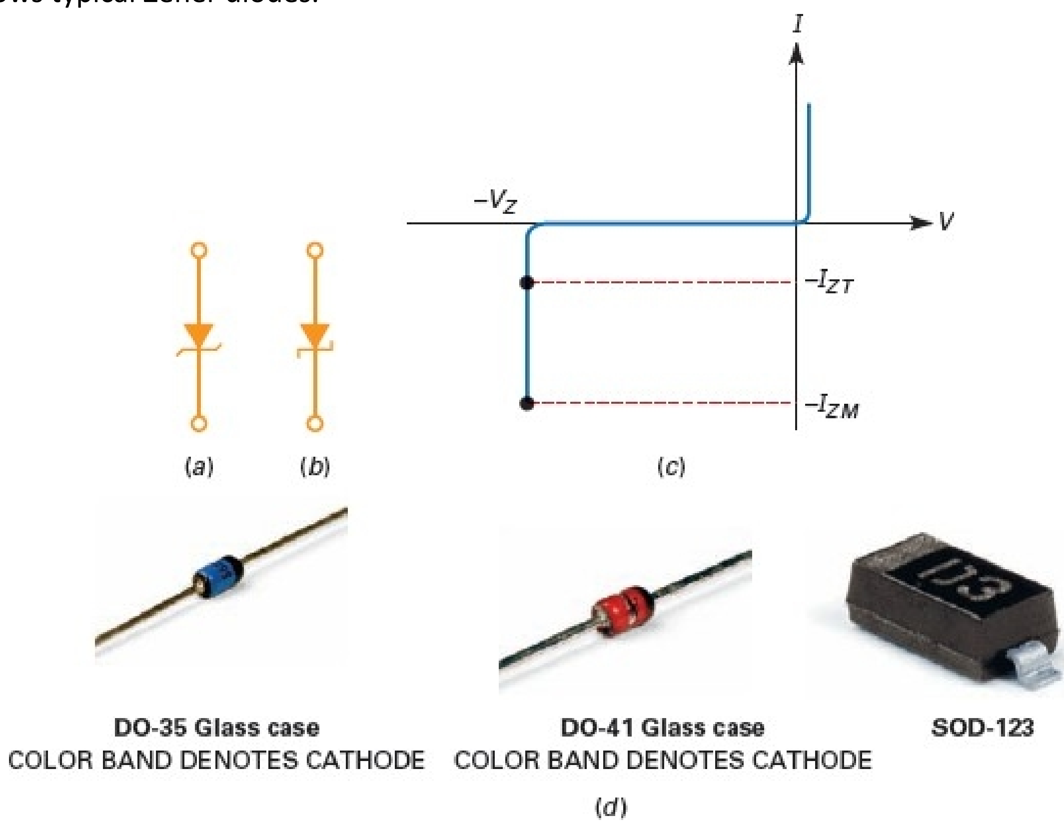


Figure-1 (a) Schematic symbol; (b) alternative symbol; (c) graph of current versus voltage; (d) typical Zener diodes

1.2.3 Zener Regulator

- A Zener diode is sometimes called a voltage-regulator diode because it maintains a constant output voltage even though the current through it changes. For normal operation, you have to reverse-bias the Zener diode, as shown in Figure-2a.

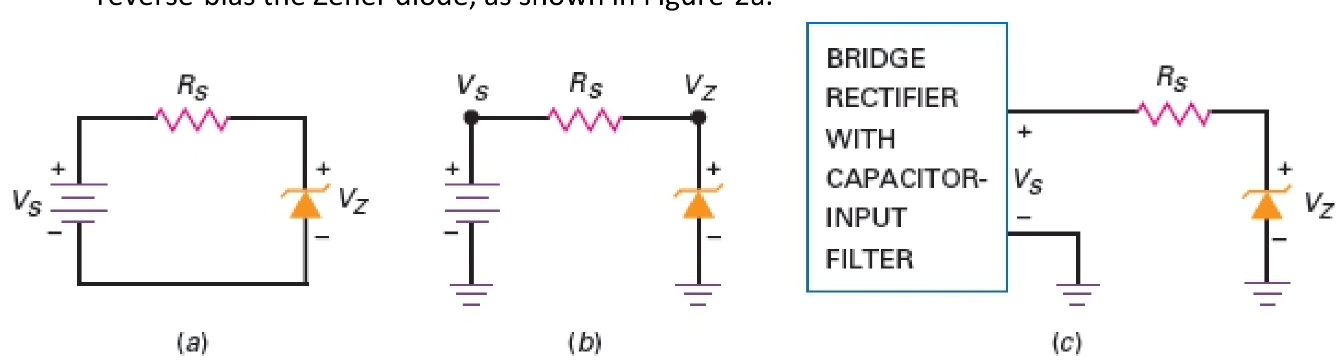


Figure-2 Zener regulator. (a) Basic circuit; (b) same circuit with grounds; (c) power supply drives regulator

- Furthermore, to get breakdown operation, the source voltage V_S must be greater than the Zener breakdown voltage V_Z. A series resistor R_S is always used to limit the Zener current to less than its maximum current rating. Otherwise, the Zener diode will burn out, like any device with too much power dissipation.
- Figure-2b shows an alternative way to draw the circuit with grounds. Whenever a circuit has grounds, you can measure voltages with respect to ground.
- For instance, suppose you want to know the voltage across the series resistor of Figure-2b. Here is the one way to find it when you have a built-up circuit.
- First, measure the voltage from the left end of R_S to ground. Second, measure the voltage from the right end of R_S to ground. Third, subtract the two voltages to get the voltage across R_S. If you have a floating ***VOM*** or ***DMM***, you can connect directly across the series resistor.
- Figure-2c shows the output of a power supply connected to a series resistor and a Zener diode. This circuit is used when you want a dc output voltage that is less than the output of the power supply. A circuit like this is called a Zener voltage regulator, or simply a Zener regulator.

1.2.4 Ohm's Law Again

- In Figure-2, the voltage across the series or current-limiting resistor equals the difference between the source voltage and the Zener voltage. Therefore, the current through the resistor is:

$$I = \underline{VS-VZ} \text{ ---------------------------------- } (1)$$

- Once you have the value of series current, you also have the value of Zener current. This is because Figure-2 is a series circuit. Note that I_S must be less than I_{ZM}.

1.2.5 Ideal Zener Diode

- For troubleshooting and preliminary analysis, we can approximate the breakdown region as vertical. Therefore, the voltage is constant even though the current changes, which is equivalent to ignoring the Zener resistance.
- Figure-3 shows the ideal approximation of a Zener diode. This means that a Zener diode operating in the breakdown region ideally acts like a battery.

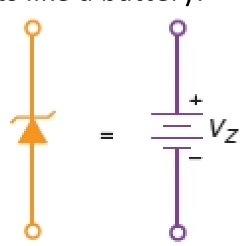


Figure-3 Ideal approximation of a Zener diode.

- In a circuit, it means that you can mentally replace a Zener diode by a voltage source of V_Z, provided the Zener diode is operating in the breakdown region.

Example-1

Suppose the Zener diode of Figure-4a has a breakdown voltage of 10 V. What are the minimum and maximum Zener currents?

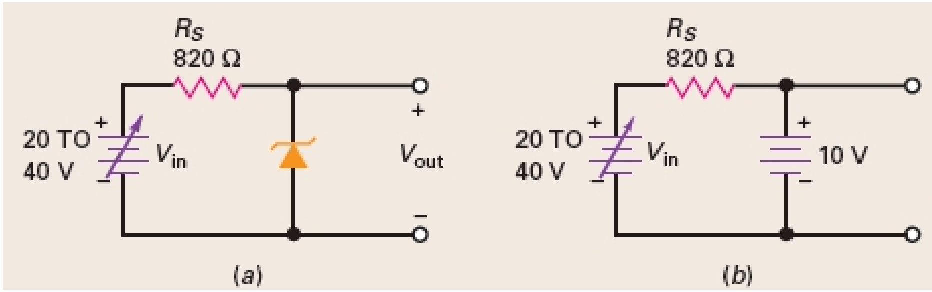


Figure-4 Example-1

SOLUTION

The applied voltage may vary from 20 to 40 V. Ideally, a Zener diode acts like the battery shown in Figure-4b. Therefore, the output voltage is 10 V for any source voltage between 20 and 40 V.

The minimum current occurs when the source voltage is minimum. Visualize 20 V on the left end of the resistor and 10 V on the right end. Then you can see that the voltage across the resistor is 20 V - 10 V, or 10 V. The rest is

Ohm's law:

$$= \frac{}{\mathbf{820\,\Omega}} = \quad .$$

The maximum current occurs when the source voltage is 40 V. In this case, the voltage across the resistor is 30 V, which gives a current of

$$= \frac{}{\mathbf{820\,\Omega}} = \quad .$$

In a voltage regulator like Figure-4a, the output voltage is held constant at 10 V, despite the change in source voltage from 20 to 40 V. The larger source voltage produces more Zener current, but the output voltage holds rock-solid at 10 V.

(If the Zener resistance is included, the output voltage increases slightly when the source voltage increases.)

PRACTICE PROBLEM -1

Using Figure-4, what is the Zener current IS if Vin = 30 V?

1.3 The Loaded Zener Regulator

- Figure-5a shows a loaded Zener regulator, and Figure-5b shows the same circuit with grounds. The Zener diode operates in the breakdown region and holds the load voltage constant. Even if the source voltage changes or the load resistance varies, the load voltage will remain fixed and equal to the Zener voltage.

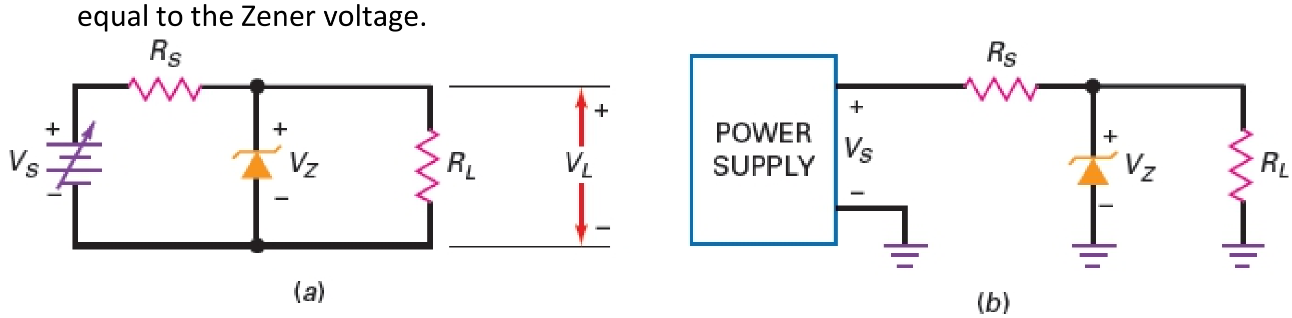


Figure-5 Loaded Zener regulator. (a) Basic circuit; (b) practical circuit

1.3.1 Breakdown Operation

- How can you tell whether the Zener diode of Figure-5 is operating in the breakdown region? Because of the voltage divider, the Thevenin voltage facing the diode is:

$$=\frac{\quad}{+} \text{ ---------------------------------- } \mathit{(2)}$$

- This is the voltage that exists when the Zener diode is disconnected from the circuit. This Thevenin voltage has to be greater than the Zener voltage; otherwise, breakdown cannot occur.

1.3.2 Series Current

- Unless otherwise indicated, in all subsequent discussions we assume that the Zener diode is operating in the breakdown region. In Figure-5, the current through the series resistor is given by:

$$=\frac{V_S - V_Z}{\quad}$$

- This is Ohm's law applied to the current-limiting resistor. It is the same whether or not there is a load resistor. In other words, if you disconnect the load resistor, the current through the series resistor still equals the voltage across the resistor divided by the resistance.

1.3.3 Load Current

- Ideally, the load voltage equals the Zener voltage because the load resistor is in parallel with the Zener diode. As an equation:

$$= \text{ ------------------------------------ } \mathit{(3)}$$

- This allows us to use Ohm's law to calculate the load current:

$$= \frac{\quad}{\quad}\text{------------------------------------- } \mathit{(4)}$$

1.3.4 Zener Current

- With Kirchhoff's current law:

$$= \quad + \text{ ----------------------------- } \mathit{(5)}$$

- The Zener diode and the load resistor are in parallel. The sum of their currents has to equal the total current, which is the same as the current through the series resistor.
- We can rearrange the foregoing equation to get this important formula:

$$\boldsymbol{I_Z = I_S - I_L}\text{---------------------------- } \mathbf{(6)}$$

- This tells you that the Zener current no longer equals the series current, as it does in an unloaded Zener regulator. Because of the load resistor, the Zener current now equals the series current minus the load current.

1.3.5 Zener Effect

- When the breakdown voltage is greater than 6 V, the cause of the breakdown is the avalanche effect. The basic idea is that minority carriers are accelerated to high enough speeds to dislodge other minority carriers, producing a chain or avalanche effect that results in a large reverse current.

- The Zener effect is different. When a diode is heavily doped, the depletion layer becomes very narrow. Because of this, the electric field across the depletion layer (voltage divided by distance) is very intense.
- When the field strength reaches approximately 300,000 V/cm, the field is intense enough to pull electrons out of their valence orbits. The creation of free electrons in this way is called the Zener effect (also known as high-field emission).
- This is distinctly different from the avalanche effect, which depends on high-speed minority carriers dislodging valence electrons.
- When the breakdown voltage is less than 4 V, only the Zener effect occurs. When the breakdown voltage is greater than 6 V, only the avalanche effect occurs. When the breakdown voltage is between 4 and 6 V, both effects are present.
- The Zener effect was discovered before the avalanche effect, so all diodes used in the breakdown region came to be known as Zener diodes. Although you may occasionally hear the term avalanche diode, the name Zener diode is in general use for all breakdown diodes.

Example-2

Is the Zener diode of Figure-6a operating in the breakdown region?

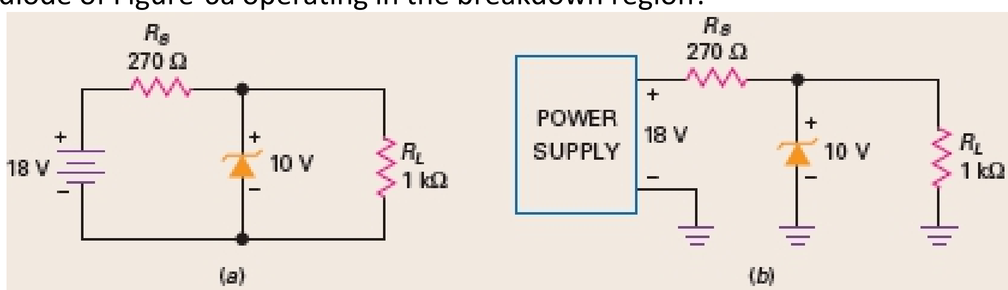


Figure-6 Example-2

SOLUTION

With Eq. (2):

$$= \frac{\mathbf{1}\ \boldsymbol{k}\Omega}{\mathbf{270}\ \Omega + \mathbf{1}\ \boldsymbol{k}\Omega}(\quad) = \quad .$$

Since this Thevenin voltage is greater than the Zener voltage, the Zener diode is operating in the breakdown region.

Example-3

What does the Zener current equal in Figure-6b?

SOLUTION

You are given the voltage on both ends of the series resistor. Subtract the voltages, and you can see that 8 V is across the series resistor. Then Ohm's law gives:

$$= \frac{\quad}{\mathbf{270}\ \Omega} = \quad .$$

Since the load voltage is 10 V, the load current is:

$$= \frac{\quad}{\mathbf{1}\ \boldsymbol{k}\Omega} =$$

The Zener current is the difference between the two currents:

$$\boldsymbol{I_Z = I_S - I_L = 29.6\ mA - 10\ mA = 19.6\ mA}$$

PRACTICE PROBLEM 5-3
Using Figure-6b, change the power supply to 15 V and calculate I_S, I_L, and I_Z.

1.4 Light-Emitting Diodes (LEDs)

- Optoelectronics is the technology that combines optics and electronics. This field includes many devices based on the action of a pn junction. Examples of optoelectronic devices are light-emitting diodes (LEDs), photodiodes, optocouplers, and laser diodes. Our discussion begins with the LED.

1.4.1 Light-Emitting Diode

- LEDs have replaced incandescent lamps in many applications because of the LED's lower energy consumption, smaller size, faster switching and longer lifetime.
- Figure-7 shows the parts of a standard low-power LED. Just as in an ordinary diode, the LED has an anode and a cathode that must be properly biased.
- The outside of the plastic case typically has a flat spot on one side which indicates the cathode side of the LED. The material used for the semiconductor die will determine the LED's characteristics.

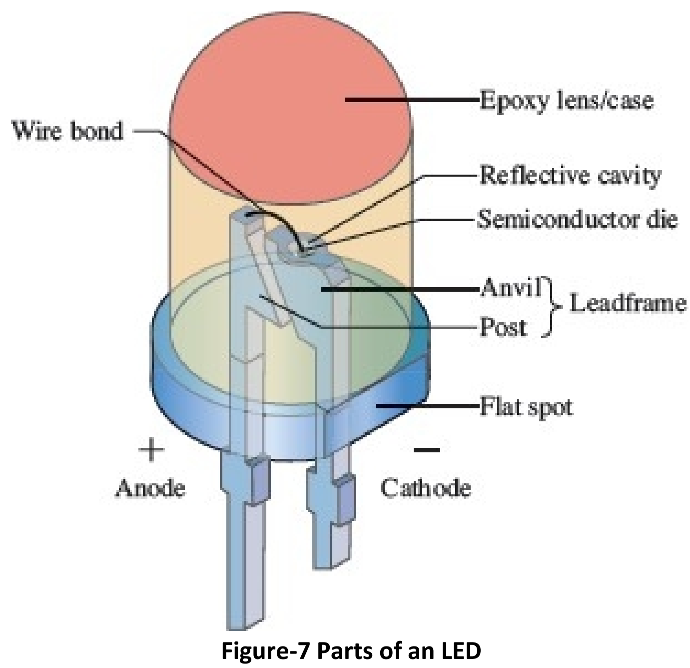


Figure-7 Parts of an LED

- Figure-8a shows a source connected to a resistor and an LED. The outward arrows symbolize the radiated light. In a forward-biased LED, free electrons cross the pn junction and fall into holes.
- As these electrons fall from a higher to a lower energy level, they radiate energy in the form of photons.
- In ordinary diodes, this energy is radiated in the form of heat. But in an LED, the energy is radiated as light. This effect is referred to as electroluminescence.
- The color of the light, which corresponds to the wavelength energy of the photons, is primarily determined by the energy band gap of the semiconductor materials that are used.

- By using elements like gallium, arsenic, and phosphorus, a manufacturer can produce LEDs that radiate red, green, yellow, blue, orange, white or infrared (invisible) light.
- LEDs that produce visible radiation are useful as indicators in applications such as instrumentation panels, internet routers, and so on.
- The infrared LED finds applications in security systems, remote controls, industrial control systems, and other areas requiring invisible radiation.

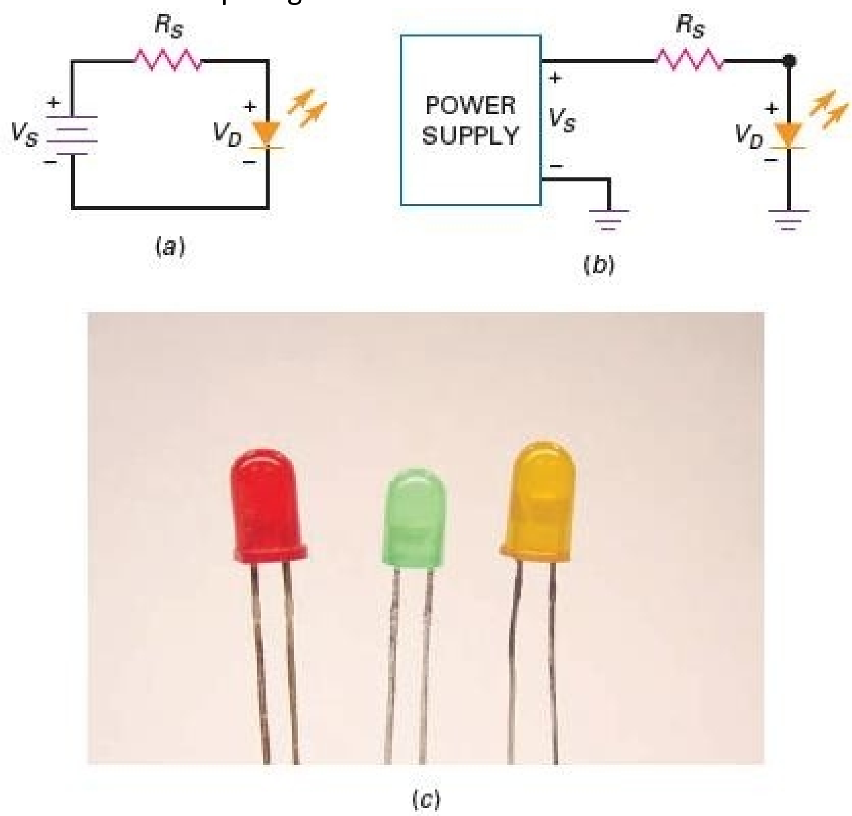


Figure-8 LED indicator. (a) Basic circuit; (b) practical circuit; (c) typical LEDs

1.4.2 LED Voltage and Current

- The resistor of Figure-8b is the usual current-limiting resistor that prevents the current from exceeding the maximum current rating of the diode. Since the resistor has a node voltage of V_S on the left and a node voltage of V_D on the right, the voltage across the resistor is the difference between the two voltages. With Ohm's law, the series current is:

$$I = \frac{V_S - V_D}{} \quad \text{-------------------------} (7)$$

- For most commercially available low-power LEDs, the typical voltage drop is from 1.5 to 2.5 V for currents between 10 and 50 mA. The exact voltage drop depends on the LED current, color, tolerance, along with other factors.
- Unless otherwise specified, we will use a nominal drop of 2 V when troubleshooting or analyzing low-power LED circuits in this book. Figure-8c shows typical low-power LEDs with housings made to help radiate the respective color.

1.4.3 LED Brightness

- The brightness of an LED depends on the current. The amount of light emitted is often specified as its luminous intensity $\boldsymbol{I_V}$ and is rated in candelas (***cd***).
- Low-power LEDs generally have their ratings given in millicandelas (**mcd**). For instance, a TLDR5400 is a red LED with a forward voltage drop of 1.8 V and an $\boldsymbol{I_V}$ rating of 70 mcd at 20 mA. The luminous intensity drops to 3 mcd at a current of 1 mA. When $\boldsymbol{V_S}$ is much greater than $\boldsymbol{V_D}$ in Eq. (7), the brightness of the LED is approximately constant.
- If a circuit like Figure-8b is mass-produced using a TLDR5400, the brightness of the LED will be almost constant if $\boldsymbol{V_S}$ is much greater than $\boldsymbol{V_D}$. If $\boldsymbol{V_S}$ is only slightly more than $\boldsymbol{V_D}$, the LED brightness will vary noticeably from one circuit to the next.
- The best way to control the brightness is by driving the LED with a current source. This way, the brightness is constant because the current is constant.
- When we discuss transistors (they act like current sources), we will show how to use a transistor to drive an LED.

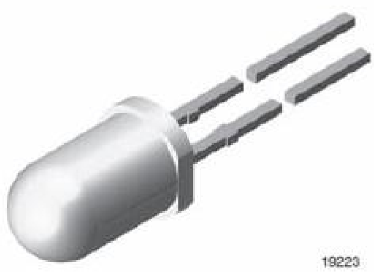
1.4.4 LED Specifications and Characteristics

- A partial datasheet of a standard TLDR5400 5 mm T-1¾ red LED is shown in Figure-9. This type of LED has thru-hole leads and can be used in many applications.

VISHAY
www.vishay.com

TLDR5400
Vishay Semiconductors

High Intensity LED, Ø 5 mm Tinted Diffused Package



APPLICATIONS

- Bright ambient lighting conditions
- Battery powered equipment
- Indoor and outdoor information displays
- Portable equipment
- Telecommunication indicators
- General use

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)
TLDR5400

PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
Reverse voltage (1)		V_R	6	V
DC forward current		I_F	50	mA
Surge forward current	$t_p \leq 10$ µs	I_{FSM}	1	A
Power dissipation		P_V	100	mW
Junction temperature		T_j	100	°C
Operating temperature range		T_{amb}	- 40 to + 100	°C

Note
(1) Driving the LED in reverse direction is suitable for a short term application

OPTICAL AND ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)
TLDR5400, RED

PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Luminous intensity	I_F = 20 mA	I_V	35	70	-	mcd
Luminous intensity	I_F = 1 mA	I_V	-	3	-	mcd
Dominant wavelength	I_F = 20 mA	λ_d	-	648	-	nm
Peak wavelength	I_F = 20 mA	λ_p	-	650	-	nm
Spectral line half width		$\Delta\lambda$	-	20	-	nm
Angle of half intensity	I_F = 20 mA	φ	-	± 30	-	deg
Forward voltage	I_F = 20 mA	V_F	-	1.8	2.2	V
Reverse current	V_R = 6 V	I_R	-	-	10	µA
Junction capacitance	V_R = 0 V, f = 1 MHz	C_j	-	30	-	pF

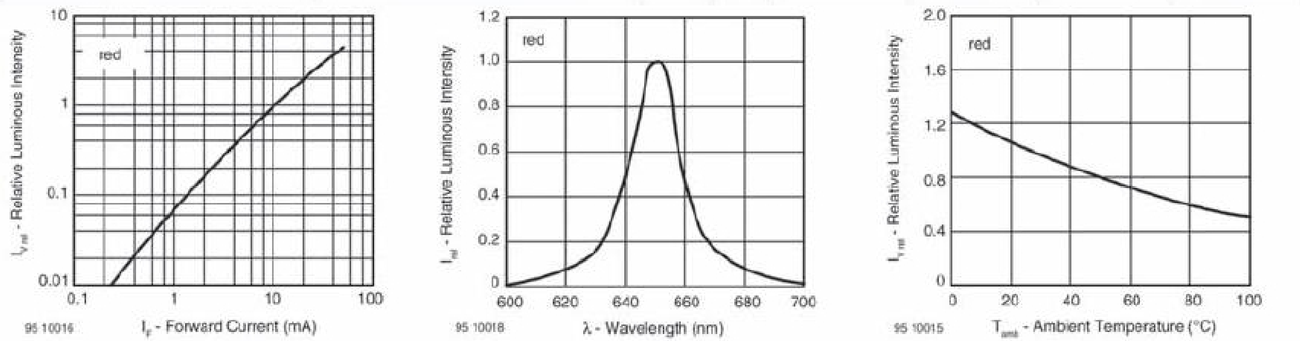


Fig. 6 - Relative Luminous Intensity vs. Forward Current   Fig. 4 - Relative Intensity vs. Wavelength   Fig. 8 - Relative Luminous Intensity vs. Ambient Temperature

Figure-9 TLDR5400 Partial Datasheet. Datasheets courtesy of Vishay Intertechnology

- The Absolute Maximum Rating table specifies that the LED's maximum forward current I_F is 50 mA and its maximum reverse voltage is only 6 V. To extend the life of this device, be sure to use an appropriate safety factor.
- The LED's maximum power rating is 100 mW at an ambient temperature of 25 °C and must be derated at higher temperatures.
- The Optical and Electrical Characteristics table indicates that this LED has a typical luminous intensity I_V of 70 mcd at 20 mA and drops to 3 mcd at 1 mA. Also specified in this table, the dominant wavelength of the red LED is 648 nanometers and the light intensity drops off to approximately 50 percent when viewed at a 30° angle.
- The Relative Luminous Intensity versus Forward Current graph displays how the light intensity is effected by the LED's forward current.
- The graph of Relative Luminous Intensity versus Wavelength visually displays how the luminous intensity reaches a peak at a wavelength of approximately 650 nanometers. What happens when the ambient temperature of the LED increases or decreases?
- The graph of Relative Luminous Intensity versus Ambient Temperature shows that an increase in ambient temperature has a substantial negative effect on the LED's light output. This becomes important when LEDs are used in applications with large temperature variations.

1.4.5 High-Power LEDs

- Typical power dissipation levels of the LEDs discussed up to this point are in the low milliwatt range.

- As an example, the TLDR5400 LED has a maximum power rating of 100 mW and generally operates at approximately 20 mA with a typical forward voltage drop of 1.8 V. This results in a power dissipation of 36 mW.
- High-power LEDs are now available with continuous power ratings of 1 W and above. These power LEDs can operate in the hundreds of mAs to over 1 A of current. An increasing array of applications are being developed including automotive interior, exterior, and forward lighting, architectural indoor and outdoor area lighting, along with digital imaging and display backlighting.
- Figure-10 shows an example of a high-power LED emitter that has the benefit of high luminance for directional applications such as down lights and indoor area lighting.

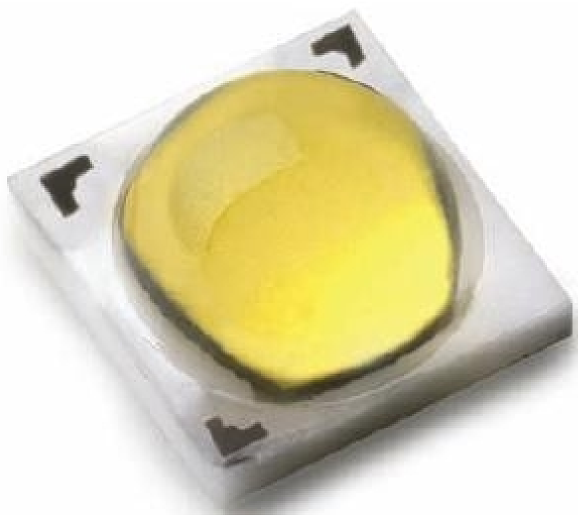


Figure-10 LUXEON TX High-Power Emitter

- LEDs, such as this, use much larger semiconductor die sizes to handle the large power inputs. Because this device will need to dissipate over 1 W of power, it is critical to use proper mounting techniques to a heat sink. Otherwise, the LED will fail within a short period of time.
- Efficiency of a light source is an essential factor in most applications. Because an LED produces both light and heat, it is important to understand how much electrical power is used to produce the light output.
- A term used to describe this is called luminous efficacy. Luminous efficacy of a source is the ratio of output luminous flux (lm) to electrical power (W) given in lm/W.
- Figure-11 shows a partial table for LUXEON TX high-power LED emitters giving their typical performance characteristics.
- Notice that the performance characteristics are rated at 350 mA, 700 mA, and 1,000 mA. With a test current of 700 mA, the LIT2-3070000000000 emitter has a typical luminous flux output of 245 lm.
- At this forward current level, the typical forward voltage drop is 2.80 V. Therefore, the amount of power dissipated is

$$\boldsymbol{P_D = I_F \times V_F = 700\ mA \times 2.8\ V = 1.96\ W}$$

- The efficacy value for this emitter would be found by:

$$= \frac{\quad}{\quad} = \frac{\qquad}{.} = \qquad /$$

- As a comparison, the luminous efficacy of a typical incandescent bulb is 16 lm/W and a compact fluorescent bulb has a typical rating of 60 lm/W. When looking at the overall efficiency of these types of LEDs, it is important to note that electronic circuits, called drivers, are required to control the LED's current and light output. Since these drivers also use electrical power, the overall system efficiency is reduced.

Product Selection Guide for LUXEON TX Emitters, Junction Temperature = 85°C

Table 1.

Typical Performance Characteristics												
Base Part Number	Nominal ANSI CCT	Min CRI	Min Luminous Flux (lm)	Typical Luminous Flux (lm)			Typical Forward Voltage (V)			Typical Efficacy (lm/W)		
		700 mA	700 mA	350 mA	700 mA	1000 mA	350 mA	700 mA	1000 mA	350 mA	700 mA	1000 mA
LIT2-3070000000000	3000K	70	230	135	245	327	2.71	2.80	2.86	142	125	114
LIT2-4070000000000	4000K	70	250	147	269	360	2.71	2.80	2.86	155	137	126
LIT2-5070000000000	5000K	70	260	151	275	369	2.71	2.80	2.86	159	140	129
LIT2-5770000000000	5700K	70	260	151	275	369	2.71	2.80	2.86	159	140	129
LIT2-6570000000000	6500K	70	260	151	275	369	2.71	2.80	2.86	159	140	129
LIT2-2780000000000	2700K	80	200	118	216	289	2.71	2.80	2.86	124	110	101
LIT2-3080000000000	3000K	80	210	124	227	304	2.71	2.80	2.86	131	116	106
LIT2-3580000000000	3500K	80	220	130	238	319	2.71	2.80	2.86	137	121	112
LIT2-4080000000000	4000K	80	230	136	247	331	2.71	2.80	2.86	143	126	116
LIT2-5080000000000	5000K	80	230	135	247	332	2.71	2.80	2.86	142	126	116

Notes for Table 1:

1. Philips Lumileds maintains a tolerance of ± 6.5% on luminous flux and ± 2 on CRI measurements.

Courtesy of Philips Lumileds

Figure-11 Partial data sheet for LUXEON TX emitters

1.5 Other Optoelectronic Devices

- Besides standard low-power through high-power LEDs, there are many other optoelectronic devices which are based on the photonic action of a pn junction.
- These devices are used to source, detect and control light in an enormous variety of electronic applications.

1.5.1 Seven-Segment Display

- Figure-12a shows a seven-segment display. It contains seven rectangular LEDs (A through G). Each LED is called a segment because it forms part of the character being displayed. Figure-12b is a schematic diagram of the seven-segment display. External series resistors are included to limit the currents to safe levels.
- By grounding one or more resistors, we can form any digit from 0 through 9. For instance, by grounding A, B, and C, we get a 7. Grounding A, B, C, D, and G produces a 3.
- A seven-segment display can also display capital letters A, C, E, and F, plus lowercase letters b and d. Microprocessor trainers often use seven-segment displays that show all digits from 0 through 9, plus A, b, C, d, E, and F.

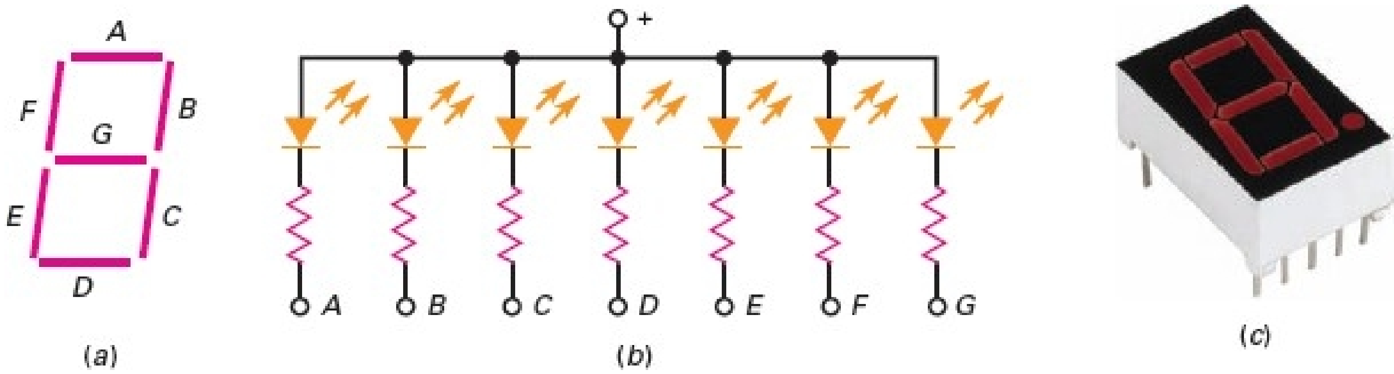


Figure-12 Seven-segment indicator. (a) Physical layout of segments; (b) schematic diagram; (c) Actual display with decimal point. Courtesy of Fairchild Semiconductor

- The seven-segment indicator of Figure-12b is referred to as the common-anode type because all anodes are connected together. Also available is the common-cathode type, in which all cathodes are connected together.
- Figure-12c shows an actual seven-segment display with pins for fitting into a socket or for soldering to a printed-circuit board. Notice the extra dot segment used for a decimal point.

1.5.2 Photodiode

- As previously discussed, one component of reverse current in a diode is the flow of minority carriers. These carriers exist because thermal energy keeps dislodging valence electrons from their orbits, producing free electrons and holes in the process.
- The lifetime of the minority carriers is short, but while they exist, they can contribute to the reverse current. When light energy bombards a pn junction, it can dislodge valence electrons. The more light striking the junction, the larger the reverse current in a diode.
- A photodiode has been optimized for its sensitivity to light. In this diode, a window lets light pass through the package to the junction. The incoming light produces free electrons and holes. The stronger the light, the greater the number of minority carriers and the larger the reverse current.
- Figure-13 shows the schematic symbol of a photodiode. The arrows represent the incoming light. Especially important, the source and the series resistor reverse-bias the photodiode. As the light becomes brighter, the reverse current increases. With typical photodiodes, the reverse current is in the tens of microamperes.

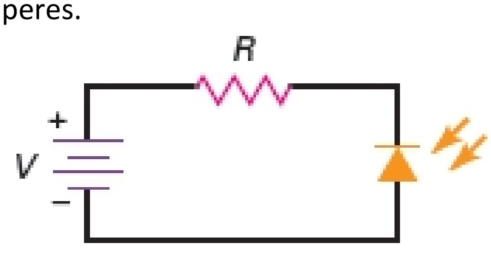


Figure-13 Incoming light increases reverse current in photodiode

1.5.3 Optocoupler

- An Optocoupler (also called an optoisolator) combines an LED and a photodiode in a single package. Figure-14 shows an Optocoupler.

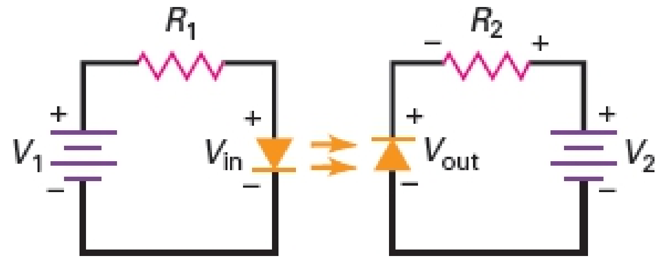


Figure-14 Optocoupler combines an LED and a photodiode

- It has an LED on the input side and a photodiode on the output side. The left source voltage and the series resistor set up a current through the LED. Then the light from the LED hits the photodiode, and this sets up a reverse current in the output circuit.
- This reverse current produces a voltage across the output resistor. The output voltage then equals the output supply voltage minus the voltage across the resistor.
- When the input voltage is varying, the amount of light is fluctuating. This means that the output voltage is varying in step with the input voltage. This is why the combination of an LED and a photodiode is called an Optocoupler.
- The device can couple an input signal to the output circuit. Other types of optocouplers use phototransistors, photo-thyristors, and other photo devices in their output circuit side.
- The key advantage of an Optocoupler is the electrical isolation between the input and output circuits. With an Optocoupler, the only contact between the input and the output is a beam of light. Because of this, it is possible to have an insulation resistance between the two circuits in the thousands of mega-ohms.
- Isolation like this is useful in high-voltage applications in which the potentials of the two circuits may differ by several thousand volts.

1.6 The Schottky Diode

- As frequency increases, the action of small-signal rectifier diodes begins to deteriorate. They are no longer able to switch off fast enough to produce a well- defined half-wave signal. The solution to this problem is the Schottky diode.
- Before describing this special-purpose diode, let us look at the problem that arises with ordinary small-signal diodes.

1.6.1 Charge Storage

- Figure-15a shows a small-signal diode, and Figure-15b illustrates its energy bands. As you can see, conduction-band electrons have diffused across the junction and traveled into the p region before recombining (path A).
- Similarly, holes have crossed the junction and traveled into the n region before recombination occurs (path B). The greater the lifetime, the farther the charges can travel before recombination occurs.
- For instance, if the lifetime equals 1 μs, free electrons and holes exist for an average of 1 μs before recombination takes place. This allows the free electrons to penetrate deeply into the p region, where they remain temporarily stored at the higher energy band.

- Similarly, the holes penetrate deeply into the n region, where they are temporarily stored in the lower energy band.

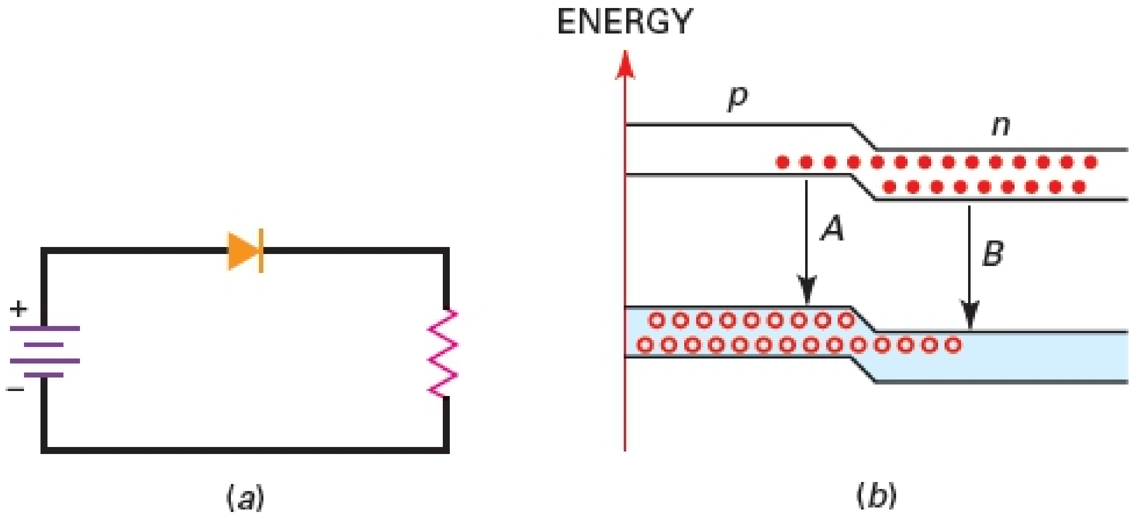


Figure-15 Charge storage. (a) Forward bias creates stored charges; (b) stored charges in high and low energy bands

- The greater the forward current, the larger the number of charges that have crossed the junction. The greater the lifetime, the deeper the penetration of these charges and the longer the charges remain in the high and low energy bands.
- The temporary storage of free electrons in the upper energy band and holes in the lower energy band is referred to as charge storage.

1.6.2 Charge Storage Produces Reverse Current

- When you try to switch a diode from on to off, charge storage creates a problem. Why? Because if you suddenly reverse-bias a diode, the stored charges will flow in the reverse direction for a while.
- The greater the lifetime, the longer these charges can contribute to reverse current. For example, suppose a forward-biased diode is suddenly reverse biased, as shown in Figure-16a.

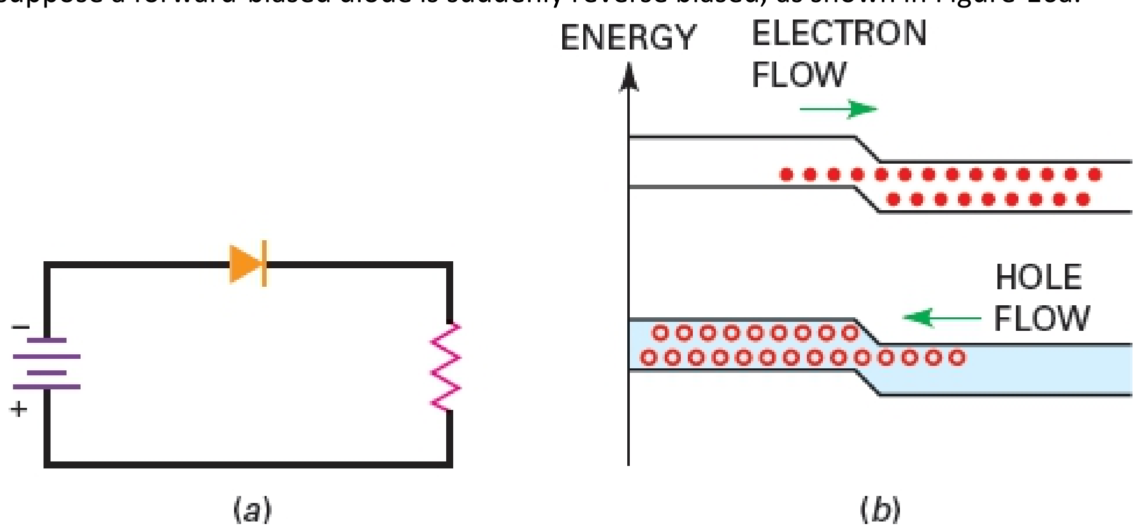


Figure-16 Stored charges allow a brief reverse current. (a) Sudden reversal of source voltage; (b) flow of stored charges in reverse direction

- Then a large reverse current can exist for a while because of the flow of stored charges in Figure-16b. Until the stored charges either cross the junction or recombine, the reverse current will continue.

1.6.3 Reverse Recovery Time

- The time it takes to turn off a forward-biased diode is called the reverse recovery time t_{rr}. The conditions for measuring t_{rr} vary from one manufacturer to the next.
- As a guide, t_{rr} is the time it takes for the reverse current to drop to 10 percent of the forward current.
- For instance, the 1N4148 has a t_{rr} of 4 ns. If this diode has a forward current of 10 mA and it is suddenly reverse biased, it will take approximately 4 ns for the reverse current to decrease to 1 mA. Reverse recovery time is so short in small-signal diodes that you don't even notice its effect at frequencies below 10 MHz or so. It's only when you get well above 10 MHz that you have to take t_{rr} into account.

1.6.4 Poor Rectification at High Frequencies

- What effect does reverse recovery time have on rectification? Take a look at the half-wave rectifier shown in Figure-17a.

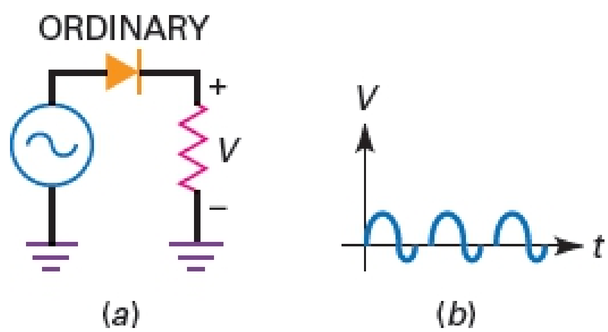


Figure-17 Stored charges degrade rectifier behavior at high frequencies. (a) Rectifier circuit with ordinary small-signal diode; (b) tails appear on negative half-cycles at higher frequencies

- At low frequencies, the output is a half-wave rectified signal. As the frequency increases well into megahertz, however, the output signal begins to deviate from the half-wave shape, as shown in
- Figure-17b.
- Some reverse conduction (called tails) is noticeable near the beginning of the reverse half-cycle. The problem is that the reverse recovery time has become a significant part of the period, allowing conduction during the early part of the negative half-cycle.
- For instance, if t_{rr} = 4 ns and the period is 50 ns, the early part of the reverse half-cycle will have tails similar to those shown in Figure-17b. As the frequency continues to increase, the rectifier becomes useless.

1.6.5 Eliminating Charge Storage

- The solution to the problem of tails is a special-purpose device called a Schottky diode. This kind of diode uses a metal such as gold, silver, or platinum on one side of the junction and doped silicon (typically n-type) on the other side.

- Because of the metal on one side of the junction, the Schottky diode has no depletion layer. The lack of a depletion layer means that there are no stored charges at the junction.
- When a Schottky diode is unbiased, free electrons on the n side are in smaller orbits than are the free electrons on the metal side. This difference in orbit size is called the Schottky barrier, approximately 0.25 V.
- When the diode is forward biased, free electrons on the n side can gain enough energy to travel in larger orbits. Because of this, free electrons can cross the junction and enter the metal, producing a large forward current. Since the metal has no holes, there is no charge storage and no reverse recovery time.

1.6.6 Hot-Carrier Diode

- The Schottky diode is sometimes called a hot-carrier diode. This name came about as follows. Forward bias increases the energy of the electrons on the n side to a higher level than that of the electrons on the metal side of the junction.
- This increase in energy inspired the name hot carrier for the n-side electrons. As soon as these high-energy electrons cross the junction, they fall into the metal, which has a lower-energy conduction band.

1.6.7 High-Speed Turnoff

- The lack of charge storage means that the Schottky diode can switch off faster than an ordinary diode can. In fact, a Schottky diode can easily rectify frequencies above 300 MHz. When it is used in a circuit like Figure-18a, the Schottky diode produces a perfect half-wave signal like Figure-18b even at frequencies above 300 MHz.

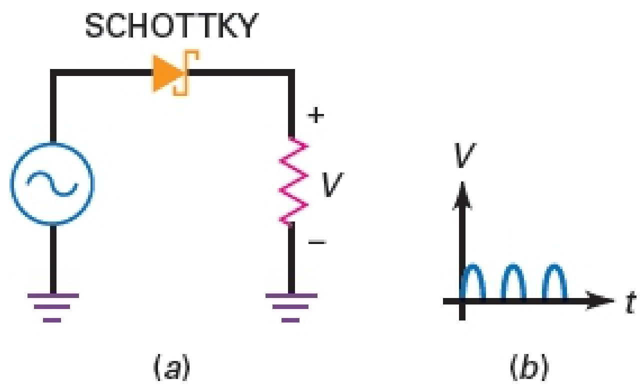


Figure-18 Schottky diodes eliminate tails at high frequencies. (a) Circuit with Schottky diode; (b) half-wave signal at 300 MHz

- Figure-18a shows the schematic symbol of a Schottky diode. Notice the cathode side. The lines look like a rectangular S, which stands for Schottky. This is how you can remember the schematic symbol.

1.6.8 Applications

- The most important application of Schottky diodes is in digital computers. The speed of computers depends on how fast their diodes and transistors can turn on and off. This is where the Schottky diode comes in.

- Because it has no charge storage, the Schottky diode has become the backbone of low-power Schottky TTLs, a group of widely used digital devices.
- A final point. Since a Schottky diode has a barrier potential of only 0.25 V, you may occasionally see it used in low-voltage bridge rectifiers because you subtract only 0.25 V instead of the usual 0.7 V for each diode when using the second approximation. In a low-voltage supply, this lower diode voltage drop is an advantage.

1.7 The Varactor

- The Varactor (also called the voltage-variable capacitance, varicap, epicap, and tuning diode) is widely used in television receivers, FM receivers, and other communications equipment because it can be used for electronic tuning.

1.7.1 Basic Idea

- In Figure-19a, the depletion layer is between the p region and the n region. The p and n regions are like the plates of a capacitor, and the depletion layer is like the dielectric.
- When a diode is reverse biased, the width of the depletion layer increases with the reverse voltage. Since the depletion layer gets wider with more reverse voltage, the capacitance becomes smaller.
- It's as though you moved apart the plates of a capacitor. The key idea is that capacitance is controlled by reverse voltage.

1.7.2 Equivalent Circuit and Symbol

- Figure-19b shows the ac-equivalent circuit for a reverse-biased diode. In other words, as far as an ac signal is concerned, the Varactor acts the same as a variable capacitance.
- Figure-19c shows the schematic symbol for a Varactor. The inclusion of a capacitor in series with the diode is a reminder that a Varactor is a device that has been optimized for its variable-capacitance properties.

1.7.3 Capacitance Decreases at Higher Reverse Voltages

- Figure-19d shows how the capacitance varies with reverse voltage. This graph shows that the capacitance gets smaller when the reverse voltage gets larger.

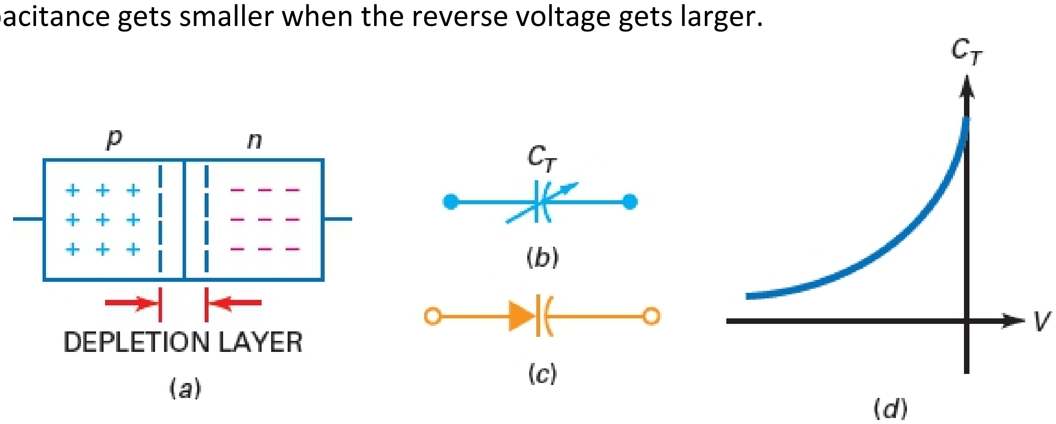


Figure-19 Varactor.(a) Doped regions are like capacitor plates separated by a dielectric; (b) ac-equivalent circuit; (c) schematic symbol; (d) graph of capacitance versus reverse voltage

- The really important idea here is that reverse dc voltage controls capacitance. How is a Varactor used? It is connected in parallel with an inductor to form a parallel resonant circuit. This circuit has only one frequency at which maximum impedance occurs. This frequency is called the resonant frequency.
- If the dc reverse voltage to the Varactor is changed, the resonant frequency is also changed. This is the principle behind electronic tuning of a radio station, a TV channel, and so on.

1.7.4 Varactor Characteristics

- Because the capacitance is voltage controlled, Varactors have replaced mechanically tuned capacitors in many applications such as television receivers and automobile radios. Data sheets for Varactors list a reference value of capacitance measured at a specific reverse voltage, typically 23 V to 24 V.
- Figure-20 shows a partial data sheet for an MV209 Varactor diode. It lists a reference capacitance
- Ct of 29 pF at ‑3 V.

	C_t, Diode Capacitance V_R = 3.0 Vdc, f = 1.0 MHz pF			Q, Figure of Merit V_R = 3.0 Vdc f = 50 MHz	C_R, Capacitance Ratio C_3/C_{25} f = 1.0 MHz (Note 1)	
Device	Min	Nom	Max	Min	Min	Max
MMBV109LT1, MV209	26	29	32	200	5.0	6.5

1. C_R is the ratio of C_t measured at 3 Vdc divided by C_t measured at 25 Vdc.

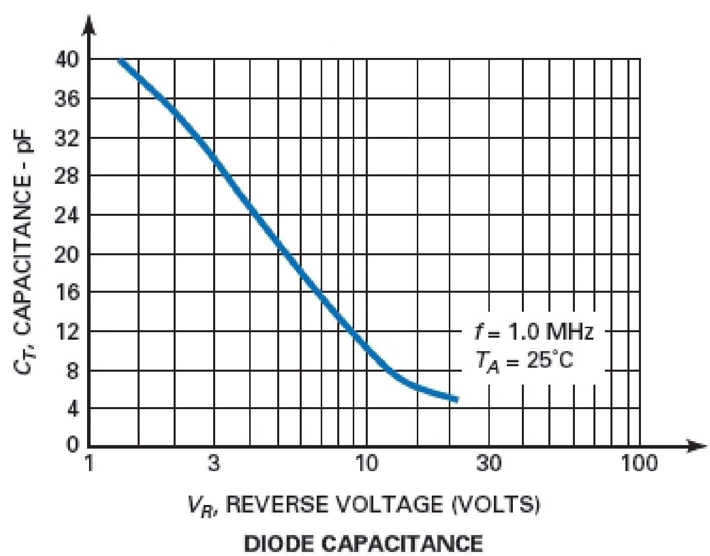


Figure-20 MV209 Partial Data Sheet. (Used with permission from SCILLC dba ON Semiconductor.)

- In addition to providing the reference value of capacitance, data sheets normally list a capacitance ratio CR, or tuning range associated with a voltage range.
- For example, along with the reference value of 29 pF, the data sheet of an MV209 shows a minimum capacitance ratio of 5:1 for a voltage range of ‑3 V to ‑25 V.

- This means that the capacitance, or tuning range, decreases from 29 to 6 pF when the voltage varies from ‑3 V to ‑25 V. The tuning range of a Varactor depends on the doping level.
- For instance, Figure-21a shows the doping profile for an abrupt-junction diode (the ordinary type of diode).

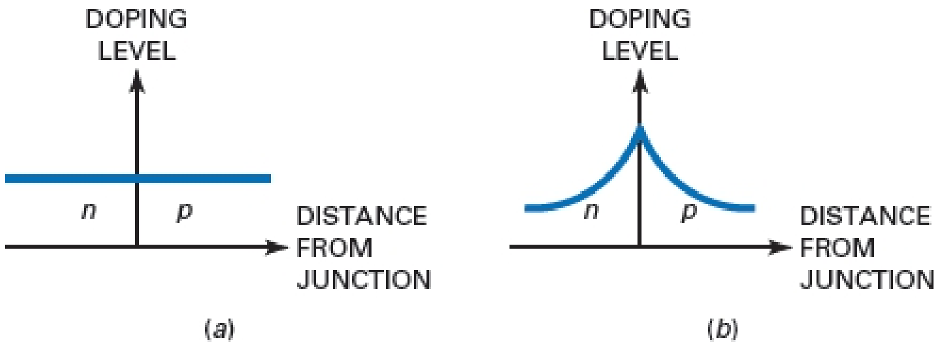


Figure-21 Doping profiles. (a) Abrupt junction; (b) hyper abrupt junction

- The profile shows that the doping is uniform on both sides of the junction. The tuning range of an abrupt-junction diode is between 3:1 and 4:1. To get larger tuning ranges, some Varactors have a hyper abrupt junction, one whose doping profile looks like Figure-21b.
- This profile tells us that the doping level increases as we approach the junction. The heavier doping produces a narrower depletion layer and a larger capacitance.
- Furthermore, changes in reverse voltage have more pronounced effects on capacitance. A hyper abrupt Varactor has a tuning range of about 10:1, enough to tune an AM radio through its frequency range of 535 to 1605 kHz. (Note: You need a 10:1 range because the resonant frequency is inversely proportional to the square root of capacitance.)

1.8 Other Diodes

- Besides the special-purpose diodes discussed so far, there are others you should know about. Because they are so specialized, only a brief description follows.

1.8.1 Varistors

- Lightning, power-line faults, and transients can pollute the ac line voltage by superimposing dips and spikes on the normal 120 V rms. Dips are severe voltage drops lasting microseconds or less. Spikes are very brief over voltages up to 2000 V or more.
- In some equipment, filters are used between the power line and the primary of the transformer to eliminate the problems caused by ac line transients. One of the devices used for line filtering is the Varistor (also called a transient suppressor).
- This semiconductor device is like two back-to-back Zener diodes with a high breakdown voltage in both directions. Varistors are commercially available with breakdown voltages from 10 to 1000 V. They can handle peak transient currents in the hundreds or thousands of amperes.
- For instance, a V130LA2 is a Varistor with a breakdown voltage of 184 V (equivalent to 130 V rms) and a peak current rating of 400 A. Connect one of these across the primary winding as shown in Figure-22, and you don’t have to worry about spikes. The Varistor will clip all spikes at the 184-V level and protect your power supply.

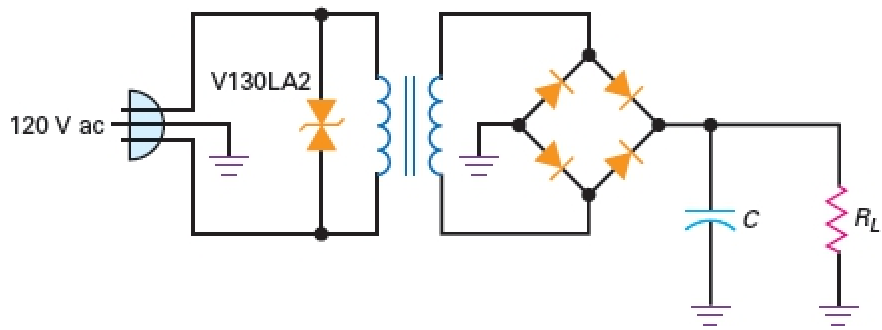


Figure-22 Varistor protects primary from ac line transients

1.8.2 Tunnel Diodes

- By increasing the doping level of a back diode, we can get breakdown to occur at 0 V. Furthermore, the heavier doping distorts the forward curve, as shown in Figure-23a.

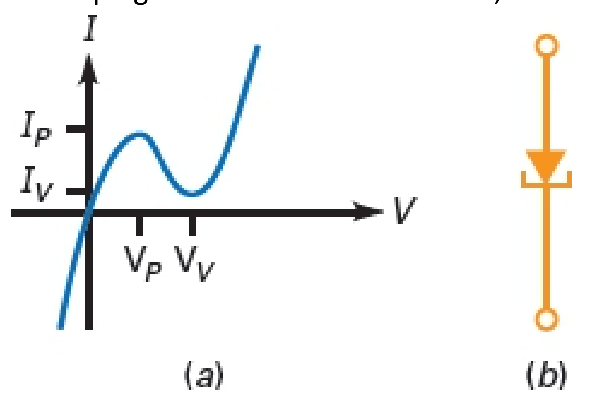


Figure-23 Tunnel diode. (a) Breakdown occurs at 0 V; (b) schematic symbol

- A diode with this graph is called a tunnel diode. Figure-23b shows the schematic symbol for a tunnel diode. This type of diode exhibits a phenomenon known as negative resistance.
- This means that an increase in forward voltage produces a decrease in forward current, at least over the part of the graph between V_P and V_V. The negative resistance of tunnel diodes is useful in high-frequency circuits called oscillators.
- These circuits are able to generate a sinusoidal signal, similar to that produced by an ac generator. But unlike the ac generator that converts mechanical energy to a sinusoidal signal, an oscillator converts dc energy to a sinusoidal signal.

1.8.3 PIN Diodes

- A PIN diode is a semiconductor device that operates as a variable resistor at RF and microwave frequencies. Figure-24a shows its construction. It consists of an intrinsic (pure) semiconductor material sandwiched between p-type and n-type materials.
- Figure-24b shows the schematic symbol for the PIN diode. When the diode is forward biased, it acts like a current-controlled resistance.
- Figure-24c shows how the PIN diode's series resistance RS decreases as its forward current increases. When reverse biased, the PIN diode acts like a fixed capacitor. The PIN diode is widely used in modulator circuits for RF and microwave applications.

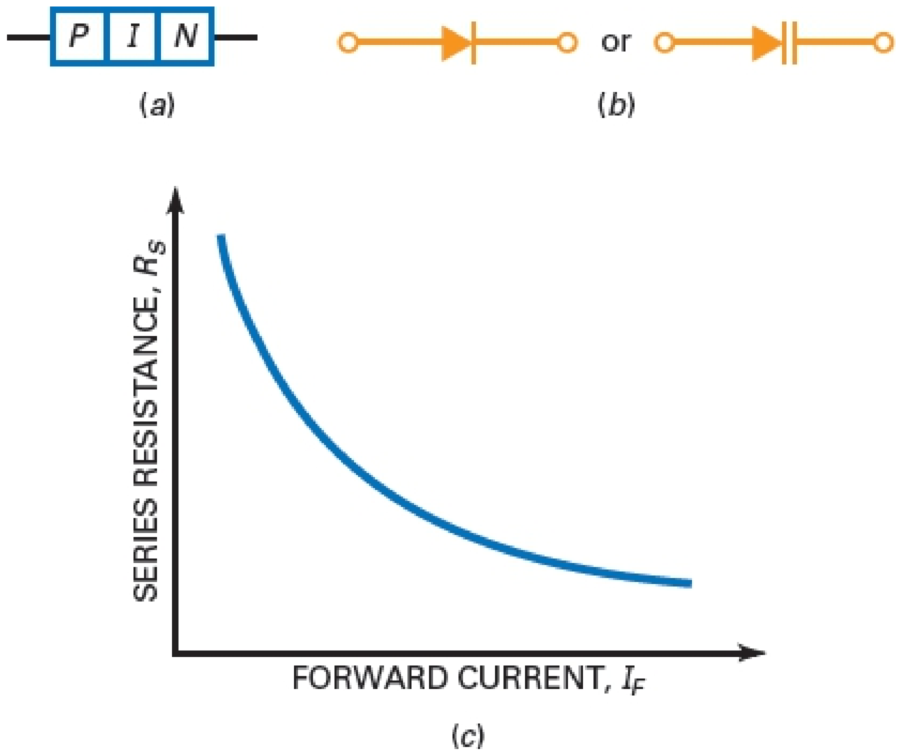


Figure-24 PIN diode. (a) Construction; (b) schematic symbol; (c) series resistance

1.9 Solar Cells

- In recent years, there has been increasing interest in the solar cell as an alternative source of energy. When we consider that the power density received from the sun at sea level is about 100 mW/cm^2 ($1\ kW/m^2$), it is certainly an energy source that requires further research and development to maximize the conversion efficiency from solar to electrical energy.
- The basic construction of a silicon p-n junction solar cell appears in figure-25. As shown in the top view, every effort is made to ensure that the surface area perpendicular to the sun is a maximum.

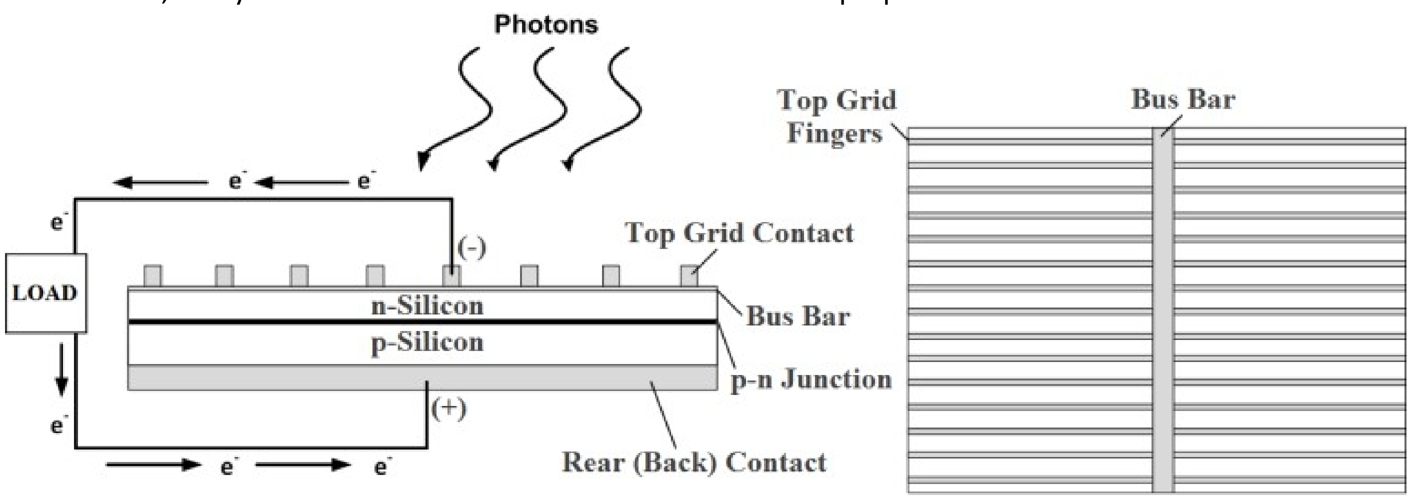


Figure-25 Basic construction of a silicon p-n junction solar cell

- Also, note that the metallic conductor connected to the p-type material and the thickness of the p-type material are such that they ensure that a maximum number of photons of light energy will reach the junction.
- A photon of light energy in this region may collide with a valence electron and impart to it sufficient energy to leave the parent atom. The result is a generation of free electrons and holes.
- This phenomenon will occur on each side of the junction. In the p-type material, the newly generated electrons are minority carriers and will move rather freely across the junction as explained for the basic p-n junction with no applied bias.
- A similar discussion is true for the holes generated in the n-type material. The result is an increase in the minority-carrier flow, which is opposite in direction to the conventional forward current of a p-n junction.
- This increase in reverse current is shown in Figure-26. Since V = 0 anywhere on the vertical axis and represents a short-circuit condition, the current at this intersection is called the short-circuit current and is represented by the notation $\boldsymbol{I_{SC}}$.
- Under open-circuit conditions (id = 0), the photovoltaic voltage $\boldsymbol{V_{OC}}$ will result.

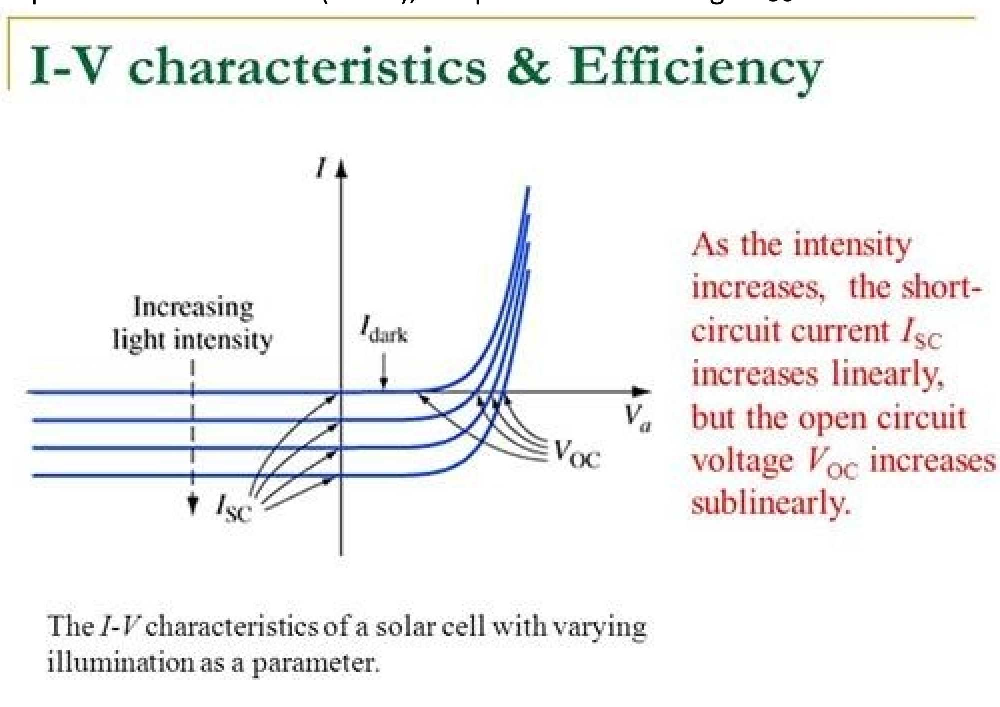


Figure-26 Short-circuit current and open-circuit voltage versus light intensity for a solar cell

- This is a logarithmic function of the illumination, as shown in Figure-27. VOC is the terminal voltage of a battery under no-load (open-circuit) conditions.
- Note, however, in the same figure that the short-circuit current is a linear function of the illumination. That is, it will double for the same increase in illumination (fC1 and 2fC1 in Figure-27) while the change in $\boldsymbol{V_{OC}}$ is less for this region.
- The major increase in $\boldsymbol{V_{OC}}$ occurs for lower-level increases in illumination. Eventually, a further increase in illumination will have very little effect on $\boldsymbol{V_{OC}}$, although $\boldsymbol{I_{SC}}$ will increase, causing the power capabilities to increase.

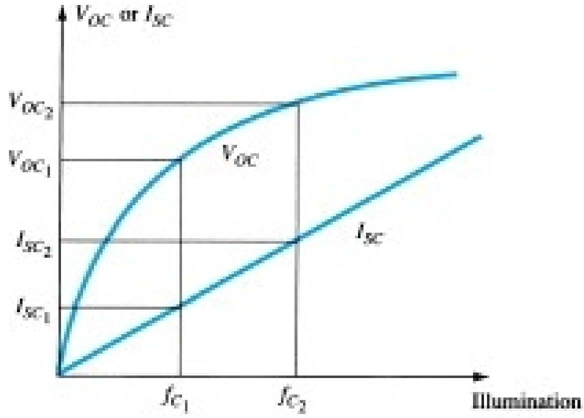


Figure-27 V_{OC} and I_{SC} versus illumination for a solar cell

- Selenium and silicon are the most widely used materials for solar cells, although gallium arsenide, indium arsenide, and cadmium sulfide, among others, are also used.

1.10 Phototransistors

- The fundamental behavior of photoelectric devices was introduced earlier with the description of the photodiode. This discussion will now be extended to include the phototransistor, which has a photosensitive collector–base p-n junction.
- The current induced by photoelectric effects is the base current of the transistor. If we assign the notation ***I*λ** for the photo induced base current, the resulting collector current, on an approximate basis, is

$$= \quad \text{------------------------------} \; \textit{(8)}$$

- A representative set of characteristics for a phototransistor is provided in Figure-28 with the symbolic representation of the device. Note the similarities between these curves and those of a typical bipolar transistor.

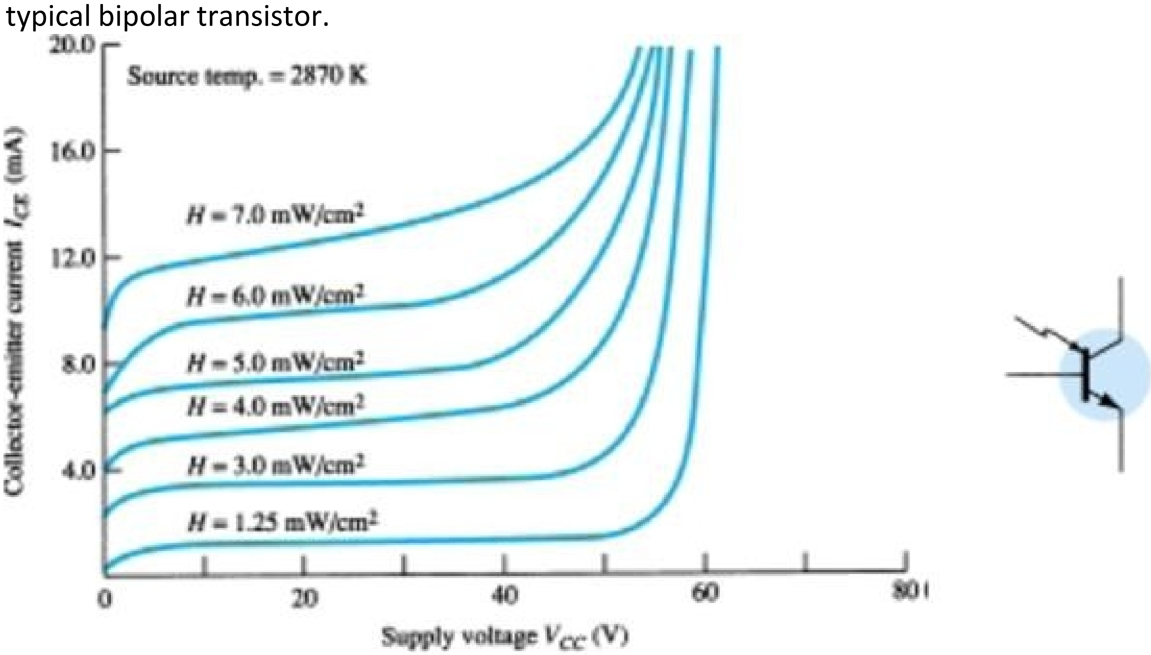


Figure-28 Phototransistor: collector characteristics (MRD300) and symbol. (Courtesy Motorola, Inc.)

- As expected, an increase in light intensity corresponds with an increase in collector current. To develop a greater degree of familiarity with the light-intensity unit of measurement, milliwatts per square centimeter, a curve of base current versus flux density appears in Figure-29.

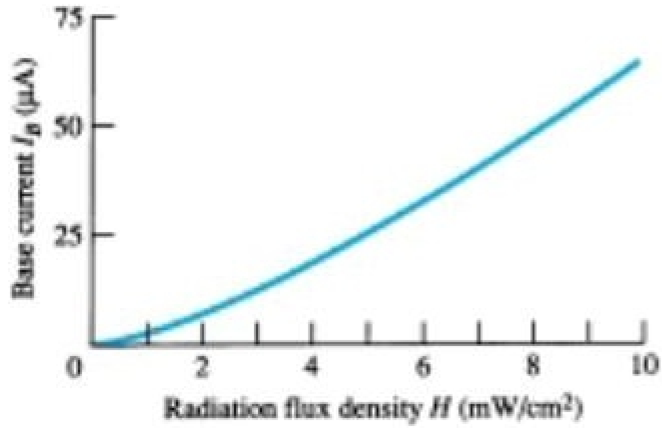


Figure-29 Base current versus flux density

- Note the exponential increase in base current with increasing flux density.
- Some of the areas of application for the phototransistor include punch-card readers, computer logic circuitry, lighting control (highways, etc.), level indication, relays, and counting systems.
- A high-isolation AND gate is shown in Figure-30 using three phototransistors and three LEDs (light-emitting diodes). The LEDs are semiconductor devices that emit light at an intensity determined by the forward current through the device.

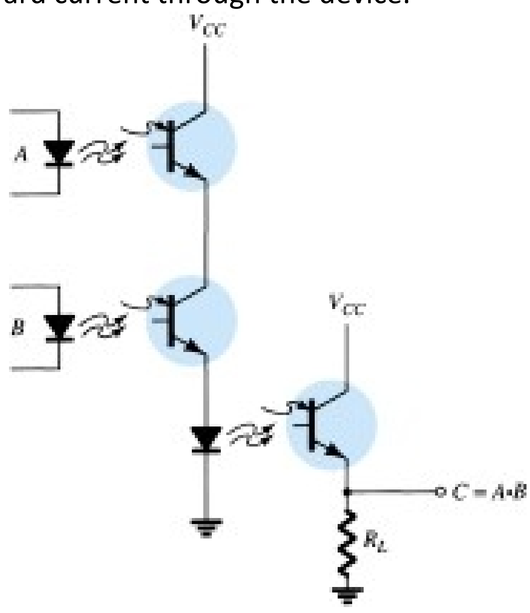


Figure-30 High-isolation AND gate employing phototransistors and light-emitting diodes (LEDs)

- With the aid of discussions in Chapter 1, the circuit behavior should be relatively easy to understand. The terminology high isolation simply refers to the lack of an electrical connection between the input and output circuits.

1.11 Sixteen-segment display

- A sixteen-segment display (SISD) is a type of display based on 16 segments that can be turned on or off according to the graphic pattern to be produced. Figure-31 shows sixteen segment display. It is an extension of the more common seven-segment display, adding four diagonal and two vertical segments and splitting the three horizontal segments in half.
- Other variants include the fourteen-segment display which does not split the top or bottom horizontal segments, and the twenty two-segment display that allows lower-case characters with descenders.
- Often a character generator is used to translate 7-bit ASCII character codes to the 16 bits that indicate which of the 16 segments to turn on or off.
- Sixteen-segment displays were originally designed to display alphanumeric characters (Latin letters and Arabic digits). Later they were used to display Thai numerals and Persian characters. Non-electronic displays using this pattern existed as early as 1902.
- Before the advent of inexpensive dot-matrix displays, sixteen and fourteen-segment displays were some of the few options available for producing alphanumeric characters on calculators and other embedded systems. However, they are still sometimes used on VCRs, car stereos, microwave ovens, telephone Caller ID displays, and slot machine readouts
- Sixteen-segment displays may be based on one of several technologies, the three most common optoelectronics types being LED, LCD and VFD. The LED variant is typically manufactured in single or dual character packages, to be combined as needed into text line displays of a suitable length for the application in question.

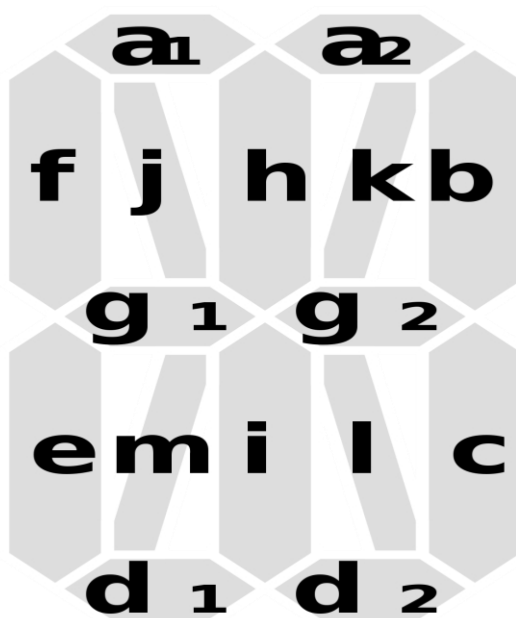


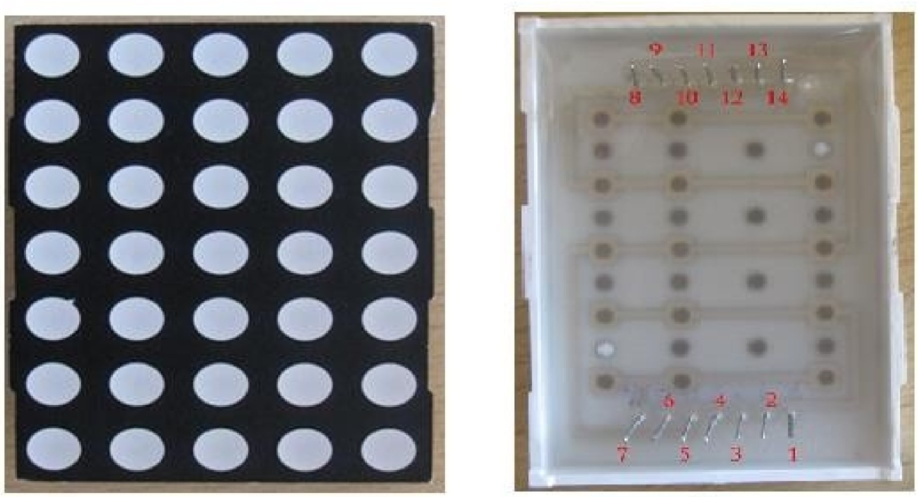
Figure-31 Sixteen segment display

- As with seven and fourteen-segment displays, a decimal point and/or comma may be present as an additional segment, or pair of segments; the comma (used for triple-digit groupings or as a decimal separator in many regions) is commonly formed by combining the decimal point with a closely 'attached' leftwards-descending arc-shaped segment.

- This way, a point or comma may be displayed between character positions instead of occupying a whole position by itself, which would be the case if employing the bottom middle vertical segment as a point and the bottom left diagonal segment as a comma.
- Such displays were very common on pinball machines for displaying the score and other information, before the widespread use of dot-matrix display panels.

1.12 Dot-matrix LED display

- A dot-matrix display is an electronic digital display device that displays information on machines, clocks and watches, public transport departure indicators and many other devices requiring a simple display device of limited resolution.
- The display consists of a dot matrix of lights or mechanical indicators arranged in a rectangular configuration (other shapes are also possible, although not common) such that by switching on or off selected lights, text or graphics can be displayed. A dot matrix controller converts instructions from a processor into signals which turns on or off lights in the matrix so that the required display is produced.
- Light emitting diodes aligned in a form of matrix constitute a dot matrix display. It is commonly used to display time, temperature, news updates and many more on digital billboards.
- Dot Matrix Display is manufactured in various dimensions like 5x7, 8x9, 128x16, 128x32 and 128x64 where the numbers represent LEDs in rows and columns, respectively.
- Arrangement of the LEDs in the matrix pattern is made in either of the two ways: row anode-column cathode or row cathode-column anode.
- In row anode-column cathode pattern, the entire row is anode while all columns serve as cathode and vice-versa pattern is there in row cathode-column anode. LED wafers are glued to the bottom of the segments and glow when powered ON.
- The interesting part is that 35 LEDs are controlled by using a combination of 14 pins. Conductor tracks are laid all over the board to power each LED.



(a) (b)

Figure-32 5x7 LED Dot-matrix display (a) Front view; (b) Rear view

- Figure-32 shows a 5x7 LED Dot-matrix display with front and rear views. A total of 35 LEDs are visible as dots on the front of the dot matrix display. The LEDs are illuminated when their respective terminals are powered.
- Back side of the display shows the in-built tracks and the pins. A total of 14 pins serve as a terminal for 35 LED's. Numbering of the pins varies depending upon the manufacturer. In this version of dot matrix display, 13, 3, 4, 11, 10 & 6 are the pin terminals for the column and rest for the row.

1.13 Question Bank

1) Explain the construction and working of LED.
2) Explain V-I characteristic of Zener diode.
3) **Describe Zener diode as a voltage regulator. (MIMP)**
4) Write a short note on photo diode.
5) **Write a short note on solar cell. (MIMP)**
6) Write a short note on PIN diode.
7) Write a short note on Varactor diode.
8) Write a short note on Schottky diode.
9) Write a short note on Tunnel diode.
10) Write a short note on Variastor.
11) Write a short note on seven segment display.
12) Write a short note on sixteen segment display.
13) Write a short note on dot-matrix LED display.
14) Write a short note on Phototransistor.
15) **Write a short note on Optocoupler. (MIMP)**