Diodes

Introduction

A diode is a two terminal circuit element that allows current flow in one direction only. Diodes are thus non-linear circuit elements because the current through them is not proportional to the potential difference (voltage) across them and this makes them quite different from linear elements like resistors, inductors and capacitors.

There are several technologies that can be used to make diodes. The first really effective diode, the vaccuum diode, was invented in 1904 by J A Fleming and was the workhorse of diode applications until the mid 1950s when semiconductor diodes began to take over. Today, diodes are almost exclusively based on semiconductors and by far the most common form is the "silicon p-n junction" diode. Other materials and stuctures are sometimes used for special purposes - eg LEDs use compound semiconductors such as gallium arsenide - but their basic behaviour is similar to that of silicon diodes.

Silicon p-n junction diodes

The structure, circuit symbol and current-voltage (*I-V*) characteristic of a p-n juction diode is shown in figures 1(a), 1(b) and 1(c).

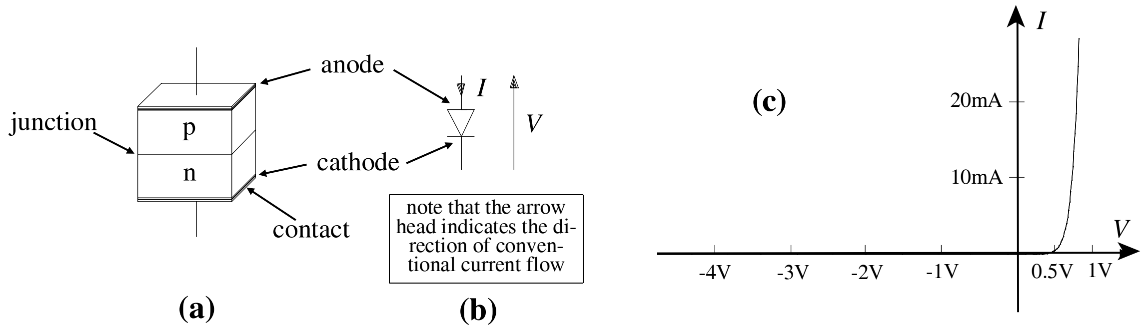

Figure 1 **(a)** *a simplified representation of diode structure,* **(b)** *the diode circuit symbol and* **(c)** a *typical I-V plot for a silicon p-n junction diode*.

Structure

The diode consists of two bits of semiconductor, one p-type and one n-type, in contact with one another. N-type semiconductor is pure semiconductor with added impurities that make it easy for negative charges (electrons) to move around. P-type material, on the other hand, is pure semiconductor with added impurities that make it easy for positive charges (holes) to move around. (A hole is really an absence of an electron where one might be expected but it behaves like a particle for most practical purposes.) The region where the two materials meet is called the junction and the outside edges of the p and n regions are covered with a conducting material, often a metal such as gold, that allows connection to other circuit elements. A diode one might buy in a shop will be packaged in a protective envelope of plastic, glass or metal with connecting wires or terminals protruding from the package. Most diodes are made from silicon.

Circuit Symbol

The diode is drawn in circuit diagrams using the symbol of figure 1b. ***The arrow gives the direction of conventional forward current flow*** so if you see a diode in a circuit you can tell immediately the direction in which it will conduct current. The correspondence between structure and symbol is indicated in figures 1a and 1b.

Characteristic Behaviour

(i) forward bias

When a positive voltage, V, is applied to the p region (or anode) with respect to the n region (or cathode), the device is said to be "forward biassed" and a current, I, called the "forward current", can flow through the device. A certain value of applied voltage is necessary before an observable current flows but once this value is reached, very small increases in applied voltage lead to very large increases in current flow. For a silicon diode the current begins to increase noticeably when the applied voltage is between 0.6V and 0.7V as can be seen in figure 1c. For this reason it is often said that silicon diodes have a "turn on voltage" of 0.7V - this is a useful figure to remember. (In fact the diode turns on over a range of voltages in the region of 0.7V but the assumption of a 0.7V turn on voltage is a very good approximation for most purposes.) The turn on voltage is sometimes called the "diode drop" or the "forward voltage drop".

(ii) reverse bias

When a negative voltage is applied to the anode with respect to the cathode, there is no current flow. (Actually there is a very very small current flowing but it is not important for most applications.) The diode is said to be "reverse biassed" and in this state it behaves very nearly like an open circuit - ie, infinite resistance. If the reverse bias is steadily increased, it will eventually reach a value, the reverse breakdown voltage, that is sufficient to cause failure of the device. The failure mechanism, which is usually destructive, is very similar to the physical mechanism that causes air to change from an insulating to a conducting state during a lightning strike.

Diode Models

The diode equation

The "diode equation", which is derived fom considerations of the device physics and accurately describes the relationship between current through and voltage across the diode, is

$$I = I_0\left(\exp\left(\frac{eV}{nkT}\right) - 1\right)$$

where
- I is the conduction current
- I_0 is a constant
- e is electronic charge
- V is applied bias
- n is a constant with a value between 1 and 2 (often taken as 1)
- k is Boltzmann's constant
- T is absolute temperature

The diode equation shows that the current through the diode is exponentially related to the voltage across it. Computer simulators that work numerically use the diode equation to model the behaviour of diodes but exponential relationships can be difficult to deal with from a human analytical point of view - especially where sinusoids or transients are involved. To get around this difficulty, piecewise linear approximations are commonly used by engineers for simple estimates of performance.

Piecewise linear models

Piecewise linear models are usually created by observing a device characteristic and representing it as two or more straight line approximations. Taking this approach with the diode suggests the use of two linear regions, one for forward bias when the diode is conducting and one for reverse bias when it is not conducting. Possible forms of such a model are shown in figures 2a, 2b and 2c.

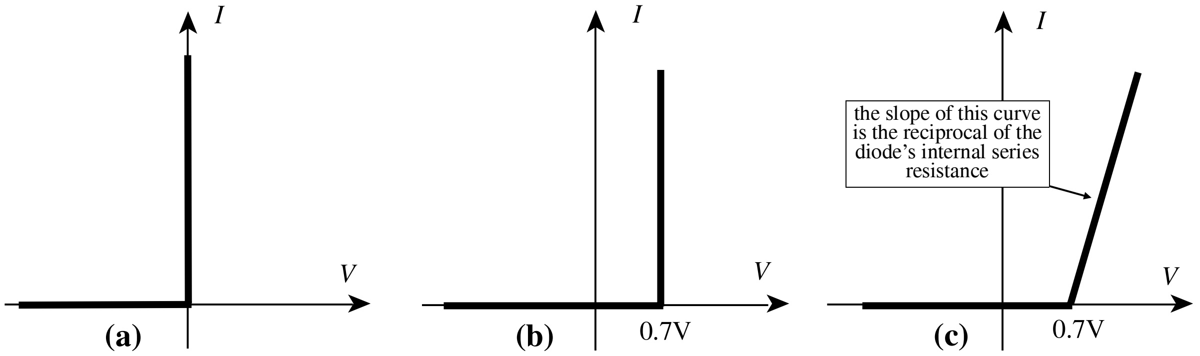

Figure 2: *Piecewise linear diode models.* **(a)** *the ideal diode*, **(b)** *diode with a turn on votage of 0.7V but otherwise ideal and* **(c)** *diode with a turn on voltage of 0.7V and internal series resistance.*

The model of figure 2a assumes that the diode conducts zero current, ie blocks perfectly, when reverse biassed and conducts perfectly when forward biassed. It is a useful starting point when trying to interpret a circuit containing diodes and gives numerically accurate predictions of circuit behaviour when the voltages in circuits are large compared to 0.7V. The model of figure 2b is similar to that of figure 2a except for the inclusion of the 0.7V forward drop which makes it more useful for circuits with voltage differences that cannot be assumed to be large compared to 0.7V. Figure 2c adds a further refinement that allows for the effect of series internal resistance, a parasitic effect present in all diodes but one that can be ignored for the purposes of this module.

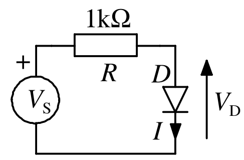

Figure 3
A simple diode circuit

To get a feel for the effect of the difference between the models of figures 2a and 2b on numerical estimates, consider the circuit of figure 3. The driving source, V_S, is in such a direction that positive V_S will tend to forward bias the diode. The current, I, is then given by

$$I = \frac{\text{voltage across } R}{R} = \frac{V_S - V_D}{R}$$

Thus if V_S = 100V, the model of figure 2a gives I = 100mA and that of figure 2b gives I = 99.3mA; if V_S = 10V and then 2V, the corresponding currents are for 10V, I = 10mA and I = 9.3mA and for 2V, I = 2mA and I = 1.3mA. The error only becomes serious for the 2V case.

If the problem was to estimate the power dissipation in the diode, of the models of figures 2a and 2b, 2b is the only sensible choice. This is because the power dissipated is $V_D I$ so it makes no sense to choose a model that approximates V_D to zero. The most important thing about using a model is to be aware of the approximations implicit in it.

How to work out a diode's conduction state

In order to use a piecewise linear model, one must identify the points at which behaviour changes from one piecewise linear mode to another. In the context of a diode in a circuit with dc driving sources this amounts to identifying whether the diode is conducting or not conducting. In circuits where sources can vary, the conditions that will put the diode at the boundary between conduction and non-conduction must be identified.

(i) with fixed sources

In circuits containing only fixed dc sources, the conduction state of the diode can be identified as follows.

1a Assume that the diode is conducting.

2a Replace the diode with a 0 V source (figure 2a diode model) or a 0.7 V source (figure 2b diode model), with its positive end at the position of the diode anode.

3a Work out the current through the source representing the diode.

4a If the current enters the p side (anode) of the diode and exits from the n side (cathode), the diode will be conducting. If the current enters the n side and exits from the p side, the current is trying to flow in a direction the diode will not allow so the diode is non conducting; in this case your initial assumption (step 1a) is wrong.

5a If the test of step 4a indicates that the diode is not conducting you must re-calculate circuit voltage differences and currents with the diode replaced by an open circuit (which is how it behaves when not conducting).

(ii) with varying sources

In circuits with a varying source, the diode may change its conduction state as the source output changes. The task here is to identify the value of source at which the diode is on the point of changing from one state to another. **The diode is on the point of changing conduction state (ie., is on the point of conducting) when $V_{\mathbf{anode}}$ -$V_{\mathbf{cathode}}$ is 0 V or 0.7 V (depending on diode model used) AND current through the diode is zero.** The steps are

1b Assume that the diode is on the point of conducting.

2b Label the voltage across the diode $V_{anode} - V_{cathode}$ as 0 V or 0.7 V (depending on model) and label the current through the diode (from anode to cathode) as 0 A

3b Work out the value of the variable source that is necessary to achieve the conditions of step 2b.

4b Work out whether a small increase in the variable source value will try to increase the diode current, I_D, whilst V_D is kept at 0.7 V (for the model of figure 2b) . If it does, the diode conducts for variable source more positive than the point of conduction value calculated in step 3b; if it doesn't, the diode conducts for variable source less positive than the point of conduction value calculated in step 3b.

Examples

(i) Consider the circuit of figure 3 repeated here for convenience as figure 3a. Find the conduction state of *D*. We will use the model of figure 2b.

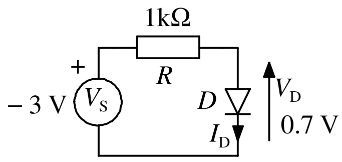

Figure 3a
Example 1

Step 1a. Assume the diode is conducting.

Step 2a. Label V_D as 0.7 V and define a variable I_D in the conventional forward direction.

Step 3a. Calculate I_D . . .

$$I_D = \frac{V_S - V_D}{R} = \frac{-3 - 0.7}{1\text{k}\Omega} = -3.7 \text{ mA} \qquad \textbf{(E 1)}$$

Step 4a. Decide whether or not the assumption is correct . . .

The fact that I_D is negative means that it is actually flowing in the opposite direction to that indicated by the I_D arrowhead. This is impossible because the diode will only allow current flow in the direction of the I_D arrow, the conventional forward direction. Thus the diode is not conducting and behaves like an open circuit (infinite resistance).

When the voltage across the diode, $V_{anode} - V_{cathode}$, is negative as in example **(i)** above, the diode is said to be reverse biassed and no current flows. If V_S in figure 3a were changed to + 3 V, equation **(E 1)** would give I_D = 2.3 mA. Here the diode would be forward biassed and would be conducting. For diodes assumed to conduct when $V_{anode} - V_{cathode}$ is 0.7 V, the region between 0 V and 0.7 V is a forward bias region but the bias is insufficient to cause conduction.

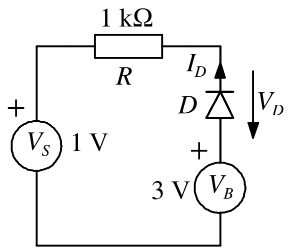

Figure 4
Example 2

(ii) Consider the circuit of figure 4. The diode in figure 4 is the opposite way up to that in figure 3a. Notice though that V_D and I_D are defined in the same way with respect to the diode symbol in both examples. To find the conduction state of the diode, follow step 1a and step 2a of example **(i)** then,

Step 3a. Calculate I_D by summing voltages around the loop . . .

$$V_S + I_D R + V_D - V_B = 0 \qquad \textbf{(E 2)}$$

or

$$I_D = \frac{V_B - V_S - V_D}{R} = \frac{3 - 1 - 0.7 \text{ V}}{1 \text{ k}\Omega} = 1.3 \text{ mA}$$

Step 4a. Decide whether or not the assumption is correct . . .

Here I_D is positive so the diode is conducting and behaves like a 0.7 V voltage source.

(iii) To find the V_S that takes the diode of figure 4 to the point of conduction, ie, the boundary between the conducting and non-conducting states, the second (b) set of steps must be followed . . .

Step 1b. Assume that the diode is on the point of conducting

Step 2b. The diode state is $V_D = 0.7$ V AND $I_D = 0$ A.

Step 3b. We need to do the same sort of calculation as in step 3a here but instead of trying to work out I_D, we are now interested in finding the V_S that will satisfy the condition $V_D = 0.7$ V AND $I_D = 0$ A. We can use the same voltage sum as used in step 3a, equation **(E 2)** but we must put into it the conditions of this problem . . .

$$V_S + I_D R + V_D - V_B = 0 = V_S + 0 + 0.7 - 3 \qquad \textbf{(E 3)}$$

or

$$V_S = 2.3 \text{ V}$$

Step 4b. When $V_S = 2.3$ V, the diode is on the point of conducting. Since V_D and V_B in equation **(E 3)** are fixed a small increase in V_S must be balanced by a small decrease in the $I_D R$ term. But at $V_S = 2.3$ V the $I_D R$ term = 0 so a decrease in that term will make I_D a negative quantity. This cannot happen so the diode becomes non-conducting and V_D has a value that is less than 0.7 V. Thus for $V_S > 2.3$ V the diode is not conducting and behaves like an open circuit and for $V_S < 2.3$ V the diode conducts and its terminal voltage, V_D will be 0.7 V.

(iv) As a further example consider the circuit of figure 5. In this circuit there are two sources, one of which is a current source. To find the conduction state for the values given,

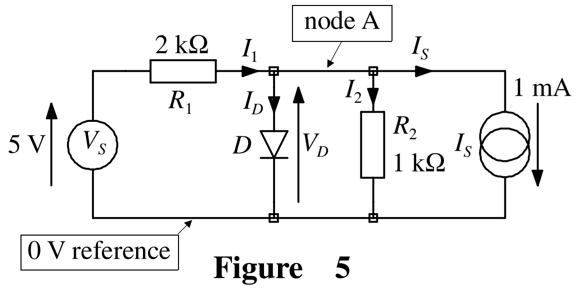

Figure 5

An example involving a current source.

Step 1a. Assume the diode is conducting

Step 2a. Label V_D as 0.7 V and define a variable I_D in the conventional forward direction.

Step 3a. Calculate I_D . . .

In this case a nodal analysis is probably the fastest route to the answer. Summing currents at node A (ie, equating the sum of currents entering to the sum of currents leaving) gives

$$I_1 = I_D + I_2 + I_S$$

$$\text{or} \qquad I_D = I_1 - I_2 - I_S = \frac{V_S - V_A}{R_1} - \frac{V_A}{R_2} - 1\text{ mA} \qquad \textbf{(E 4)}$$

Using the values given and recognising that $V_A = V_D = 0.7$ V

$$I_D = \frac{5 - 0.7}{2\text{ k}\Omega} - \frac{0.7}{1\text{ k}\Omega} - 1\text{ mA} = 0.45\text{ mA}$$

Step 4a. Decide whether or not the assumption is correct . . .

Since I_D is positive, the diode is in its conducting region so the assumption of step 1a is correct.

(v) If, for the circuit of figure 5, we wanted to find the value of I_S that put the diode on the point of conduction, we would proceed as follows . . .

Step 1b. Assume that the diode is on the point of conducting.

Step 2b. Label V_D as 0.7 V AND the I_D as zero.

Step 3b. Work out the value of I_S that will give rise to the conditions of step 2b . . .

Here we can re-use the first part of equation **(E 4)**, $I_D = I_1 - I_2 - I_S$ where I_S is now a variable and $I_D = 0$ . . .

$$0 = \frac{V_S - V_A}{R_1} - \frac{V_A}{R_2} - I_S \quad \text{or} \quad I_S = \frac{5 - 0.7}{2\text{ k}\Omega} - \frac{0.7}{1\text{ k}\Omega} = 1.45\text{ mA}$$

Step 4b. When $I_S = 1.45$ mA the diode is on the point of conducting. Since from example **(iv)** we know that the diode conducts for $I_S = 1$ mA, D must therefore conduct for $I_S < 1.45$ mA and not conduct for $I_S > 1.45$ mA.

Note that we could equally well have allowed V_S to be the varying source and calculated the value of V_S that would put the diode on the point of conduction, given all the other circuit parameters.

Other types of diode

Although the silicon p-n junction diode is by far the most commonly used diode, there are other types made for special purposes and sometimes made from other materials that you should be aware of. A brief description of the more commonly used ones follows.

Light emitting diodes

Light emitting diodes (LEDs) are diodes that emit light when they are forward biassed. The light is emitted when energetically excited electrons lose their energy and return to their resting energy state. The physics of silicon makes it much more likely that energy will be lost as heat than as a photon emission so LEDs are made from compound semiconductors such as gallium arsenide (GaAs), gallium phosphide (GaP) and gallium nitride (GaN) where optical emission is a very probaable energy loss mechanism. (The advantages that would be gained if silicon could be made to emit photons are significant so there is a significant research effort aimed at identifying impurities that might be added to silicon to encourage photon emission.)

LEDs obey the diode equation although the constants are different from those appropriate for silicon. The *V-I* characteristic is similar in shape to that of a silicon diode but differs in turn on voltage. A red LED will have a turn on voltage of around 1.5V, a green LED of around 2V and a blue LED of around 3V. UV LEDs have even higher turn on voltages. Leds are used extensively in applications such as traffic signalling (both roadside and mobile) and instrumentation indicators and are steadily moving into the space lighting area thanks to the very high efficiency of blue LEDs.

Laser diodes

Laser diodes are finding an increasing number of applications as their power output, efficiency and reliability continue to improve. Infra red solid state lasers have for many years been used in optical fibre communication systems. Red solid state lasers have been used for several years in applications such as line of sight communications, range finders, surveying equipment, CD players, medical equipment and many others. Solid state blue lasers, based on gallium nitride related compounds, are finding increasing application in a range of areas. Blue lasers will provide the light source in a range of up-market car headlamps in the near future. The advantages they offer in that application are that the thin parallel beam they produce can be easily optically manipulated to achieve a desired headlight beam shape and that the light source can be physically separated from the lamp housing with the light being carried from one to the other by optical fibres. Some commentators believe that laser diodes will in due course dominate all aspects of the lighting market. The commentators may or may not be right in those predictions but the range of application of lasers will continue to grow as the technology matures.

Zener diodes

Zener diodes are silicon diodes that are unusual because they are designed to be operated in the usually destructive reverse breakdown region and they are designed to break down at a well defined reverse voltage. In the reverse breakdown region current flows through a reverse biassed diode and the voltage across the diode is largely unaffected by changes in reverse current through it. This ability to maintain a more or less constant voltage across when current through is changing makes the zener diode useful as a regulating element in simple power supplies. Breakdown voltages from 3V to around 300V at power ratings of a few hundred mW to over

100W are readily available.

Shottky barrier diodes

These are metal semiconductor junction devices. Their characteristics are similar to p-n junction devices except that turn on voltage is a function of the metal used in the juction. Typical turn on voltages range from 0.3V to 0.6V. They have advantages for high speed operation - they have been used for many years as signal detectors at frequencies up to 10^{11} Hz and over recent years have found increasing applications in high efficiency switching power supply circuitry.