7 Diodes

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Introduction

Nonlinear circuits play a major role in modern electronics. Examples include signal generators, communication transmitters and receivers, DC power supplies, and digital circuits.

To begin a study of nonlinear circuits, we need to examine the most fundamental two-terminal nonlinear device: the diode. The semiconductor junction diode, or *p-n* junction diode, also forms the basis for other semiconductor devices, such as the transistor.

The terminal characteristics of the diode will be presented, rather than the underlying solid-state physics, so that we can focus on providing techniques for the analysis of diode circuits. There are three types of diode circuit analysis technique – graphical, numerical and use of a linear model. *Graphical analysis* of diode circuits is done using graphs of the diode's terminal characteristic and the connected circuit. *Numerical analysis* can be performed with the nonlinear equations of the diode with a technique known as iteration. Lastly, diodes can be replaced with linear circuit models (of varying complexity), under assumed diode operating conditions, so that we revert to linear circuit analysis. Each analysis technique has its advantages and disadvantages, so it is important to choose the most appropriate technique for a given circuit.

7.1 The Silicon Junction Diode

A typical silicon *p-n* junction diode has the following *i-v* characteristic:

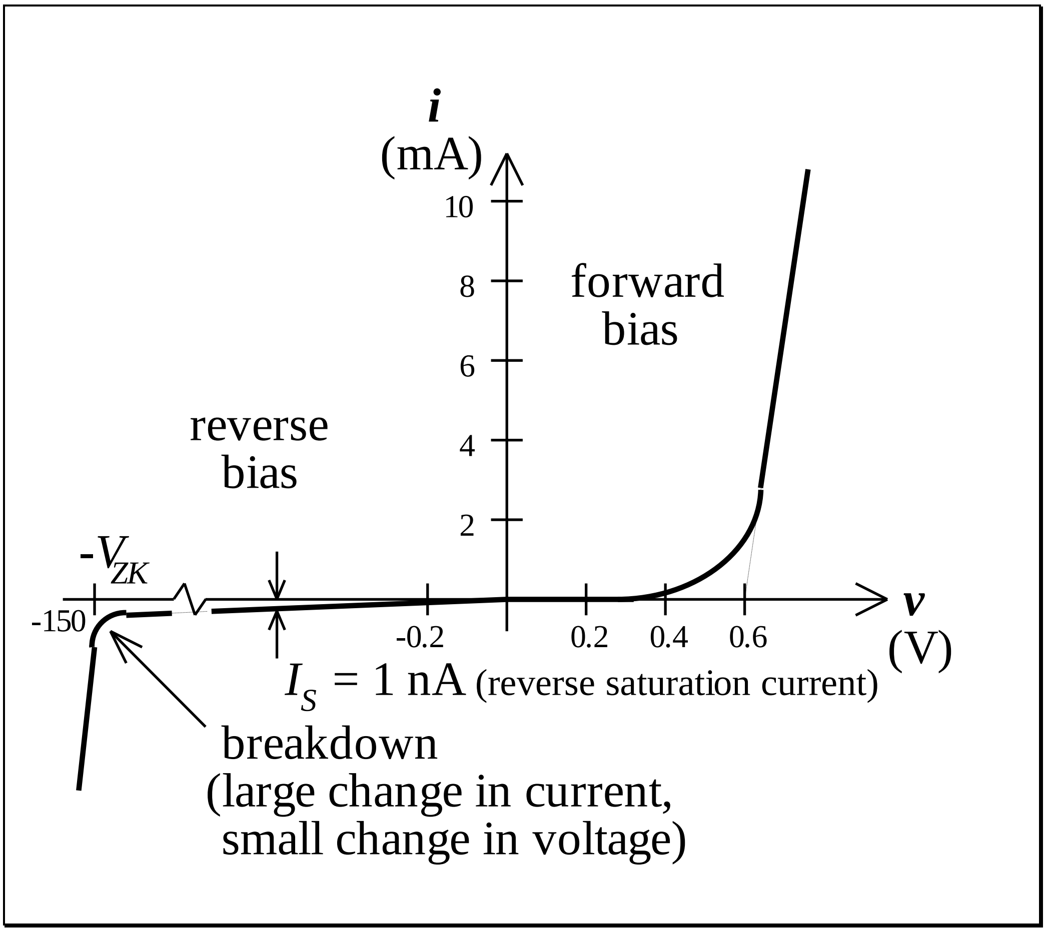


Figure 7.1

The diode is clearly a *nonlinear* element – its characteristic is not a straight line through the origin! The *i-v* characteristic can be divided up into three distinct regions:

1. The forward-bias region, determined by $v > 0$
2. The reverse-bias region, determined by $v < 0$
3. The breakdown region, determined by $v < -V_{ZK}$

7.1.1 The Forward-Bias Region

The forward-bias region of operation is entered when the terminal voltage v is positive. In the forward region the i-v relationship is closely approximated by the Shockley equation, which can be derived from semiconductor physics:

The Shockley equation

$$i = I_S \left(e^{v/nV_T} - 1 \right) \tag{7.1}$$

When forward biased, the diode conducts

There is not much increase in current until the "internal barrier voltage" is overcome (approximately 0.6 V in silicon). Then large conduction results.

Saturation current defined

The current I_S is called the *saturation current* and is a constant for a given diode at a given temperature.

Emission coefficient defined

The constant n is called the *emission coefficient*, and has a value between 1 and 2, depending on the material and the physical structure of the diode.

The voltage V_T is a constant called the *thermal voltage*, given by:

Thermal voltage defined

$$V_T = \frac{kT}{q} \tag{7.2}$$

where:

$$\begin{aligned} k &= \text{Boltzmann's constant} \\ &= 1.381 \times 10^{-23}\ \text{JK}^{-1} \end{aligned} \tag{7.3}$$

$$T = \text{temperature in degrees Kelvin} \tag{7.4}$$

$$\begin{aligned} q &= \text{magnitude of electron charge} \\ &= 1.602 \times 10^{-19}\ \text{C} \end{aligned} \tag{7.5}$$

The thermal voltage is approximately equal to 26 mV at 300 K (a temperature that is close to "room temperature" which is commonly used in device simulation software).

For appreciable current in the forward direction ($i >> I_S$), the Shockley equation can be approximated by:

$$i \approx I_S e^{v/nV_T} \tag{7.6}$$

This equation is usually "good enough" for rough hand calculations when we know that the current is appreciable.

From the characteristic we note that the current is negligibly small for v smaller than about 0.5 V (for silicon). This value is usually referred to as the *cut-in voltage*. This apparent threshold in the characteristic is simply a consequence of the exponential relationship.

Another consequence of the exponential relationship is the rapid increase of current for small changes in voltage. Thus for a "fully conducting" diode the voltage drop lies in a narrow range, approximately 0.6 to 0.8 V for silicon. We will see later that this gives rise to a simple model for the diode where it is assumed that a conducting diode has approximately a 0.7 V drop across it (again, for silicon).

The Shockley equation can be rearranged to give the voltage in terms of the current:

$$v = nV_T \ln\left(\frac{i}{I_S} + 1\right) \tag{7.7}$$

This logarithmic form is used in the numerical analysis of diode circuits.

7.1.2 The Reverse-Bias Region

When reverse biased, the diode does not conduct

The reverse-bias region of operation is entered when the diode voltage v is made negative. The Shockley equation predicts that if v is negative and a few times large than V_T in magnitude, the exponential term becomes negligibly small compared to unity and the diode current becomes:

$$i = -I_S \tag{7.8}$$

That is, the current in the reverse direction is constant and equal to I_S. This is the reason behind the term *saturation current*. However, real diodes exhibit reverse currents that, although quite small, are much larger than I_S.

7.1.3 The Breakdown Region

Breakdown occurs eventually for a large enough reverse bias

The breakdown region is entered when the magnitude of the reverse voltage exceeds a threshold value specific to the particular diode and called the *breakdown voltage*. This is the voltage at the "knee" of the *i*-*v* curve and is denoted by V_{ZK}, where the subscript Z stands for Zener (to be explained shortly) and K denotes knee.

Breakdown is not a destructive process unless the device cannot dissipate the heat produced in the breakdown process. Breakdown is actually exploited in certain types of diodes (e.g. the Zener diode) because of the near vertical characteristic in this region.

7.1.4 Diode Symbol

The circuit symbol for the diode is shown below, with the direction of current and polarity of voltage that corresponds to the characteristic:

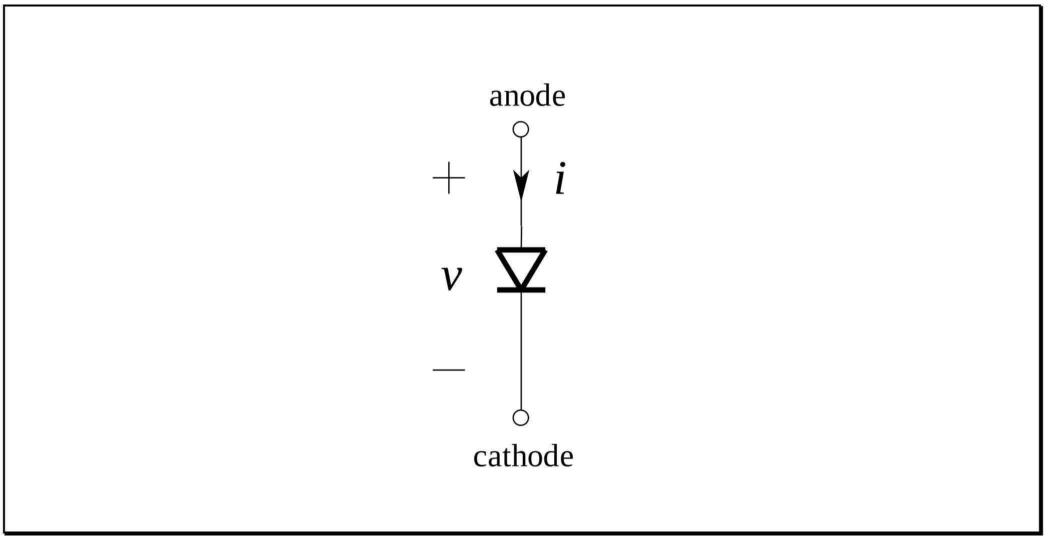


Figure 7.2

7.2 Breakdown Diodes

Some diodes are designed to operate in the breakdown region. It is usually a sharper transition than the forward bias characteristic, and the breakdown voltage is higher than the forward conduction voltage. There are two main types of breakdown.

Some diodes are designed to operate in the breakdown region

7.2.1 Zener Breakdown

The electric field in the depletion layer of a *p*-*n* junction becomes so large that it rips covalent bonds apart, generating holes and electrons. The electrons will be accelerated into the *n*-type material and the holes into the *p*-type material. This constitutes a reverse current. Once the breakdown starts, large numbers of carriers can be produced with negligible increase in the junction voltage.

Zener breakdown is caused by a large internal electric field

7.2.2 Avalanche Breakdown

If the minority carriers are swept across the depletion region of a *p*-*n* junction too fast, they can break the covalent bonds of atoms that they hit. New electron-hole pairs are generated, which may acquire sufficient energy to repeat the process. An avalanche starts.

Avalanche breakdown is caused by electrons with a large kinetic energy

7.3 Other Types of Diode

The silicon junction diode is not the only type of diode. A variety of diode constructions exist, with many of them essential to the modern world, such as the LED.

7.3.1 The Photodiode

A photodiode is controlled by light

In a photodiode, the *p*-*n* junction is very close to the surface of the crystal. The Ohmic contact with the surface material is so thin, it is transparent to light. Incident light (photons) can generate electron-hole pairs in the depletion layer (a process called photoionisation).

7.3.2 The Light Emitting Diode (LED)

An LED emits photons when forward biased

When a light-emitting diode is forward biased, electrons are able to recombine with holes within the device, releasing energy in the form of light (photons). The color of the light corresponds to the energy of the photons emitted, which is determined by the "energy gap" of the semiconductor. LEDs present many advantages over incandescent and compact fluorescent light sources including lower energy consumption, longer lifetime, improved robustness, smaller size, faster switching, and greater durability and reliability. At the moment LEDs powerful enough for room lighting are relatively expensive and require more precise current and heat management than compact fluorescent lamp sources of comparable output.

LEDs are used in diverse applications. The compact size of LEDs has allowed new text and video displays and sensors to be developed, while their high switching rates are useful in advanced communications technology. Infrared LEDs are also used in the remote control units of many commercial products including televisions, DVD players, and other domestic appliances.

7.3.3 The Schottky Diode

A Schottky diode is the result of a metal-semiconductor junction. The Schottky diode is a much faster device than the general purpose silicon diode. There are three main reasons for this: 1) the junction used is a metal-semiconductor junction, which has less capacitance than a *p-n* junction, 2) often the semiconductor used is gallium arsenide (GaAs) because electron mobility is much higher, and 3) the device size is made extremely small. The result is a device that finds applications in high speed switching.

A Schottky diode is a metal-semiconductor junction

7.3.4 The Varactor Diode

This device is also known as a variable capacitance diode. It has a relatively large capacitance, brought about by a large junction area and narrow depletion region. The applied reverse voltage changes the length of the depletion region, which changes the capacitance. Thus, the device can be used in applications that rely on a voltage controlled capacitance. Applications include electronic tuning circuits used in communication circuits, and electronic filters.

7.4 Analysis Techniques

Since the diode's characteristic is nonlinear, we can't apply linear circuit analysis techniques to circuits containing diodes. We therefore have to resort to other analysis methods: graphical, numerical and linear modelling.

7.4.1 Graphical Analysis

Circuits with a single nonlinear element can always be modelled using the Thévenin equivalent of the linear part:

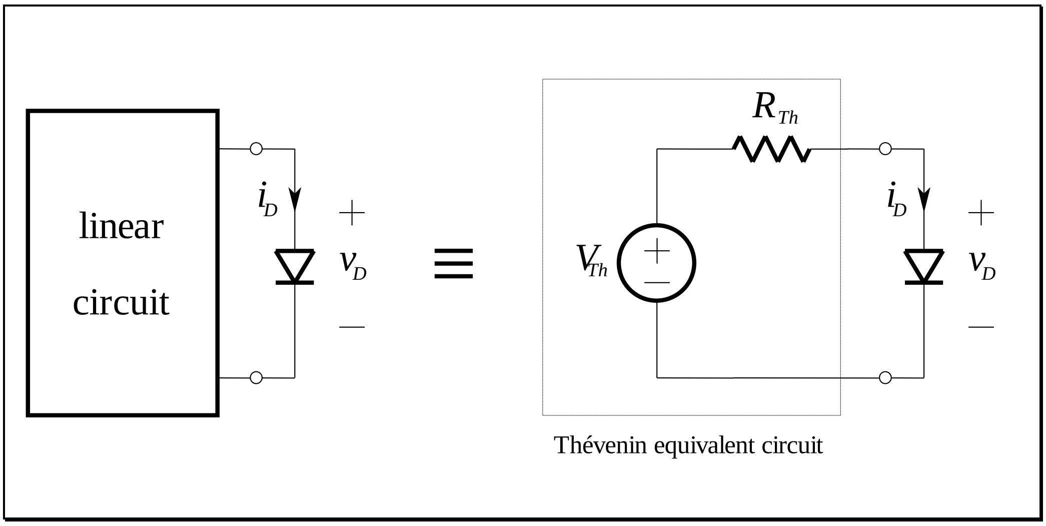


Figure 7.3

KVL around the loop gives:

$$v_D = V_{Th} - R_{Th} i_D \tag{7.9}$$

which, when rearranged to make i_D the subject, gives:

$$i_D = -\frac{1}{R_{Th}}\left(v_D - V_{Th}\right) \tag{7.10}$$

The "load line" is derived using linear circuit theory

When graphed, we call it the *load line*. It was derived from KVL, and so it is always valid. The load line gives a relationship between i_D and v_D that is determined purely by the external circuit. The diode's characteristic gives a relationship between i_D and v_D that is determined purely by the geometry and physics of the diode.

Since both the load line and the characteristic are to be satisfied, the only place this is possible is the point at which they meet. This point is called the quiescent point, or Q point for short:

The "load line" and device characteristic intersect at the Q point

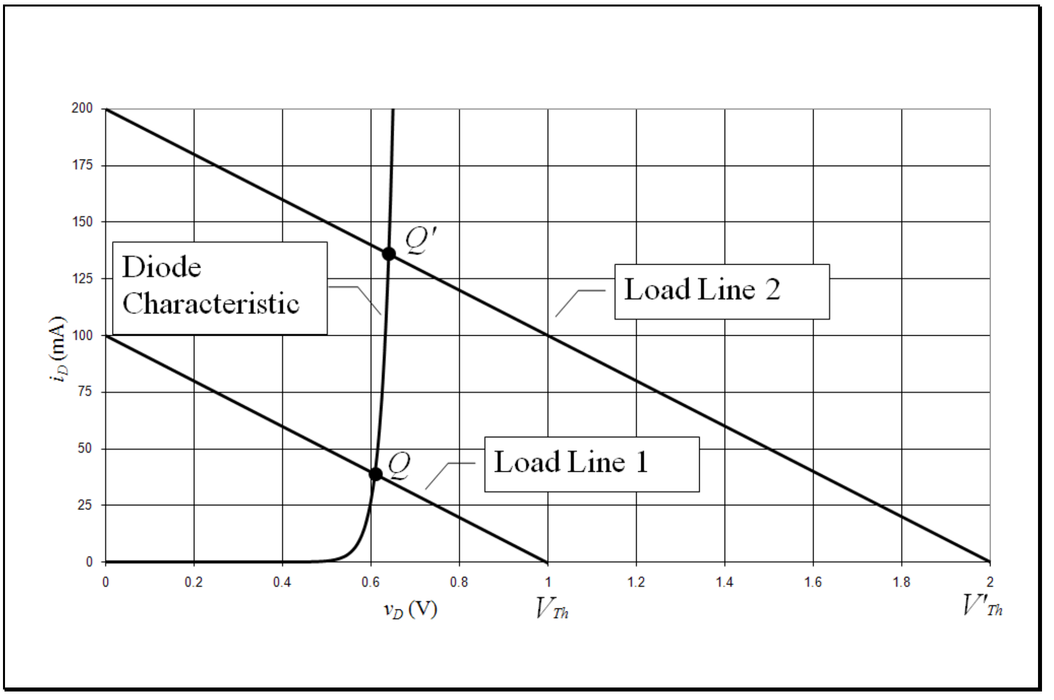


Figure 7.4 – Graphical Analysis Using a Load Line

If the Thévenin voltage changes to V'_{Th}, then the operating point moves to Q' (the DC load line is shifted to the right).

The two end points of the load line are easily determined to enable quick graphing. The two axis intercepts are:

$$v_D = 0, \quad i_D = \frac{V_{Th}}{R_{Th}} \tag{7.11}$$

and:

$$v_D = V_{Th}, \quad i_D = 0 \tag{7.12}$$

Alternatively, we can graph the load line using one known point and the fact that the slope is equal to $-\frac{1}{R_{Th}}$.

7.4.2 Numerical Analysis

Since, in the preceding analysis, we have two equations (the load line and the diode characteristic) and two unknowns, it is tempting to try and solve them simultaneously. If we substitute the voltage from the Shockley equation:

$$v_D = nV_T \ln\left(\frac{i_D}{I_S} + 1\right) \tag{7.13}$$

into the load line equation:

$$i_D = -\frac{1}{R_{Th}}\left(v_D - V_{Th}\right) \tag{7.14}$$

we get:

$$i_D = -\frac{1}{R_{Th}}\left(nV_T \ln\left(\frac{i_D}{I_S} + 1\right) - V_{Th}\right) \tag{7.15}$$

This equation is a *transcendental equation*, and its solution cannot be expressed in term of elementary functions (try it!). With a sufficiently advanced calculator (or mathematical software), we can use a special function called the Lambert W function to solve it, but for engineering purposes, there are usually simpler methods of solution.

We can solve transcendental equations graphically (as shown in the preceding section) but we can also solve them numerically using a technique known as *iteration* – which is suitable for computer simulations.

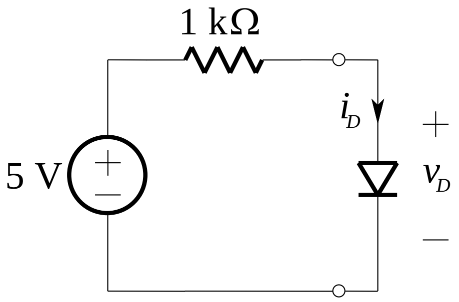
We begin with an initial "guess" for the diode current, labelled $i_{D,0}$, and then compute:

$$\begin{aligned} i_{D,1} &= -\frac{1}{R_{Th}}\left(nV_T \ln\left(\frac{i_{D,0}}{I_S}+1\right)-V_{Th}\right) \\ i_{D,2} &= -\frac{1}{R_{Th}}\left(nV_T \ln\left(\frac{i_{D,1}}{I_S}+1\right)-V_{Th}\right) \\ i_{D,3} &= \cdots \end{aligned} \tag{7.16}$$

and so on until we get "convergence", i.e. $i_{D,k+1} \approx i_{D,k}$. Convergence is not always guaranteed, and depends on the initial "guess". Computer simulation software uses several clever methods to aid in numerical convergence.

EXAMPLE 7.1 Numerical Analysis of a Circuit with a Real Diode

The following circuit contains a diode, with $n=1$ and $I_S = 2.030\ \text{fA}$. We wish to find the diode's operating point, or Q point. Assume that $V_T = 26\,\text{mV}$.



Starting with $i_{D,0} = 1\,\text{mA}$ we have:

$$\begin{aligned} i_{D,1} &= -\frac{1}{10^3}\left(0.026 \ln\left(\frac{0.001}{2.03\times10^{-15}}+1\right)-5\right) = 4.3\,\text{mA} \\ i_{D,2} &= -\frac{1}{10^3}\left(0.026 \ln\left(\frac{0.0043}{2.03\times10^{-15}}+1\right)-5\right) = 4.262\ \text{mA} \end{aligned}$$

Since the second value is very close to the value obtained after the first iteration, no further iterations are necessary, and the solution is $i_D = 4.262\,\text{mA}$ and $v_D = 0.7379\,\text{V}$.

7.5 Summary

- The silicon junction diode forms the basis of modern electronics. It is a device that effectively allows a current in only one direction.

- The forward conduction region of practical silicon diodes is accurately characterised by the Shockley equation:

$$i = I_S\left(e^{v/nV_T} - 1\right)$$

- Beyond a certain value of reverse voltage (that depends on the diode) breakdown occurs, and current increases rapidly with a small corresponding increase in voltage. This property is exploited in diodes known as breakdown diodes.

- A variety of diode constructions exist, with many of them essential to the modern world, such as the LED.

- Since the diode's characteristic is nonlinear, we can't apply linear circuit analysis techniques to circuits containing diodes. We therefore have to resort to other analysis methods: graphical, numerical and linear modelling

7.6 References

Sedra, A. and Smith, K.: *Microelectronic Circuits*, Saunders College Publishing, New York, 1991.