Diode: Diodes

Diode.1 Basic Operation

semiconductor diode
p-type material
n-type material
pn junction

A *semiconductor diode* is fabricated from two types of semiconductor material, called *p*-type and *n*-type, that are brought into contact with each other as shown in Figure Diode-1(a). This is basically the same material that is used in *p*-channel and *n*-channel MOS transistors. The point of contact between the *p* and *n* materials is called a *pn junction.* (Actually, a diode is normally fabricated from a single monolithic crystal of semiconductor material in which the two halves are “doped” with different impurities to give them *p*-type and *n*-type properties.)

diode action

The physical properties of a *pn* junction are such that positive current can easily flow from the *p*-type material to the *n*-type. Thus, if we build the circuit shown in Figure Diode-1(b), the *pn* junction acts almost like a short circuit. However, the physical properties also make it very difficult for positive current to flow in the opposite direction, from *n* to *p*. Thus, in the circuit of Figure Diode-1(c), the *pn* junction behaves almost like an open circuit. This is called *diode action*.

diode
anode
cathode

Although it’s possible to build vacuum tubes and other devices that exhibit diode action, modern systems use *pn* junctions—semiconductor diodes—which we’ll henceforth call simply *diodes.* Figure Diode-2(a) shows the schematic symbol for a diode. As we’ve shown, in normal operation significant amounts of current can flow only in the direction indicated by the two arrows, from *anode* to *cathode*. In effect, the diode acts like a short circuit as long as the voltage across the anode-to-cathode junction is nonnegative. If the anode-to-cathode voltage is negative, the diode acts like an open circuit and no current flows.

Figure Diode-1 Semiconductor diodes: (a) the *pn* junction; (b) forward-biased junction allowing current flow; (c) reverse-biased junction blocking current flow.

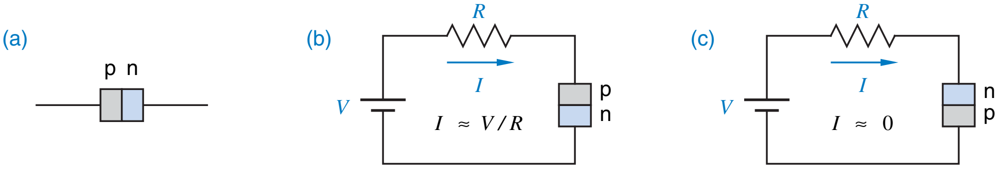
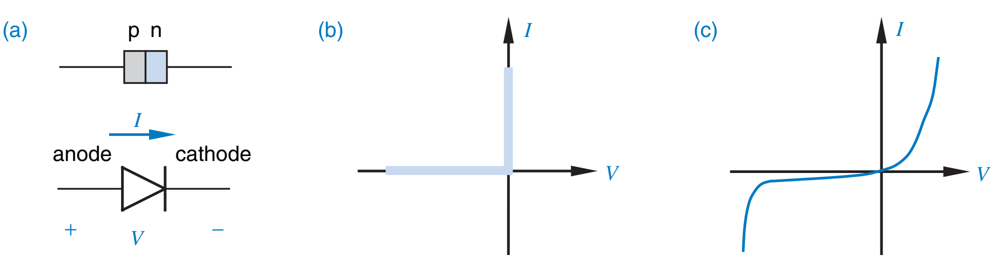


Figure Diode-2 Diodes: (a) symbol; (b) transfer characteristic of an ideal diode; (c) transfer characteristic of a real diode.



YES, THERE ARE TWO ARROWS

. . . in Figure Diode-2(a). The second arrow is built into the diode symbol to help you remember the direction of current flow. Once you know this, there are many ways to remember which end is called the anode and which is the cathode. Aficionados of vacuum-tube hi-fi amplifiers may remember that electrons travel from the hot cathode to the anode, and therefore positive current flow is from anode to cathode. Those of us who were still watching "Sesame Street" when most vacuum tubes went out of style might like to think in terms of the alphabet—current flows alphabetically from A to C. (Thanks to Big-Bird-fan Rick Casey for suggesting this memory crutch.)

The transfer characteristic of an ideal diode shown in Figure Diode-2(b) further illustrates this principle. If the anode-to-cathode voltage, V, is negative, the diode is said to be *reverse biased* and the current I through the diode is zero. If V is nonnegative, the diode is said to be *forward biased* and I can be an arbitrarily large positive value. In fact, V can never get larger than zero, because an ideal diode acts like a zero-resistance short circuit when forward biased.

reverse-biased diode
forward-biased diode

A nonideal, real diode has a resistance that is less than infinity when reverse biased, and greater than zero when forward biased, so the transfer characteristic looks like Figure Diode-2(c). When forward biased, the diode acts like a small nonlinear resistance; its voltage drop increases as current increases, but not strictly proportionally. When the diode is reverse biased, a small amount of negative *leakage current* flows. If the voltage is made too negative, the diode *breaks down,* and large amounts of negative current can flow; in most applications, this type of operation is avoided.

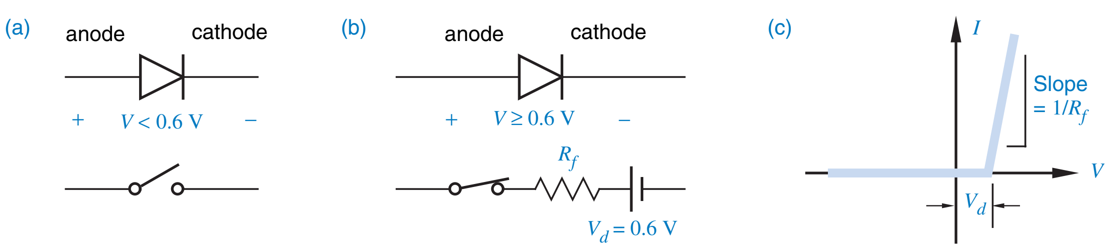
leakage current
diode breakdown

A real diode can be modeled very simply as shown in Figure Diode-3(a) and (b). When the diode is reverse biased, it acts like an open circuit; we ignore leakage current. When the diode is forward biased, it acts like a small resistance, R_f, in series with V_d, a small voltage source. R_f is called the *forward resistance* of the diode, and V_d is called a *diode-drop.*

forward resistance
diode-drop

Careful choice of values for R_f and V_d yields a reasonable piecewise-linear approximation to the real diode transfer characteristic, as in Figure Diode-3(c). In a typical small-signal diode such as a 1N914, the forward resistance R_f is about 25 Ω and the diode-drop V_d is about 0.6 V.

Figure Diode-3 Model of a real diode: (a) reverse biased; (b) forward biased; (c) transfer characteristic of forward-biased diode.



ZENER DIODES *Zener diodes* take advantage of diode breakdown, in particular the steepness of the *V–I* slope in the breakdown region. A Zener diode can function as a voltage regulator when used with a resistor to limit the breakdown current. A wide variety of Zeners with different breakdown voltages are produced for voltage-regulator applications.

In order to get a feel for diodes, you should remember that a real diode does not actually contain the 0.6-V source that appears in the model. It's just that, due to the nonlinearity of the real diode's transfer characteristic, significant amounts of current do not begin to flow until the diode's forward voltage V has reached about 0.6 V. Also note that in typical applications, the 25-Ω forward resistance of the diode is small compared to other resistances in the circuit, so that very little additional voltage drop occurs across the forward-biased diode once V has reached 0.6 V. Thus, for practical purposes, a forward-biased diode may be considered to have a fixed drop of 0.6 V or so.

Diode.2 Diode Logic

Diode action can be exploited to perform logical operations. Consider a logic system with a 5-V power supply and the characteristics shown in Table Diode-1. Within the 5-volt range, signal voltages are partitioned into two ranges, LOW and HIGH, with a 1-volt noise margin between. A voltage in the LOW range is considered to be a logic 0, and a voltage in the HIGH range is a logic 1.

LOW
HIGH

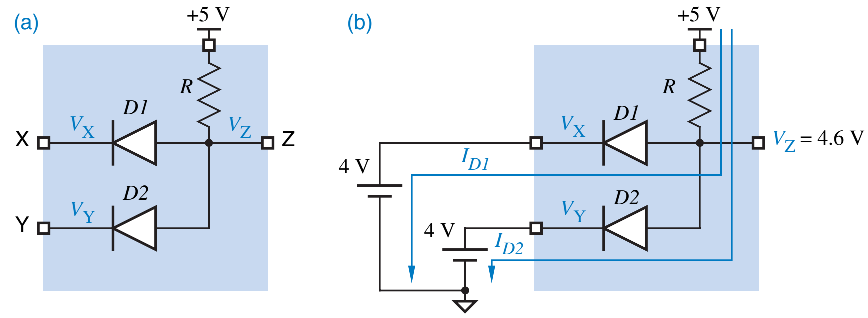
With these definitions, a *diode AND gate* can be constructed as shown in Figure Diode-4(a) on the next page. In this circuit, suppose that both inputs X and Y are connected to HIGH voltage sources, say 4 V, so that V_X and V_Y are both 4 V as in (b). Then both diodes are forward biased, and the output voltage V_Z is one diode-drop above 4 V, or about 4.6 V. A small current, determined by the value of R, flows from the 5-V supply through the two diodes and into the 4-V sources. The colored arrows in the figure show the path of this current flow.

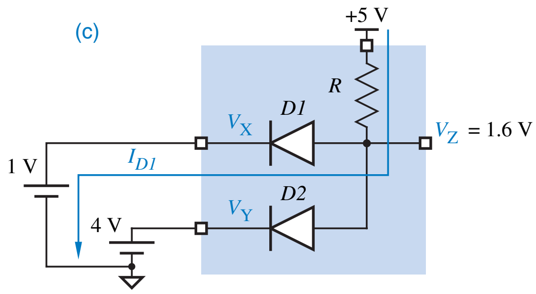
diode AND gate

Now suppose that V_X drops to 1 V as in Figure Diode-4(c). In the diode AND gate, the output voltage equals the lower of the two input voltages plus a diode-drop. Thus, V_Z drops to 1.6 V, and diode $D2$ is reverse biased (the anode is at 1.6 V and the cathode is still at 4 V). The single LOW input "pulls down" the output of the diode AND gate to a LOW value. Obviously, two LOW inputs create a LOW output as well. This functional operation is summarized in (d) and is repeated in terms of binary logic values in (e); clearly, this is an AND gate.

Signal Level	*Designation*	*Binary Logic Value*
0–2 volts	LOW	0
2–3 volts	noise margin	undefined
3–5 volts	HIGH	1

Table Diode-1 Logic levels in a simple diode logic system.





(d)

V_X	V_Y	V_Z
low	low	low
low	high	low
high	low	low
high	high	high

(e)

X	Y	Z
0	0	0
0	1	0
1	0	0
1	1	1

Figure Diode-4
Diode AND gate: (a) electrical circuit; (b) both inputs HIGH; (c) one input HIGH, one LOW; (d) function table; (e) truth table.

Figure Diode-5(a) shows a logic circuit with two AND gates connected together; Figure Diode-5(b) shows the equivalent electrical circuit with a particular set of input values. This example shows the necessity of diodes in the AND circuit: *D3* allows the output Z of the first AND gate to remain HIGH while the output C of the second AND gate is being pulled LOW by input B through *D4*.

When diode logic gates are cascaded as in Figure Diode-5, the voltage levels of the logic signals move away from the power-supply rails and toward the undefined region. Thus, in practice, a diode AND gate normally must be followed by a transistor amplifier to restore the logic levels; this is the scheme used in TTL NAND gates, described in Section TTL.1. Still, digital designers are occasionally tempted to use discrete diodes to perform logic under special circumstances; for example, see Exercise 3.86.

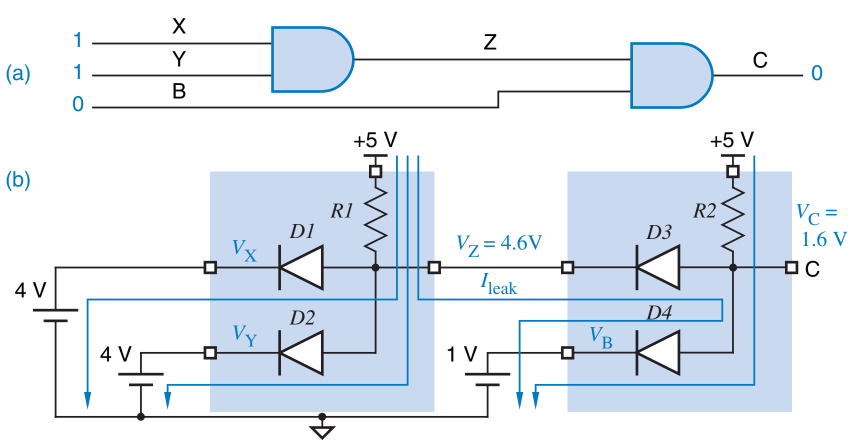


Figure Diode-5
Two AND gates: (a) logic diagram; (b) electrical circuit.

Exercises

Diode.1 If both V_Z and V_B in Figure Diode-5(b) are 4.6 V, can we get $V_C = 5.2$ V? Explain.