

Chapter 3

pn Junction Diodes and Applications

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Electronics: Principles, Concepts and Practices

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Intro

Introduction

- In this chapter, the student is introduced to an important semiconductor device, the **pn junction diode**.
- First, we shall discuss the pn junction in thermal equilibrium.
- The next step is to force this junction out of equilibrium by applying a voltage called biasing.
- Thereafter, the different equivalent circuits that model a diode in circuit analysis will be introduced.
- We shall conclude by studying some applications of this simple pn junction device.

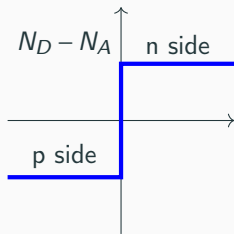


pn Junction at Equilibrium

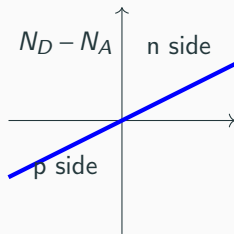
pn Junction

In the extrinsic material of interest, a doping variation in which the semiconductor changes over a relatively short distance from a p-type to an n-type is known as **pn junction**. In other words, the p-type material is brought in close contact with the n-type material.

Figure 1 shows two doping profiles of a pn junction.



(a) Abrupt or Step Junction



(b) Linearly-graded Junction



Figure 1: Doping profile of a pn Junction

pn Junction at Equilibrium

At the abrupt junction, the charge carriers in each region of the junction interact.

On the n-type side, the majority carrier, electrons are far more than on the p-type side, consequently, electrons diffuse across the abrupt junction to the p-type side, to combine with free holes.

Similarly, on the p-type side, the holes diffuse to the n-type side to combine with free electrons.

This action of diffusion and recombination produces a region with very little or no free charge carrier. This region is known as the **depletion region** or **space-charge** region.



pn Junction at Equilibrium continued ...

Figure 2 a, b and c, shows the net charge density ρ , electrostatic field E and diffusion potential or built-in potential ϕ distribution respectively, across the junction at thermal equilibrium.

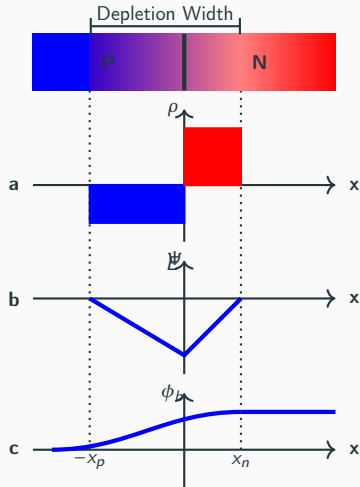


Figure 2: A pn Junction at thermal equilibrium



pn Junction at Equilibrium continued ...

Under the equilibrium (open-circuit) conditions, no external current exists. Consequently, the equilibrium condition is written as $I_D = I_S$.

The barrier potential ($\phi_n - \phi_p$) also known as the built-in potential is given as

$$\phi_b = V_T \ln \left(\frac{N_{Dn} N_{Ap}}{n_i^2} \right) \quad (1)$$

The typical barrier potential value for silicon is about $0.7V$ and $0.3V$ for germanium.

The width of the depletion region can be obtained using

$$x_n = \sqrt{\frac{2\epsilon\phi_b}{q} \frac{N_{Ap}}{N_{Dn}(N_{Ap} + N_{Dn})}} \quad (2)$$

$$x_p = \sqrt{\frac{2\epsilon\phi_b}{q} \frac{N_{Dn}}{N_{Ap}(N_{Ap} + N_{Dn})}} \quad (3)$$



pn Junction at Equilibrium continued ...

The depletion width on the p side, x_p and on the n side x_n are related by

$$\frac{x_n}{x_p} = \frac{N_{Ap}}{N_{Dn}} \quad (4)$$

The total depletion region width w is given by

$$w = x_n + x_p = \sqrt{\frac{2\varepsilon\phi_b}{q} \left(\frac{N_{Ap} + N_{Dn}}{N_{Ap}N_{Dn}} \right)} \quad (5)$$

where ε is the electrical permittivity. Another interesting parameter to note is the charge stored on either side of the depletion region which is given as

$$Q = A \sqrt{2\varepsilon q \frac{N_{Ap}N_{Dn}}{N_{Ap} + N_{Dn}}} \phi_b \quad (6)$$



Biased pn Junction continued ...

When an external voltage v_{AB} is applied across the pn junction device, all of the voltage appears across the depletion region as a change in the potential step from ϕ_b to $\phi_b - v_{AB}$. Therefore, the depletion width will vary with the applied external source, equation 5 is modified as

$$w = x_n + x_p = \sqrt{\frac{2\varepsilon(\phi_b - v_{AB})}{q} \frac{(N_{Ap} + N_{Dn})}{N_{Ap}N_{Dn}}} \quad (7)$$

such that

$$x_n = w \frac{N_{Ap}}{N_{Ap} + N_{Dn}} \quad (8)$$

$$x_p = w \frac{N_{Dn}}{N_{Ap} + N_{Dn}} \quad (9)$$



Biased pn Junction continued ...

The electric field is also affected by the width of the depletion region and can be written as

$$E_{pk}(v_{AB}) = \sqrt{\frac{2q(\phi_b - v_{AB})}{\epsilon} \left(\frac{N_{Ap}N_{Dn}}{N_{Ap} + N_{Dn}} \right)} \quad (10)$$

where $E_{pk}(v_{AB})$ is the peak electric field when an external source v_{AB} is applied. In the case of no external source applied, the peak E field is at $v_{AB} = 0$. The charge stored on either side of the depletion region is

$$Q = A \sqrt{2\epsilon q \frac{N_{Ap}N_{Dn}}{N_{Ap} + N_{Dn}} (\phi_b - v_{AB})} \quad (11)$$

where A is the cross-sectional area of the junction.



Biased pn Junction continued ...

The depletion capacitor may be written as

$$C_{dp}(V_{AB}) = A \sqrt{\frac{q\epsilon}{2(\phi_b - V_{AB})} \left(\frac{N_{Ap}N_{Dn}}{N_{Ap} + N_{Dn}} \right)} \quad (12)$$

Equation 12 can be expressed in terms of equation 7 as

$$C_{dp}(V_{AB}) = \frac{\epsilon A}{w} \quad (13)$$

here w is the depletion region width at the applied potential V_{AB}



Biased pn Junction continued ...

Fig. 3 (a) shows the pn Junction under the equilibrium condition. Figures 3 (b) and 3 (c) show the condition under reverse biased and forward biased conditions respectively.

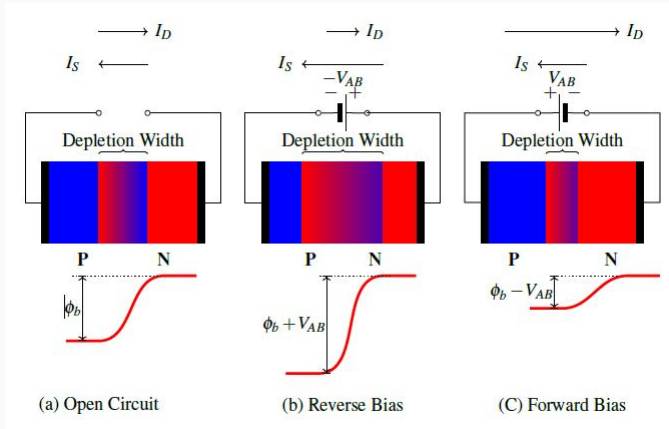


Figure 3: Barrier Potential, ϕ_b across the pn Junction for $\pm V_{AB}$

Biased pn Junction continued ...

The current flow across the diode is

$$i_D = I_S \left(\exp^{\frac{qv_{AB}}{kT}} - 1 \right) \quad (14)$$

where I_S , is the saturation or the scale current. From derivations it has been shown that I_S

$$I_S = Aqn_i^2 \left(\frac{D_p}{L_p N_{Dn}} + \frac{D_n}{L_n N_{Ap}} \right) \quad (15)$$

where A is the junction area, L_p , is the diffusion length of holes in the n material and L_n is the diffusion length of electron in the p material. $w_p \approx L_n$ and $w_n \approx L_p$. Also w_p and w_n are the effective widths of the p and n sides, respectively.



Terminal Characteristics of Diodes

Terminal Characteristics of Diodes

As shown in Figure 4, the diode i - v characteristics can be divided into three regions of operation:

1. The forward bias region, defined by the voltage region $v > 0$
2. The reverse bias region, defined by the voltage region $v < 0$
3. The break-down region, defined by the voltage region $v < -V_Z$

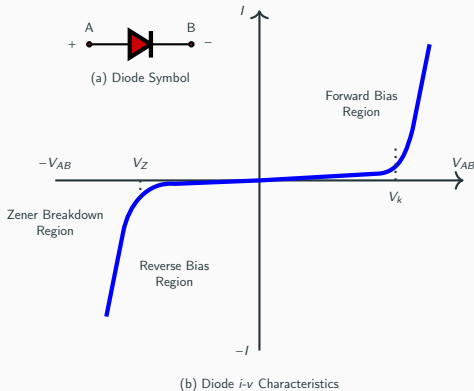


Figure 4: Diode Symbol and i - v Characteristics



Diodes Equivalent Circuit

Diodes Equivalent Circuit

Figure 5 is a simple circuit employing a diode. A variety of diode models employed in circuit analyses include:

- The ideal diode model
- Piecewise-linear model
- Constant voltage drop
- Exponential diode model
- Zener Diode model
- Small signal Diode model and
- High Frequency diode model

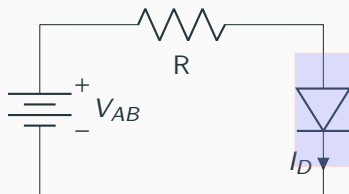


Figure 5: A Simple Diode Circuit



The Ideal Diode Model

Ideal diode is a hypothetical diode that conducts perfectly when forward biased as depicted in Figure 6a.

It acts as an insulator when reverse biased, Figure 6b. In this case, the barrier potential is negligible when forward bias and the forward resistance is zero.

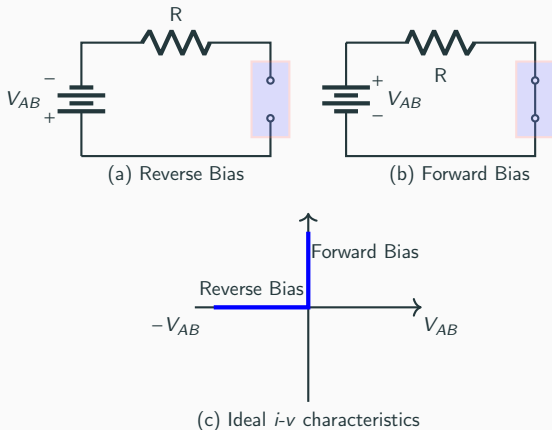


Figure 6: The ideal equivalent circuit with i - v characteristic



Constant Voltage Drop Model

It is based on the observation that a forward conducting diode has a voltage drop of approximately $0.7V$ for silicon and $0.3V$ in the case of germanium.

The forward resistance is zero as indicated by the steep slope of figure 7c.

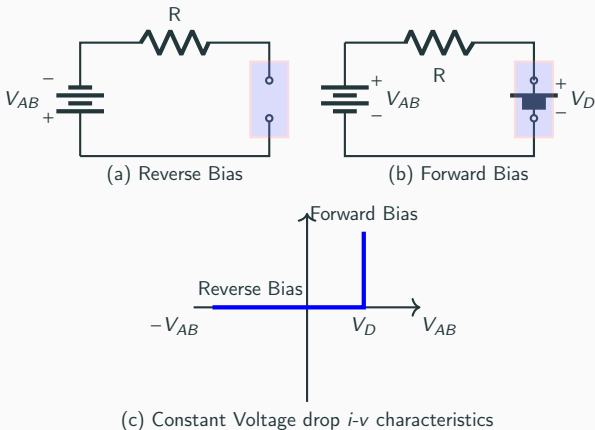
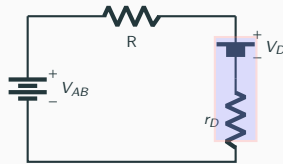


Figure 7: The constant voltage drop (V_D) equivalent circuit with $i-v$ characteristic

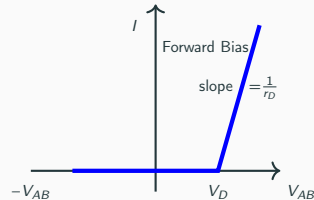


Piecewise Linear Model

The piecewise linear model approximates the diode characteristic curve to that shown in Figure 8 and introduces a forward resistance r_D known as static DC resistance.



(a) Forward Bias



(b) PWL model $i-v$ characteristics

Figure 8: The piece-wise linear model with $i-v$ characteristic



Exponential Model

It involves superimposing the specific diode i - v characteristics curve with the load line drawn from the diode circuit as shown in Figure 9.

Using KVL the equation describing the load line is obtain from Figure 9 as

$$I_D = \frac{V_{DD} - V_D}{R} \quad (16)$$

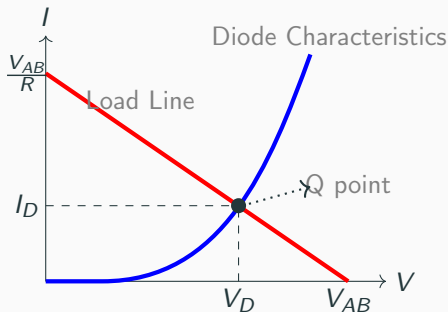


Figure 9: Analysis using the exponential model



Zener Diode Model

The Zener diode operate in the breakdown region, see Fig.11(b). Figure 10 shows the circuit of a Zener diode. Zener diode can be used in circuits for voltage regulation. In normal applications of Zener diodes, current flows into the cathode, and the cathode is positive with respect to the anode so that in figure 11(a), I_Z and V_Z are positive.

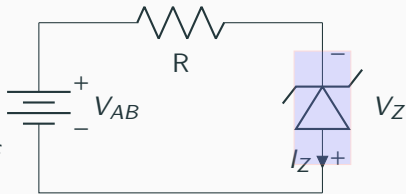


Figure 10: A Simple Zener Diode Circuit

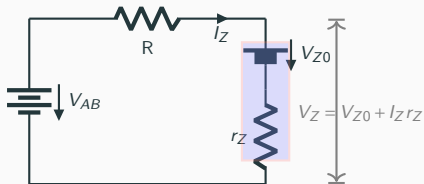


Zener Diode Model continued ...

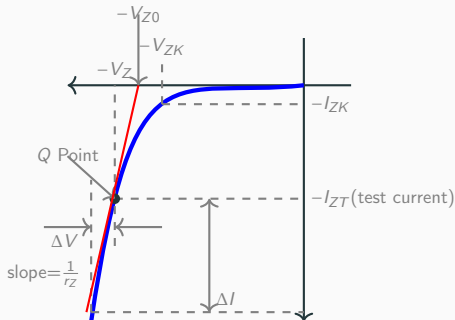
The region of operation can be approximated as

$$V_Z = V_{Z0} + I_Z r_Z \quad (17)$$

where V_{Z0} denotes the point at which the straight line of the slope intersects the voltage axis in figure 11(b). Note that for desired voltage regulation, the Zener diode is operated at the Q point.



(a) Zener Diode equivalent Circuit



(b) Zener Diode $i-v$ Characteristics



Linear Small-Signal Diode model

It is an AC equivalent circuit in which the non-linear circuit diodes are replaced by linear AC dynamic resistor r_d and all DC sources are replaced in the circuit as shown in Figure 12.

The small-signal resistance is given by

$$r_d = \frac{V_T}{I_D} \quad (18)$$

v_d can be obtained using the voltage divider rule as

$$v_d = \frac{r_d}{r_d + R} v_s \quad (19)$$

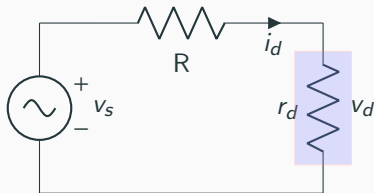


Figure 12: Linear small-signal Diode model



High Frequency Model

At high frequency, capacitive effect of the depletion region becomes prominent. The equivalent circuit then becomes as shown in Figure 13.

We only present this model for you on a need to know basis and will not be discussing details, however, in later chapter, when discussing the transistor's frequency response you will understand the effect of the junction capacitors and how it affects the gain of a transistor.

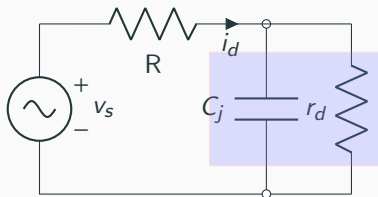


Figure 13: High frequency diode model



Diode Applications

Diode Application

In this section, we will discuss some of diodes applications, which include the following:

1. Rectification;
2. Clipping circuit;
3. Clamping circuit;
4. Logic gate;
5. Voltage multiplier; and
6. Switching.



Rectification

Rectification is the process of converting alternating current (AC) into direct current (DC) or the process of removing either the positive or negative portion of an AC signal entirely.

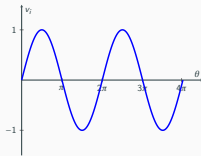
In many electronics applications, DC voltage is required. In order to realize this, the input AC voltage is converted to DC using rectification circuits comprising diodes and some other circuitry.

The rectification can be termed half-wave rectification or full-wave rectification depending on the circuit arrangements.

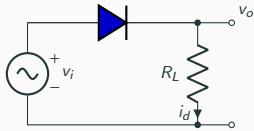


Half-Wave Rectification

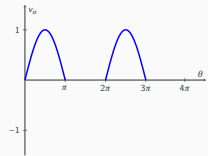
During the positive half-cycle of the input signal, the diode conducts and acts as a closed circuit, allowing the signal to flow. However, during the negative half-cycle, the diode acts as an open circuit and blocks the signal. This results in an output waveform as shown in Figure 14(c).



(a) Input signal



(b) Half-wave rectification circuit



(c) Output signal

Figure 14: Illustration of half-wave rectification



Full-Wave Rectification

Full-wave rectification is a technique used to convert alternating current (AC) into direct current (DC) with continuous current flow through the load.

Unlike half-wave rectification, where only half of the input AC signal is utilized, full-wave rectification ensures that the current flows through the load for both halves of the input signal. This is achieved through a special circuit arrangement that allows the current to always flow in the same direction through the load.

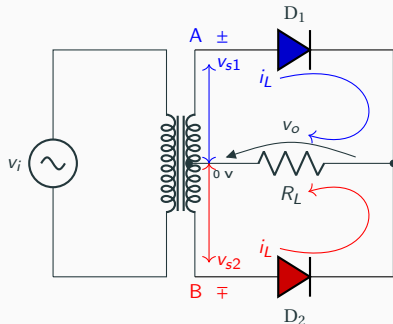
There are two commonly used circuits for full-wave rectification, namely:

1. Centre-tapped transformer; and
2. Bridge Rectifier.

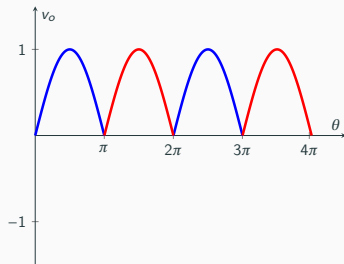


Full-wave rectification with centre-tapped transformer

Diode D_1 conducts while D_2 is reverse-biased during the positive half. Conversely, D_2 conducts and D_1 is reverse-biased during the negative half. Hence, current flows through the diodes, the load R_L , and to the centre-tap in both halves.



(a) Centre-tapped transformer rectifier



(b) Output signal



Figure 15: Full-wave centre-tapped rectification

Full-wave rectification with bridge rectifier

Figure 16 illustrates the implementation of a bridge rectifier circuit for full-wave rectification. By using the ideal diode model, we can understand its operation.

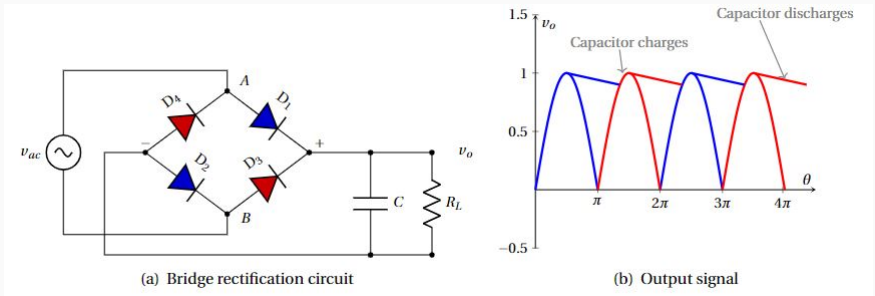


Figure 16: Bridge rectifier



Full-wave rectification with bridge rectifier

During the positive half of the input signal, terminal A is positive relative to terminal B.

As a result, diodes D_1 and D_2 become forward-biased, allowing current to flow through D_1 , the load, and diode D_2 . Conversely, diodes D_3 and D_4 are reverse-biased and do not conduct current.

The same principle applies during the negative half-cycle. Again, current flows in the same direction through the load, this time through diodes D_3 and D_4 , while diodes D_1 and D_2 are reverse-biased.

It is worth noting that during both halves of the input signal, current flows through the load in the same direction, resulting in full-wave rectification.



Clipping circuit

A clipping circuit is used to select that part of a signal waveform which lies above or below the predetermined reference voltage level. Clipping may be achieved either at one level or two levels.

A clipper (limiter, amplitude selector or slicer) is used to clip off or remove a portion of an AC signal. The half-wave rectifier is basically a clipper that eliminates one half of the alternating input signal.

They find useful applications in radio receiver circuits, radars, digital computers, wave generators, signal processing, and many more.



Clipping circuit

Clipping circuits may be categorized as follows:

1. Based on the non-linear devices used. Examples include:
 - Diode clippers,
 - Transistor clippers.
2. According to the biasing. Examples are:
 - Biased clippers,
 - Unbiased clippers.
3. Based on level of clipping. This include:
 - Positive clippers,
 - Negative clippers,
 - Combination clippers.
4. Based on the network arrangement of the diodes. Examples are:
 - Series clippers,
 - Shunt clippers.



Clipping circuit

In Figure 16, for the positive half of the signal, the diode is forward-biased, resulting in an output voltage of 0.7 V (using the constant voltage drop model). However, during the negative half, the diode is reverse-biased and acts as an open circuit so that all the input voltage drops across the open circuit.

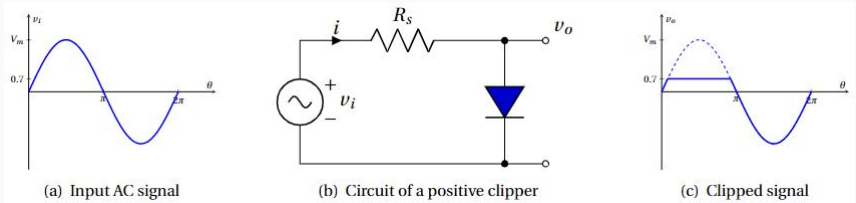


Figure 17: Example of a positive clipping circuit



Clipping circuit

One can achieve a negative biased clipper simply by reversing the diode orientation in Figure 17 as shown in Figure 18.

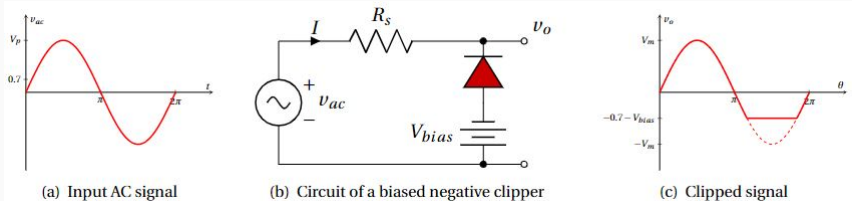


Figure 18: Example of a negative clipping circuit



Clamping circuit

A clamping circuit is an electronic circuit that adjusts the DC level of a signal to a desired level without altering the shape of the original signal. In simple terms, a clamping circuit shifts the entire signal vertically, either upwards or downwards, to align the positive or negative peak of the signal with the desired level.

A clamper or DC restorer, is an electronic circuit used to restore or modify the DC reference level of an AC signal.

It is particularly useful when you have an AC signal that oscillates symmetrically above and below a certain DC voltage reference, such as a 5 V DC reference. The purpose of a clamper circuit is not to change the shape of the AC signal or its root mean square (r.m.s) or peak-to-peak value. Instead, it adjusts both the peak and average values of the signal.



Clamping Circuit continued . . .

Clamping circuits can be categorized into three types:

1. Positive Clamper: A positive clamper shifts the entire AC signal upwards, so that its peaks become more positive relative to the DC reference level.
2. Negative Clamper: In contrast to the positive clamper, a negative clamper shifts the AC signal downwards, making its peaks more negative relative to the DC reference level.
3. Biased Clamper: A biased clamper allows you to modify both the positive and negative peaks of the AC signal with respect to the DC reference level.

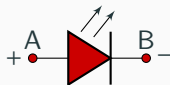


Other Diodes

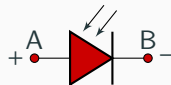
Other Diodes

There are other special diodes worthy of mentions, they include the following:

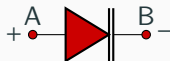
1. Light Emitting Diode (LED)
2. Photodiodes
3. Varactors
4. Schottky-Barrier diode (SBD)



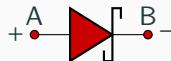
(a) LED Symbol



(b) Photodiode Symbol



(c) Varactor diode Symbol



(d) SBD Symbol

Figure 19: Some Special Diodes



Homework:
Check with the class rep for numerical task!



Recommendation:

See worked examples in reference material!

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