Transistor Circuit Techniques

discrete and integrated

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TUTORIAL GUIDES IN ELECTRONIC ENGINEERING

This series is aimed at first- and second-year undergraduate courses. Each text is complete in itself, although linked with others in the series. Where possible, the trend towards a 'systems' approach is acknowledged, but classical fundamental areas of study have not been excluded, neither has mathematics, although titles wholly devoted to mathematical topics have been eschewed in favour of including necessary mathematical concepts under appropriate applied headings. Worked examples feature prominently and indicate, where appropriate, a number of approaches to the same problem.

A format providing marginal notes has been adopted to allow the authors to include ideas and material to support the main text. These notes include references to standard mainstream texts and commentary on the applicability of solution methods, aimed particularly at covering points normally found difficult. Graded problems are provided at the end of each chapter, with answers at the end of the book.

1. Transistor Circuit Techniques: discrete and integrated — G.J. Ritchie
2. Feedback Circuits and Op-Amps — D.H. Horrocks

Preface

It has been my experience in teaching electronic circuit design that many first-year degree students are frustrated by the lack of suitable texts at the right level of practical and theoretical content. Introductory volumes tend to be rather elementary while authoritative reference texts prove too extensive for this sensitive audience.

In this book my aim has been to guide the student gently through the analysis and design of transistor circuits, providing worked examples and design examples as illustration. Spread liberally throughout each chapter are exercises to test the reader's grasp of the material and a set of problems at the end of each chapter provides useful and realistic assessment. Extensive use has been made of margin comments to reinforce the main text by way of highlighting the most important features, giving references for further reading, recalling earlier material, summarising the approach and emphasising practical points.

It was considered essential to introduce, at an early stage, the concept of representing semiconductor devices by simple d.c. and a.c. models which prove so useful in circuit analysis. A brief description of semiconductors and device operation is justified in providing a basis for understanding diode and transistor behaviour, their characterisation and limitations. Great importance is attached to a basic appreciation of integrated devices, bipolar and field-effect, particularly in terms of their matching and thermal tracking properties, as well as the fundamental economic law of integration, minimise chip area, which dictates the techniques used in modern circuit design.

A very simple model of the bipolar transistor is developed using a single resistor (r_{be}) and a current source (βi_b). This is adequate for most low-frequency requirements; only when considering current sources has the r_{ce} parameter of the full hybrid-π equivalent circuit been invoked. The author does not favour the use of h-parameters since they are purely numbers and do not give the inherent prediction of parameter variation with bias current and current gain which is the forte of the hybrid-π and simple models.

A wide range of transistor circuitry, both linear and switching, is covered in terms of fundamental qualitative circuit operation followed by analysis and design procedure. No apology is made for the extensive analytic treatment of circuits presented in this text — practice in analysis and engendering familiarity with design procedures are essential facets of the training of an electronic circuit designer.

It is hoped that this book instils a sound foundation of concept and approach which, even in this most rapidly developing area of modern electronics, will prove to be of lasting value.

I am grateful to my colleagues at Essex University, in particular Professors G.B.B. Chaplin and J.A. Turner and Dr. J.K. Fidler, for many useful discussions. I also wish to thank my Consultant Editor, Dr. A.P. Dorey of Southampton University, for his enthusiasm and very constructive assistance with this project.

Contents

Introduction to Semiconductor Devices 1

Objectives

- ☐ To define terms such as intrinsic (pure) and extrinsic (doped) semiconductors, majority and minority carriers.
- ☐ To explain in simple terms how a semiconductor diode operates and how its d.c. characteristic is expressed analytically by the diode equation.
- ☐ To approximate the d.c. behaviour of a forward biased diode to a constant voltage and represent its a.c. behaviour by the dynamic slope resistance.
- ☐ To explain junction breakdown and how a breakdown diode can be used as a simple voltage stabiliser.
- ☐ To describe the operation of a bipolar junction transistor (BJT).
- ☐ To define the terms current gain, cut-off and saturation applied to a BJT.
- ☐ To describe the structure of integrated circuit components — BJT's, resistors and capacitors.
- ☐ To explain the value of the (planar) integrated circuit process in being able to produce components which are matched and whose parameters track with temperature.

In the design of electronic circuits it is important to know about discrete semiconductor devices such as diodes and transistors, their terminal properties and limitations. While device behaviour can be expressed in terms of complex equations, it is much more important to be able to characterise devices in the form of approximate, simple, a.c. and d.c. models which assist in both the analysis and design processes.

This chapter aims to develop a simple understanding of device operation and characterisation which subsequently is applied to the design of amplifiers and switching circuits. Although the emphasis is on discrete components and fundamental circuit techniques, the influence of integrated circuit design is equally important.

The following general references are useful for this chapter:

Millman, J. *Microelectronics* (McGraw-Hill, 1979) (Chapters 1–4).

Kano, K. *Physical and Solid State Electronics* (Addison-Wesley, 1972) (Chapters 4–7).

Anderson, J.C. and Leaver, K.D. *Materials Science* (Van Nostrand Reinhold, 1969) (Chapter 13).

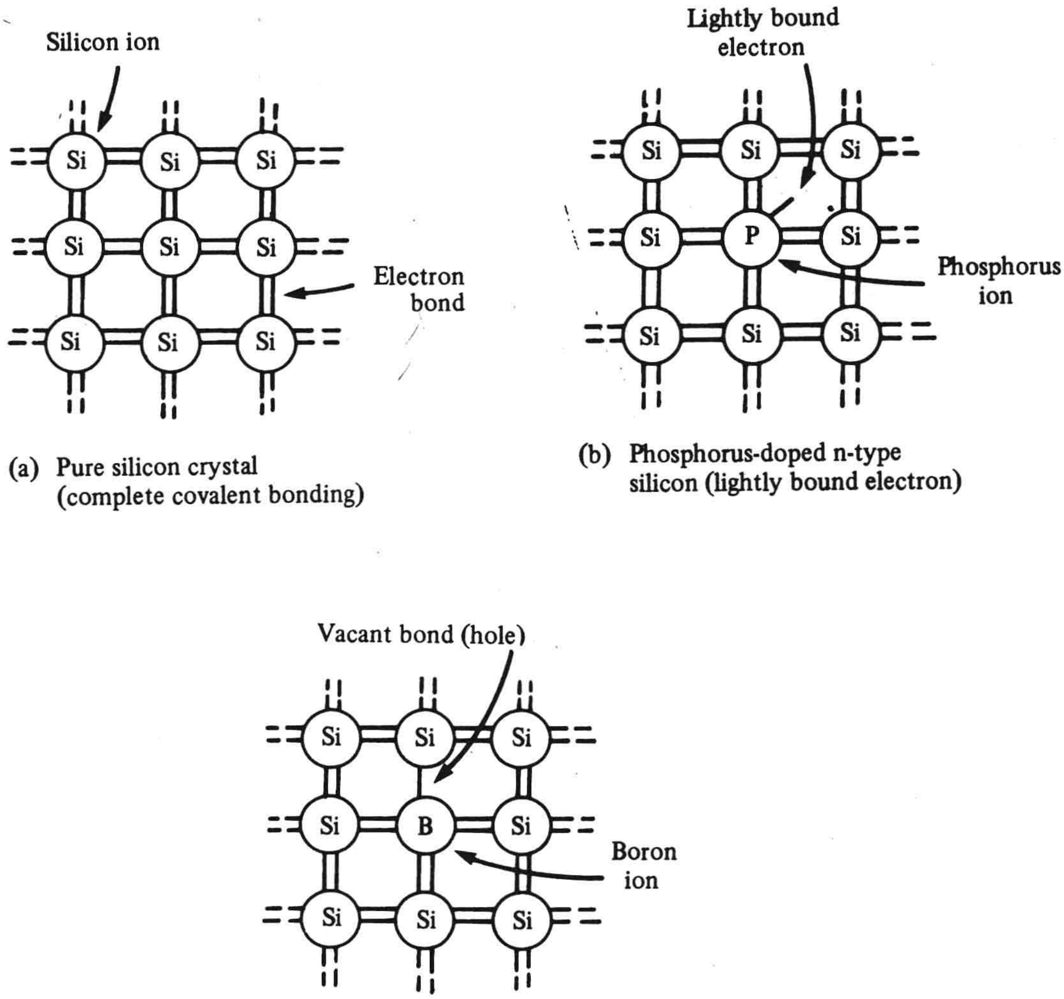
Semiconductors

A pure or intrinsic semiconductor is conveniently recognised as having a conductivity between that of a metal and of an insulator although, as we shall see later, this is not the formal definition of the term. Many elements and compounds exhibit semiconductor properties but in this text we shall restrict our discussion to Group 4 elements such as silicon.

Fig. 1.1a shows a very simple representation of the covalent bonding between silicon atoms in a crystal lattice structure. At a temperature of absolute zero the valence electrons are very tightly bound into the structure; none are free for conduction and the resistivity of the material is very high, approaching that of a

GaAs, GaP and GaAlAs are particularly important as materials for optical devices such as light-emitting diodes, photodetectors and lasers. Germanium has largely been supplanted by silicon for diodes and transistors and is not used in integrated circuit fabrication.

A formal treatment of conduction mechanisms in semiconductors is beyond the scope of this text.



(a) Pure silicon crystal (complete covalent bonding)

(b) Phosphorus-doped n-type silicon (lightly bound electron)

(c) Boron-doped p-type silicon (vacant bond ≡ hole)

Fig. 1.1

perfect insulator. However, as the temperature is raised the valence electrons gain more and more thermal (kinetic) energy and lose their immediate association with host ions; they become mobile and permit electrical conduction within the material. Thus resistivity falls with increasing temperature: a more correct definition of a semiconductor is a material which exhibits a negative temperature coefficient of resistivity, at least over a certain temperature range. It is important to appreciate that the silicon *ions* are locked into the crystal lattice and, being immobile, do not contribute to the conduction mechanism.

In their pure crystalline state intrinsic semiconductors have little application to devices and are usually doped by the addition of a controlled amount of impurity.

If a Group 5 impurity element such as phosphorus is introduced, each phosphorus atom bonds covalently within the silicon crystal lattice and introduces one extra, lightly bound electron (Fig. 1.1b). These electrons take part in the conduction process at all but very low temperatures and are termed *majority carriers* in *n-type*, Group 5 doped semiconductors. The resistivity of a doped semiconductor is significantly less than that of the intrinsic material.

n-type → *negatively* charged electrons

In contrast, if a Group 3 element such as boron is introduced as impurity into the silicon crystal, the three bonding electrons of each boron atom form covalent bonds with adjacent silicon atoms leaving one vacant bonding site, or *hole* (Fig. 1.1c). A hole may be considered mobile, as an electron from a neighbouring atom can fill it leaving a vacant site behind; in this way, the hole has moved. It is convenient to think of holes as positively charged mobile carriers — majority carriers in Group 3 doped, *p-type* semiconductors.

p-type → *positively* charged holes

Doped semiconductors, both n-type and p-type, are also known as extrinsic semiconductors and the dopant ions, Group 3 or Group 5, are fixed in the crystal lattice just as are the silicon ions.

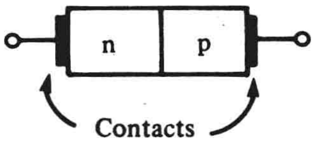
At normal ambient temperatures (around 290 K), mobile holes and electrons *both* exist in a semiconductor. However, the type of doping dictates which charge carrier dominates as the majority carrier (as described above), depressing below intrinsic level the concentration of the other carrier — the minority carrier. In n-type semiconductors, electrons are the majority carriers, holes the minority carriers; for p-type material, holes are the majority carriers and electrons the minority ones.

The concentration of both majority and minority carriers increases with temperature and this effect is used in fabricating negative temperature coefficient resistors (thermistors).

The Junction Diode

The simplest semiconductor component fabricated from both n-type and p-type material is the junction diode, a two-terminal device which, ideally, permits conduction with one polarity of applied voltage and completely blocks conduction when that voltage is reversed.

Consider a slice of semiconductor material one end of which is doped n-type, the other p-type. The n-type impurity dopant may be regarded as introducing fixed positively charged ions with loosely bound (negatively charged) electrons into the crystal lattice; the p-type dopant produces negative ions with attendant (positive) mobile holes.



Diode in Equilibrium

In the immediate junction region between the n-type and p-type material, electrons can easily diffuse from the n-type into the p-type region filling hole locations. This process is called recombination and leaves a band of ions fixed in the crystal lattice on either side of the junction — positive ions on the n-type side, negative ions on the p-type side. As diffusion and recombination proceed, an electron in the n-type material experiences an increasing repelling electric field owing to the negative ions. Eventually, recombination ceases when the thermal energy of the electrons is insufficient to overcome the field. In this equilibrium state there exists on either side of the junction a region which has become devoid of mobile carriers — the *transition*, or *depletion*, region shown in Fig. 1.2a.

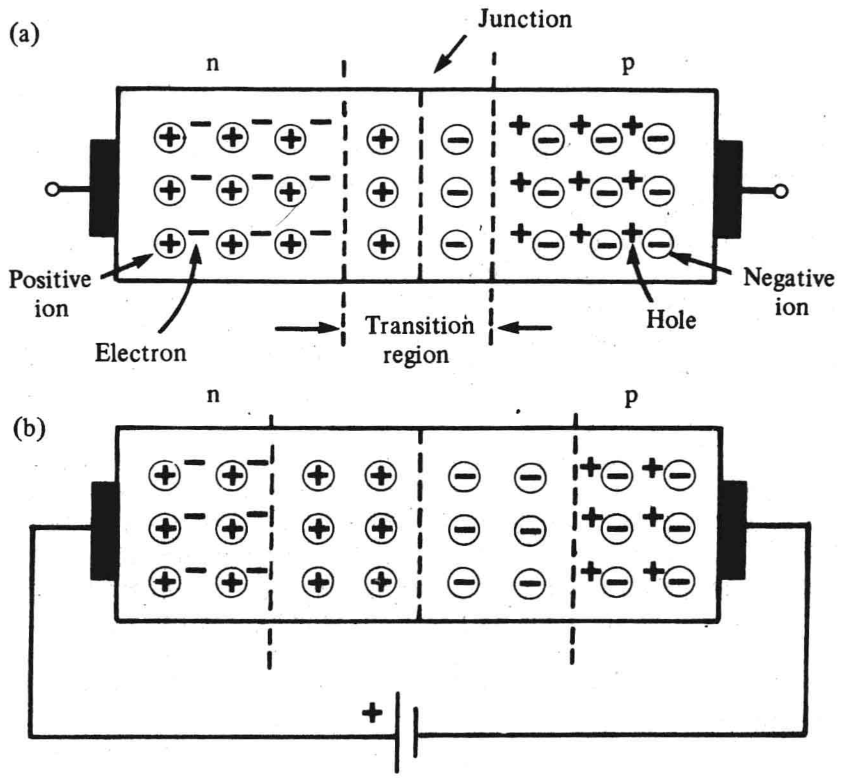


Fig. 1.2

Reverse Bias

If an external potential is applied to the device making the p-type material negative with respect to the n-type, the electric field strength at the junction is increased, repelling mobile carriers further from the junction and widening the transition region (Fig. 1.2b). Under such circumstances, it would be expected that no current would flow across the junction with this reverse bias applied; however, in practice, a small current does flow. The *leakage* (or reverse) current is due to the *minority* carriers (the low-concentration holes in n-type and electrons in p-type) being attracted across the junction by the applied potential. It is temperature-dependent since, as the temperature is increased, more carriers are thermally generated.

Positive attracts negative, and vice versa.

Leakage current can be as low as several tens of nanoamps at room temperature.

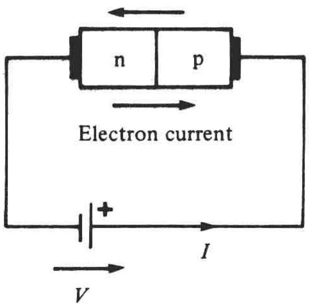
In practice it is reasonable to assume that the leakage current doubles approximately every 10 °C.

Variation of the width (w) of the transition region by applied voltage is important when considering the operation of junction field-effect transistors (see Chapter 7) and is given by

$$w \propto (\psi + V_r)^x \qquad (1.1)$$

where V_r is the applied reverse voltage, ψ is the diffusion potential associated with the electric field at the junction ($\psi \approx 0.6$ V for silicon). and x is a constant, either 1/2 or 1/3 depending on the method used in fabricating the junction.

Forward Bias



p-type *positive* and n-type *negative* for forward bias.

If the external bias potential is now reversed so that the p-type material is positive with respect to the n-type, a different set of conditions apply. Increasing the bias voltage, a larger and larger number of electrons gain sufficient (potential) energy to cross the junction into the p-type material; likewise, holes in the p-type readily cross into the n-type. The electron and hole currents in opposite directions are additive (since they involve oppositely charged carriers) and are controlled by the forward bias in an exponential manner as

$$I \propto \exp\left(\frac{qV}{kT}\right) \qquad (1.2)$$

where I is the forward current (amps), q is the electronic charge (1.602×10^{-19} coulombs), V is the forward bias potential (volts), k is Boltzmann's constant (1.38×10^{-23} Joule/K), and T is the temperature (K).

In correspondence with thermionic valve terminology, the p-type terminal is called the *anode* and the n-type the *cathode*.

At a nominal ambient temperature of 290 K, kT/q can be evaluated as approximately 25 mV. This is an important figure, as will be seen later, and should be committed to memory.

The electron and hole currents (and the total current) may be regarded as the *injection* of majority carriers across the junction, the level of injection being controlled by the applied forward potential. The relative magnitudes of these current components is determined by the doping of the n-type and p-type regions. If the n-type region is much more heavily doped than the p-type then the forward current is almost all electron current; if the relative doping levels are reversed, the hole current is predominant. While this feature is of little significance with regard to the performance of junction diodes, it is vital in the manufacture of high-quality bipolar junction transistors.

The Diode Equation

The behaviour of a semiconductor junction diode may be summarised as

(a) passing current under forward bias, with an associated forward voltage drop, and
(b) exhibiting a very small leakage current under reverse bias.

This can be expressed as a *diode equation*:

Derivation of the diode equation is complex; the reader is asked to take it on trust or to consult specialised texts.

$$I = I_s\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \qquad (1.3)$$

where I_s is the reverse leakage (or saturation) current. Fig. 1.3 shows this equation graphically (the device characteristic) and the diode symbol with defined directions of voltage and (positive) current.

Equation 1.3 is a simplification of the full diode equation which contains, in the exponential term, an extra factor which is current and material dependent.

Correspondence between the analytic expression of Equation 1.3 and the device characteristic can be checked. In the reverse region, for a sufficiently negative reverse voltage, the $\exp(qV/kT)$ term is very small and may be ignored relative to the (-1) term. Under this condition, the reverse leakage current is given by $I = I_s$. For a forward bias (V positive) of greater than 115 mV, the (-1) term has less than 1% significance and conveniently may be discarded leaving the forward bias region of the characteristic described by the approximate relationship

The direction of current flow is conventionally defined as that of positive charge carriers despite the fact that the current may be electron current or, as here, the sum of electron and hole currents.

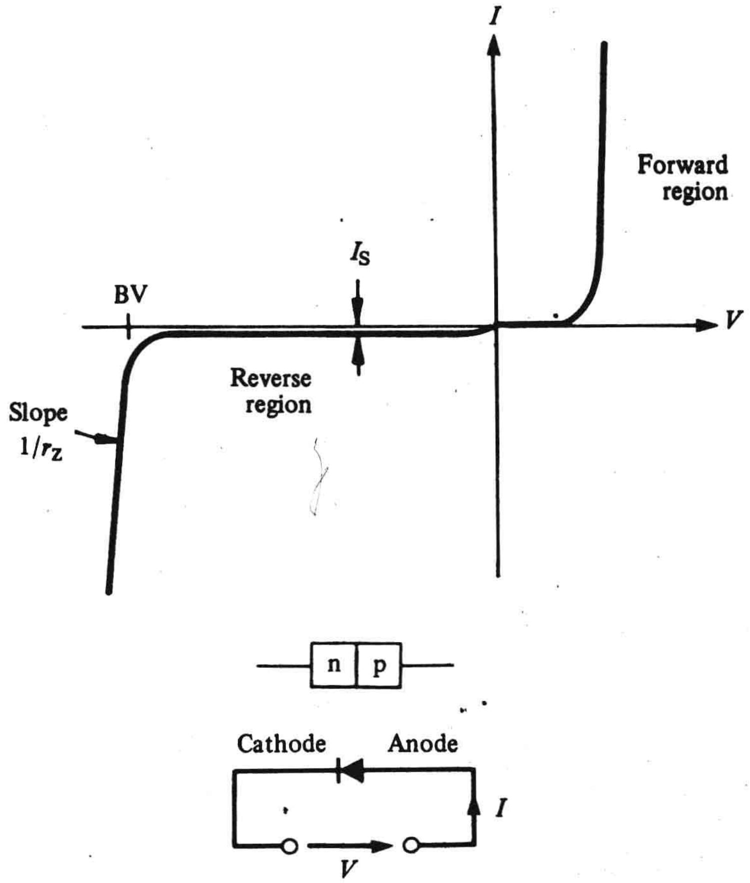


Fig. 1.3 Junction diode characteristic (not to scale), symbol and defined current and voltage directions.

$$I \approx I_s.\exp\left(\frac{qV}{kT}\right) \tag{1.4}$$

This corresponds with the injection description given by Equation 1.2.

The exponential nature of the forward characteristic makes it possible to calculate the change in forward voltage which results from increasing or decreasing the forward current by a certain ratio. Two useful ratios are the octave, a factor of 2 (or 1/2), and the decade, a factor of 10 (or 1/10).

There are corresponding voltages V_1 and V_2 for the two different currents I_1 and I_2.

It is interesting that we do not need to know the value of I_s to perform the voltage increment calculations. However, if we required the actual voltage, the value of I_s is necessary for calculation.

$$I_1 = I_s.\exp\left(\frac{qV_1}{kT}\right)$$

and

$$I_2 = I_s.\exp\left(\frac{qV_2}{kT}\right)$$

Therefore

$$\frac{I_2}{I_1} = \exp\left[\frac{q}{kT}(V_2 - V_1)\right] \tag{1.5}$$

or

$$(V_2 - V_1) = \frac{kT}{q}.\ln\left(\frac{I_2}{I_1}\right) \quad (1.6)$$

If $I_2 = 2 \times I_1$, an octave relationship, then at $T = 290$ K:

$$V_2 - V_1 = \frac{kT}{q}\ln 2 \approx 17.3 \text{ mV}$$

This implies that increasing the forward current by a factor of two increases the forward voltage by 17.3 mV irrespective of I_s and of the actual current level, provided that the (– 1) term in the diode equation may be ignored. If $I_2 = 0.5\ I_1$, a halving of forward current, Equation 1.6 also shows that the forward diode voltage is *reduced* by 17.3 mV.

Note that the voltage increments are proportional to absolute temperature (K).

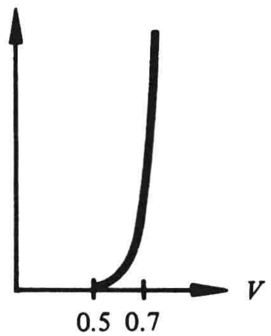
Now, for a decade change in current, $I_2 = 10 \times I_1$,

$$V_2 - V_1 = \frac{kT}{q}\ln 10 \approx 57.6 \text{ mV} \quad \text{at 290 K}$$

and for a reduction in current by a factor of 10, i.e. $I_2 = 0.1\ I_1$,

$$V_2 - V_1 \approx -57.6 \text{ mV}$$

Another result of the sharply rising nature of the exponential forward characteristic, when it is plotted against linear current and voltage scales, is that there appears to be little conduction until (for a silicon diode) a voltage of approximately 0.5 V is reached. Above that voltage the current rises more and more rapidly such that, for normal operating currents, there is little change of forward voltage in the region of 0.7 V. This feature arises as a result of plotting the characteristic on linear scales; if diode voltage is plotted against the logarithm of the forward current, the characteristic becomes, over much of its length, a straight line with slope approximately 60 mV/decade.



Exercise 1.1

Given that the forward voltage of a diode is 0.7 V for a forward current of 5 mA at a temperature of 290 K, calculate the reverse leakage current, I_s.
[*Answer*: $I_s = 3.4 \times 10^{-15}$ A; a surprisingly low figure! In practice, low-power diodes usually exhibit leakage currents in the order of tens of nA. The discrepancy between the two figures is due to current leakage across the physical surface of the diode which is additive to the junction leakage predicted by the diode equation. Another factor which destroys the exponential nature of the diode equation, particularly at higher current levels, is the resistance of the bulk doped semiconductor on either side of the junction; this gives an increased forward voltage at a given current.]

Temperature dependence of the diode characteristic can be determined by considering Equation 1.4 in the form

$$V = \frac{kT}{q}.\ln\frac{I}{I_s} \quad (1.7)$$

Since we have already recognised that I_s increases with temperature then, to maintain a constant forward current I, the forward voltage V must be reduced as temperature is increased. Thus the forward voltage drop has a negative temperature coefficient which, in practice, is approximately – 2 mV/°C.

This may seem to be an insignificant figure but it does represent 200 mV over a temperature range of 100 °C, a sizeable fraction of the normal forward voltage.

Breakdown

One feature of the diode characteristic not yet described is breakdown in the reverse bias region. When a certain reverse voltage, the reverse breakdown voltage (BV), is exceeded the reverse current increases dramatically for increasing reverse voltage (see Fig. 1.3) owing to the very high electric fields at the junction. The breakdown voltage can be controlled in manufacture by adjusting the doping levels: the higher the doping level, the lower the magnitude of the breakdown voltage. A diode with sufficiently high breakdown voltage should be chosen to preserve true rectifying action in normal circuit operation.

Depending on intended application, the breakdown voltage can range from several volts (breakdown diodes) to over 20 kV (high voltage rectifiers).

Diode Capacitance

While the nonlinear static (or d.c.) behaviour of a junction diode is characterised by the diode equation (Equation 1.3) or its approximation in the forward region (Equation 1.4) the device possesses capacitive properties which can be described in terms of transistion capacitance and diffusion capacitance.

Transition capacitance: A junction diode under reverse bias may be considered as acting as a parallel-plate capacitor, the two plates being the bulk n-type and p-type semiconductor separated by the transistion region dielectric. This transition capacitance (C_t) is proportional to the cross-sectional area (A) of the junction and inversely proportional to the width (w) of the transistion region, i.e. the separation of the plates.

$$C_t \propto \frac{A}{w}$$

Since the transition width is a function of the applied reverse voltage as given by Equation 1.1, the transition capacitance is also a function of voltage

$$C_t \propto (\psi + V_r)^{-x}$$

which approximates to

$$C_t \propto V_r^{-x} \qquad (1.8)$$

(where $x = 1/2$ or $1/3$) for a reverse voltage (V_r) greater than several volts. Diodes used as voltage-variable capacitors (varicaps or varactors) find wide application in the tuning sections of radio and television receivers.

The capacitance of a varicap diode can be varied over a range of several hundred picofarads (large area device). Signal diodes generally have a capacitance of less than 10 pF.

Diffusion capacitance: A junction diode also possesses capacitive properties under forward bias conditions by virtue of charge crossing the junction region. This is a complex concept and the reader should refer to more advanced texts for detail. However, it is sufficient to note that the diffusion capacitance (C_d) in forward bias is directly proportional to the forward current flowing through the device.

Diode ratings

Although semiconductor devices are robust and reliable, circuit designers must still ensure that they are operated within the range of capabilities for which they are manufactured. Diodes are no exception and information regarding maximum permissible parameter limits (or ratings) can be found published in manufacturers' data. The important factors for a diode are maximum reverse voltage (before break-down), maximum forward current, and maximum power dissipation (the product of

Imagine the consequences of failure in a nuclear power station, an aircraft navigation system or even a domestic television receiver!