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).

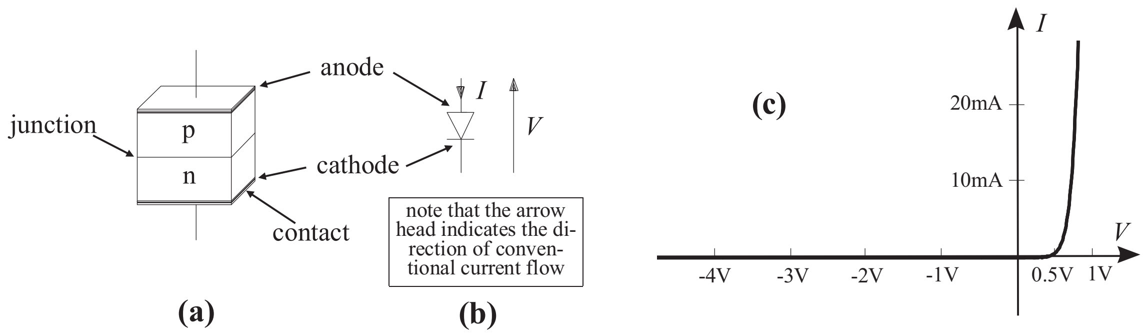

Figure 1 **(a)** *a simplified representation of diode structure,* **(b)** *the diode circuit symbol and* **(c)** a *typical I-V plot for a silicon p-n junction diode*.

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.

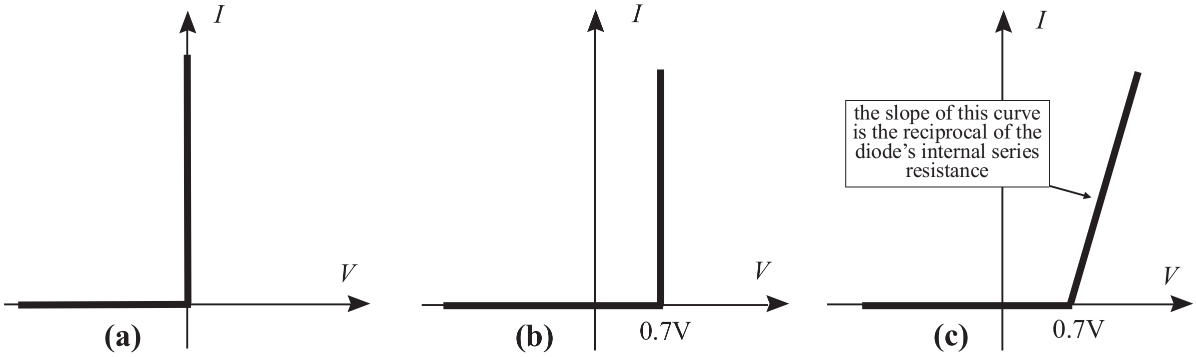

Figure 2: *Piecewise linear diode models.* **(a)** *the ideal diode*, **(b)** *diode with a turn on votage of 0.7V but otherwise ideal and* **(c)** *diode with a turn on voltage of 0.7V and internal series resistance.*

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.

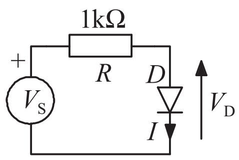

Figure 3
A simple diode circuit

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.

1 Make an assumption about the state of the diode - ie, conducting or not conducting.

2 Replace the diode with a circuit element appropriate for the choice made in step 1 - this would be an infinite resistance (open circuit) for "not conducting" or a 0.7V source, with its positive end at the position of the diode anode, for "conducting". [*Note that this assumes the model of figure 2b is being used. If the model of figure 2a is used, a conducting diode behaves like a short circuit - ie a zero ohm link.*]

3 Work out, as appropriate, the voltage across or the current through the element representing the diode.

4 Test the result of your calculation for physical sensibility. A conducting diode would give a positive I flowing through the 0.7V source from its "+" end to its "-" end. A non conducting diode would give a voltage difference between the circuit nodes to which the anode and cathode were connected that was less than 0.7V. [*Notes: The voltage difference must be in the direction* $V_{anode\ node}$ - $V_{cathode\ node}$. *The use of 0.7V assumes the model of figure 2b is being used; less than 0V would be the critical test for the model of figure 2a.*]

5 Since there are only two options, conducting or non conducting, if one is incorrect, the other must be correct. If the guess in step 1 was wrong, replace the diode by the correct representation and repeat step 3 to find either the reverse bias voltage or forward current as appropriate.

(ii) with varying sources

In circuits with varying source(s), the diode may change its conduction state as the source(s) change over their operating range of output. 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. Essentially the question that needs to be answered is

> "what source voltage or current conditions will put a voltage V_{anode} -V_{cathode} of 0.7V across the diode with a current through it of zero?".

In some circuits it is fairly easy to identify the value of source at which the diode will change state but for others it is necessary to use analysis.

As an example of the easier form of problem, consider the circuit of figure 3. If the diode is replaced by an infinite resistance and the source varied, the diode will be in a non conducting state for all V_S that results in a V_D *l*ess than 0.7V. For V_S = 0.7V and V_D = 0.7V, the diode is on the point of changing state (although the current through it would still be zero because there would be no voltage drop across R). For V_S greater than 0.7V the diode will be forward biassed and the infinite resistance must be replaced by a 0.7V fixed source so that the diode current can be calculated.

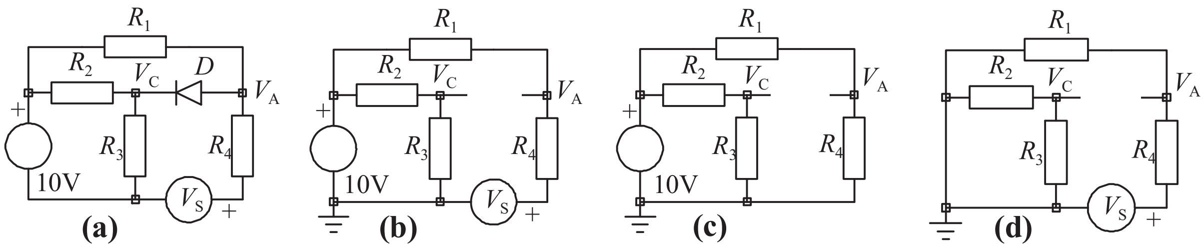

Figure 4: **(a)** *the full circuit,* **(b)** *with diode replaced by an infinite resistance and a reference point added,* **(c)** *with the* V_S *source replaced by a short circuit and* **(d)** *with the 10V source replaced by a short circuit.*

For the circuit of figure 4a, identification of the value of V_S at which the diode will change from a non conducting to a conducting state is more difficult and some analysis is necessary as follows.

1 Make an assumption about the state of the diode - let us assume that it is not conducting.

2 Replace the diode by the appropriate circuit element for the choice in 1 - in this case an open circuit.

3 Choose a reference point with respect to which all voltages will be measured and choose an appropriate analysis method.

The decisions so far leave a modified circuit of figure 4b where the bottom of R_3 has been chosen as a suitable reference node and the diode has been replaced by an infinite resistance.

4 Work out V_A - V_C in terms of circuit components and sources. The following process uses the superposition principle as the analysis method ......

First, work out V_A and V_C due to the 10V source with V_S replaced by its Thevenin equivalent impedance - ie, a short circuit. The partial circuit is shown in figure 4c.

V_A and V_C are a potential divisions of the 10V source through (R_1 and R_4) and (R_2 and R_3) respectively

$$V_{A\,(10)} = \frac{10R_4}{R_1 + R_4} \quad \text{and} \quad V_{C\,(10)} = \frac{10R_3}{R_2 + R_3}$$

Second, work out V_A and V_C due to V_S with the 10V source being replaced by a short circuit. This partial circuit is shown in figure 4d.

V_A is a potential division of V_S through R_4 and R_1 (note that it is the voltage across R_1 that gives V_A w.r.t. the reference point). V_C must be zero because both R_2 and R_3 are connected to the reference point, so

$$V_{A\,(V_S)} = \frac{V_S R_1}{R_1 + R_4} \quad \text{and} \quad V_{C\,(V_S)} = 0$$

Then add the various contributions together

$$V_A - V_C = (V_{A\,(10)} + V_{A\,(V_S)}) - (V_{C\,(10)} - V_{C\,(V_S)}) = \frac{10R_4}{R_1 + R_4} + \frac{V_S R_1}{R_1 + R_4} - \frac{10R_3}{R_2 + R_3} - 0$$

If the component values are known, the point at which the diode is on the point of conducting can be evaluated. For example, if $R_1 = 1k\Omega$, $R_2 = 2k\Omega$, $R_3 = 3k\Omega$ and $R_4 = 4k\Omega$,

$$V_A - V_C = \frac{10 \text{ x } 4}{5} + \frac{V_S \text{ x } 1}{5} - \frac{10 \text{ x } 3}{5} = 2 - \frac{V_S}{5}$$

and equating this to 0.7V will give the V_S at which the diode is on the boundary between its two piecewise linear states. In this example, the diode will be on the point of changing state when $V_S = 6.5$V. If V_S is bigger than this value it will try to make V_A - V_C bigger than 0.7V so the diode will conduct a forward current.

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 will 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 slowly but steadily moving into the space lighting area.

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.