

Chapter 3

DIODES AND RECTIFIERS

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3.1 Introduction

A *diode* is an electrical device allowing current to move through it in one direction with far greater ease than in the other. The most common kind of diode in modern circuit design is the *semiconductor* diode, although other diode technologies exist. Semiconductor diodes are symbolized in schematic diagrams such as Figure 3.1. The term “diode” is customarily reserved for small signal devices, $I \leq 1$ A. The term *rectifier* is used for power devices, $I > 1$ A.

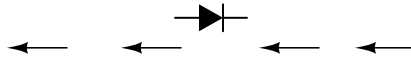


Figure 3.1: *Semiconductor diode schematic symbol: Arrows indicate the direction of electron current flow.*

When placed in a simple battery-lamp circuit, the diode will either allow or prevent current through the lamp, depending on the polarity of the applied voltage. (Figure 3.2)

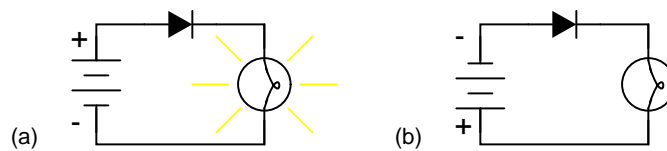


Figure 3.2: *Diode operation: (a) Current flow is permitted; the diode is forward biased. (b) Current flow is prohibited; the diode is reversed biased.*

When the polarity of the battery is such that electrons are allowed to flow through the diode, the diode is said to be *forward-biased*. Conversely, when the battery is “backward” and the diode blocks current, the diode is said to be *reverse-biased*. A diode may be thought of as like a switch: “closed” when forward-biased and “open” when reverse-biased.

Oddly enough, the direction of the diode symbol’s “arrowhead” points *against* the direction of electron flow. This is because the diode symbol was invented by engineers, who predominantly use *conventional flow* notation in their schematics, showing current as a flow of charge from the positive (+) side of the voltage source to the negative (-). This convention holds true for all semiconductor symbols possessing “arrowheads:” the arrow points in the permitted direction of conventional flow, and against the permitted direction of electron flow.

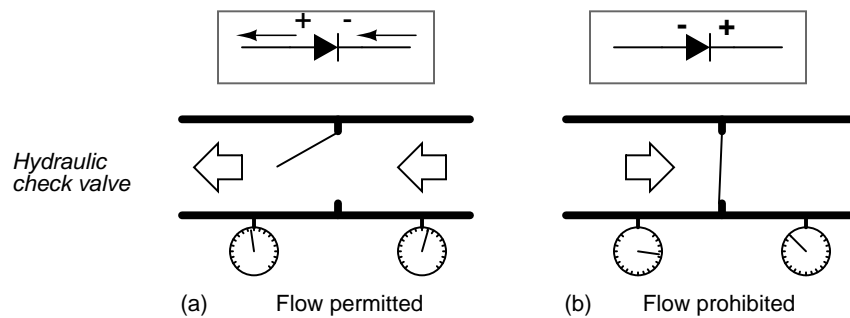


Figure 3.3: Hydraulic check valve analogy: (a) Electron current flow permitted. (b) Current flow prohibited.

Diode behavior is analogous to the behavior of a hydraulic device called a *check valve*. A check valve allows fluid flow through it in only one direction as in Figure 3.3.

Check valves are essentially pressure-operated devices: they open and allow flow if the pressure across them is of the correct “polarity” to open the gate (in the analogy shown, greater fluid pressure on the right than on the left). If the pressure is of the opposite “polarity,” the pressure difference across the check valve will close and hold the gate so that no flow occurs.

Like check valves, diodes are essentially “pressure-” operated (voltage-operated) devices. The essential difference between forward-bias and reverse-bias is the polarity of the voltage dropped across the diode. Let’s take a closer look at the simple battery-diode-lamp circuit shown earlier, this time investigating voltage drops across the various components in Figure 3.4.

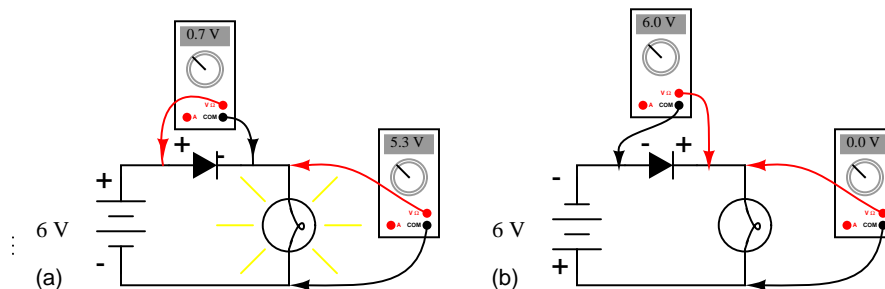


Figure 3.4: Diode circuit voltage measurements: (a) Forward biased. (b) Reverse biased.

A forward-biased diode conducts current and drops a small voltage across it, leaving most of the battery voltage dropped across the lamp. If the battery’s polarity is reversed, the diode becomes reverse-biased, and drops *all* of the battery’s voltage leaving none for the lamp. If we consider the diode to be a self-actuating switch (closed in the forward-bias mode and open in the reverse-bias mode), this behavior makes sense. The most substantial difference is that the diode drops a lot more voltage when conducting than the average mechanical switch (0.7 volts versus tens of millivolts).

This forward-bias voltage drop exhibited by the diode is due to the action of the depletion region formed by the P-N junction under the influence of an applied voltage. If no voltage applied is across a semiconductor diode, a thin depletion region exists around the region of the P-N junction, preventing current flow. (Figure 3.5 (a)) The depletion region is almost devoid of available charge carriers, and acts as an insulator:

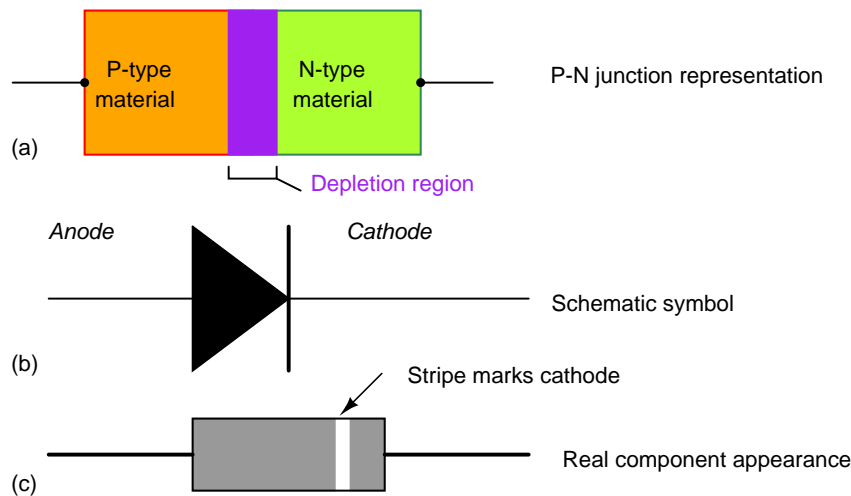


Figure 3.5: Diode representations: PN-junction model, schematic symbol, physical part.

The schematic symbol of the diode is shown in Figure 3.5 (b) such that the anode (pointing end) corresponds to the P-type semiconductor at (a). The cathode bar, non-pointing end, at (b) corresponds to the N-type material at (a). Also note that the cathode stripe on the physical part (c) corresponds to the cathode on the symbol.

If a reverse-biasing voltage is applied across the P-N junction, this depletion region expands, further resisting any current through it. (Figure 3.6)

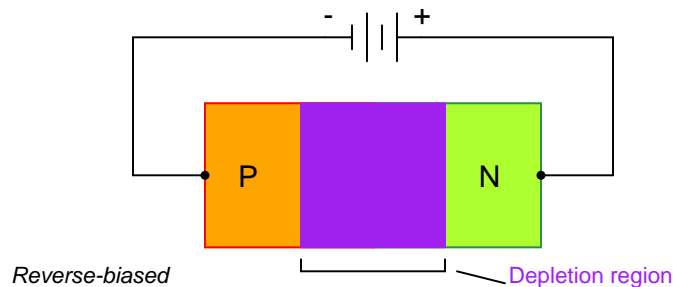


Figure 3.6: Depletion region expands with reverse bias.

Conversely, if a forward-biasing voltage is applied across the P-N junction, the depletion region collapses becoming thinner. The diode becomes less resistive to current through it. In

order for a sustained current to go through the diode; though, the depletion region must be fully collapsed by the applied voltage. This takes a certain minimum voltage to accomplish, called the *forward voltage* as illustrated in Figure 3.7.

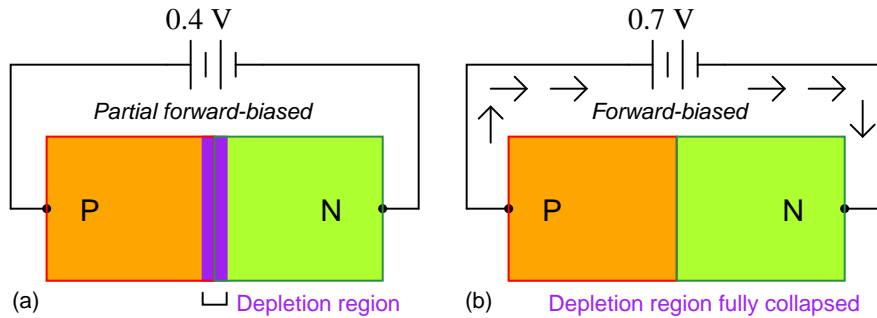


Figure 3.7: Increasing forward bias from (a) to (b) decreases depletion region thickness.

For silicon diodes, the typical forward voltage is 0.7 volts, nominal. For germanium diodes, the forward voltage is only 0.3 volts. The chemical constituency of the P-N junction comprising the diode accounts for its nominal forward voltage figure, which is why silicon and germanium diodes have such different forward voltages. Forward voltage drop remains approximately constant for a wide range of diode currents, meaning that diode voltage drop is not like that of a resistor or even a normal (closed) switch. For most simplified circuit analysis, the voltage drop across a conducting diode may be considered constant at the nominal figure and not related to the amount of current.

Actually, forward voltage drop is more complex. An equation describes the exact current through a diode, given the voltage dropped across the junction, the temperature of the junction, and several physical constants. It is commonly known as the *diode equation*:

$$I_D = I_S (e^{qV_D/NkT} - 1)$$

Where,

I_D = Diode current in amps

I_S = Saturation current in amps
(typically 1×10^{-12} amps)

e = Euler's constant (~ 2.718281828)

q = charge of electron (1.6×10^{-19} coulombs)

V_D = Voltage applied across diode in volts

N = "Nonideality" or "emission" coefficient
(typically between 1 and 2)

k = Boltzmann's constant (1.38×10^{-23})

T = Junction temperature in Kelvins

The term kT/q describes the voltage produced within the P-N junction due to the action of temperature, and is called the *thermal voltage*, or V_t of the junction. At room temperature, this is about 26 millivolts. Knowing this, and assuming a “nonideality” coefficient of 1, we may simplify the diode equation and re-write it as such:

$$I_D = I_S (e^{V_D/0.026} - 1)$$

Where,

I_D = Diode current in amps

I_S = Saturation current in amps
(typically 1×10^{-12} amps)

e = Euler’s constant (~ 2.718281828)

V_D = Voltage applied across diode in volts

You need not be familiar with the “diode equation” to analyze simple diode circuits. Just understand that the voltage dropped across a current-conducting diode *does* change with the amount of current going through it, but that this change is fairly small over a wide range of currents. This is why many textbooks simply say the voltage drop across a conducting, semiconductor diode remains constant at 0.7 volts for silicon and 0.3 volts for germanium. However, some circuits intentionally make use of the P-N junction’s inherent exponential current/voltage relationship and thus can only be understood in the context of this equation. Also, since temperature is a factor in the diode equation, a forward-biased P-N junction may also be used as a temperature-sensing device, and thus can only be understood if one has a conceptual grasp on this mathematical relationship.

A reverse-biased diode prevents current from going through it, due to the expanded depletion region. In actuality, a very small amount of current can and does go through a reverse-biased diode, called the *leakage current*, but it can be ignored for most purposes. The ability of a diode to withstand reverse-bias voltages is limited, as it is for any insulator. If the applied reverse-bias voltage becomes too great, the diode will experience a condition known as *breakdown* (Figure 3.8), which is usually destructive. A diode’s maximum reverse-bias voltage rating is known as the *Peak Inverse Voltage*, or *PIV*, and may be obtained from the manufacturer. Like forward voltage, the PIV rating of a diode varies with temperature, except that PIV *increases* with increased temperature and *decreases* as the diode becomes cooler – exactly opposite that of forward voltage.

Typically, the PIV rating of a generic “rectifier” diode is at least 50 volts at room temperature. Diodes with PIV ratings in the many thousands of volts are available for modest prices.

• REVIEW:

- A *diode* is an electrical component acting as a one-way valve for current.
- When voltage is applied across a diode in such a way that the diode allows current, the diode is said to be *forward-biased*.
- When voltage is applied across a diode in such a way that the diode prohibits current, the diode is said to be *reverse-biased*.

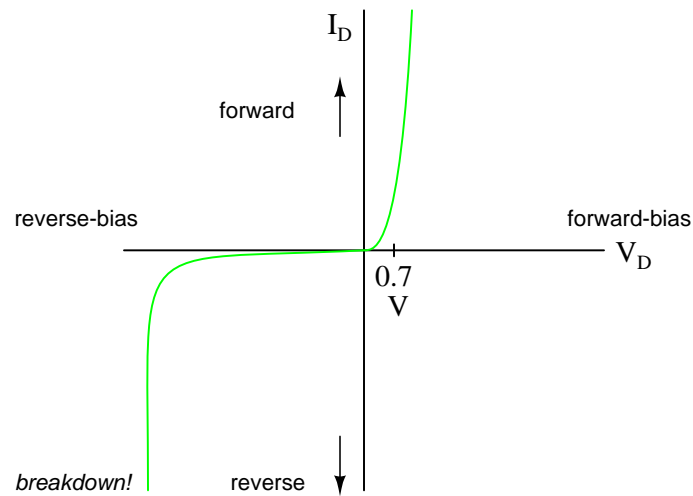


Figure 3.8: Diode curve: showing knee at 0.7 V forward bias for Si, and reverse breakdown.

- The voltage dropped across a conducting, forward-biased diode is called the *forward voltage*. Forward voltage for a diode varies only slightly for changes in forward current and temperature, and is fixed by the chemical composition of the P-N junction.
- Silicon diodes have a forward voltage of approximately 0.7 volts.
- Germanium diodes have a forward voltage of approximately 0.3 volts.
- The maximum reverse-bias voltage that a diode can withstand without “breaking down” is called the *Peak Inverse Voltage*, or *PIV* rating.

3.2 Meter check of a diode

Being able to determine the polarity (cathode versus anode) and basic functionality of a diode is a very important skill for the electronics hobbyist or technician to have. Since we know that a diode is essentially nothing more than a one-way valve for electricity, it makes sense we should be able to verify its one-way nature using a DC (battery-powered) ohmmeter as in Figure 3.9. Connected one way across the diode, the meter should show a very low resistance at (a). Connected the other way across the diode, it should show a very high resistance at (b) (“OL” on some digital meter models).

Of course, to determine which end of the diode is the cathode and which is the anode, you must know with certainty which test lead of the meter is positive (+) and which is negative (-) when set to the “resistance” or “ Ω ” function. With most digital multimeters I’ve seen, the red lead becomes positive and the black lead negative when set to measure resistance, in accordance with standard electronics color-code convention. However, this is not guaranteed for all meters. Many analog multimeters, for example, actually make their black leads positive (+)