

# Transistors

THEORY AND CIRCUITRY

K. J. Dean

# TRANSISTORS

## *Theory and Circuitry*

*by*

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## Preface

This book was written as a result of experience in teaching electronics, and in particular, transistor circuitry. In it an attempt has been made to strike a balance between circuit analysis and circuit design. At the present time, there seems to be an increasing tendency in the universities and colleges of technology to concentrate on mathematical circuit analysis, often without much examination of practical circuits. The chief use of the careful analysis of equivalent circuits, for example, must surely be that it enables the designer to make the right approximations in the situation in which he is involved. He must face practical problems on the choice of operating point, the minimization of noise, and thermal stability.

In this book, the use of some powerful mathematical tools has been deliberately avoided so that the text might be of wider use. It is hoped that this book will be of help to students working for a degree or a diploma in technology in electrical engineering or for a higher national certificate or diploma in electrical engineering or applied physics. The book may also appeal to graduates concerned with the design of transistor circuits, or who find an increasing use for electronics in research and industry. The continued high attendance at transistor courses throughout the United Kingdom and the growing interest in tunnel diodes, silicon controlled rectifiers and field effect devices, amongst others, show the wide practical use of electronics.

The recent development of silicon epitaxial transistors and the trend to modular construction have found their place in this book. The use of "building bricks" and microminiaturized packaged circuits, particularly in the fields of computation, digital control and nuclear instrumentation may well be a foretaste of things to come. Their intelligent use must depend, in the last resort, not merely on rules or loading tables, but on both circuit analysis and a thorough understanding of the principles of circuit design.

I would like to offer my thanks to those people who have helped with the preparation of this book, and in particular to Mr. F. C. Evans of Kingston College of Technology.

K.J.D.

## Glossary of Terms

$a_i$	current gain
$a_v$	voltage gain
$a_w$	power gain
$A_v$	voltage gain without negative feedback
$\alpha$	current gain of transistor in the common base mode
$\alpha'$	current gain of transistor in the common emitter mode
$\alpha''$	current gain of transistor in the common collector mode
$\alpha'_o$	current gain of transistor when $V_{cb}=0$
$\alpha'_s$	"on demand" current gain of transistor in common emitter mode
$c_o$	output capacitance (using $y$ parameters)
$c_i$	input capacitance (using $y$ parameters)
$D_n$	diffusion coefficient for electrons
$D_p$	diffusion coefficient for holes
$E_F$	Fermi energy
$\varepsilon$	the fraction of possible energy levels at an energy $E$ which is occupied at an absolute temperature $T$
$f_a$	the frequency at which the common base short-circuited current gain has fallen to 0.707 of its low frequency value
$f_1$	the frequency at which the common emitter short-circuited current gain has fallen to unity
$f_T$	the frequency at which the common emitter short-circuited current gain is calculated to fall to unity, on the assumption of a 6 dB per octave fall
$g_i$	the input conductance (using $y$ parameters)
$g_m$	the mutual conductance, i.e. a small change in output current divided by the change in input voltage producing it at constant output voltage
$g_o$	the output conductance (using $y$ parameters)
$h_i$	one of the general $h$ parameters, $(\partial V_i / \partial I_i)_{V_o}$
$h_{ib}$	the $h_i$ parameter referred to the common base mode
$h_{ic}$	the $h_i$ parameter referred to the common collector mode
$h_{ie}$	the $h_i$ parameter referred to the common emitter mode
$h_f$	one of the general $h$ parameters, $(\partial I_o / \partial I_i)_{V_o}$

$h_{fb}$	the $h_f$ parameter referred to the common base mode
$h_{fc}$	the $h_f$ parameter referred to the common collector mode
$h_{fe}$	the $h_f$ parameter referred to the common emitter mode
$h_r$	one of the general $h$ parameters, $(\partial V_i / \partial V_o)_{I_i}$
$h_{rb}$	the $h_r$ parameter referred to the common base mode
$h_{rc}$	the $h_r$ parameter referred to the common collector mode
$h_{re}$	the $h_r$ parameter referred to the common emitter mode
$h_o$	one of the general $h$ parameters, $(\partial I_o / \partial V_o)_{I_i}$
$h_{ob}$	the $h_o$ parameter referred to the common base mode
$h_{oc}$	the $h_o$ parameter referred to the common collector mode
$h_{oe}$	the $h_o$ parameter referred to the common emitter mode
$I_b$	direct base current
$i_b$	alternating component of base current
$I_c$	direct collector current
$i_c$	alternating component of collector current
$I_{cbo}$	leakage current of a common base circuit
$I_{ceo}$	leakage current of a common emitter circuit
$I_{cs}$	thermally stabilized collector current
$I_e$	direct emitter current
$i_e$	alternating component of emitter current
$I_i$	direct input current
$i_i$	alternating component of input current
$I_o$	direct output current
$i_o$	alternating component of output current
$J$	current density
$k$	thermal stability factor, $dI_{cs}/dI_{ceo}$
$\mu$	mobility
$\mu_n$	electron mobility
$\mu_p$	hole mobility
$N$	number of minority carriers
$n$	density of free carriers (in Chapter 1)
$n$	turns ratio
$\omega$	pulsatance, $2\pi \times$ frequency
$Q$	selectivity factor
$Q_b$	base charge
$Q_{bs}$	excess base charge due to saturation
$Q_{on}$	base charge necessary to turn transistor on
$Q_{off}$	base charge necessary to turn transistor off
$Q_v$	charge which is necessary to charge the depletion layer capacitance

$r_b$	one of the $T$ parameters ( $=z_r$ )
$r_c$	one of the $T$ parameters ( $=z_o - z_r$ )
$r_e$	one of the $T$ parameters ( $=z_i - z_r$ )
$r_{eb}$	$r_e + r_b$
$r_{ee}$	$r_e + (1 - \alpha)r_b$
$\rho$	resistivity
$R_L$	load resistance
$R_T$	transresistance, $(\partial V_o / \partial I_i)_{V_i}$
$s$	thermal stability, $dI_{cs}/dI_{cbo}$
$\sigma$	conductivity
$\tau$	lifetime
$T$	absolute temperature
$T_{amb}$	ambient temperature
$T_c$	collector time constant
$T_{co}$	collector time constant when $V_{cb}=0$
$t_D$	delay time
$t_F$	fall time
$\theta$	thermal resistance
$T_j$	junction temperature
$t_R$	rise time
$t_S$	storage time
$T_s$	saturation time constant
$V_{cb}$	direct collector-base voltage
$v_{cb}$	alternating component of collector-base voltage
$V_{eb}$	direct base-emitter voltage
$v_{eb}$	alternating component of base-emitter voltage
$V_{ce}$	direct collector-emitter voltage
$v_{ce}$	alternating component of collector-emitter voltage
$V_i$	direct input voltage
$v_i$	alternating component of input voltage
$V_f$	forward voltage of tunnel diode
$V_o$	direct output voltage
$v_o$	alternating component of output voltage
$V_p$	peak voltage of tunnel diode
$V_v$	valley voltage of tunnel diode
$y_f$	one of the $y$ parameters, $(\partial I_o / \partial V_i)_{V_o}$
$y_i$	one of the $y$ parameters, $(\partial I_i / \partial V_i)_{V_o}$
$Y_L$	admittance of an amplifier load
$y_o$	one of the $y$ parameters, $(\partial I_o / \partial V_o)_{V_i}$
$y_r$	one of the $y$ parameters, $(\partial I_i / \partial V_o)_{V_i}$

$z_f$	one of the $z$ parameters, $(\partial V_o / \partial I_i)_{I_o}$
$z_i$	one of the $z$ parameters, $(\partial V_i / \partial I_i)_{I_o}$
$z_{in}$	input impedance of a transistor stage
$z_o$	one of the $z$ parameters, $(\partial V_o / \partial I_o)_{I_i}$
$z_r$	one of the $z$ parameters, $(\partial V_i / \partial I_o)_{I_i}$

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## CHAPTER 1

# Semiconductor Physics

Semiconductors are substances with electrical resistivities in the range between those of insulators and metals. The resistivity of glass, for example, is about  $10^{12}$  ohm cm, and that of copper is  $10^{-6}$  ohm cm. Semiconductors invariably have a negative temperature coefficient of resistance and they often exhibit some degree of rectifier action and photoconductivity. Typical semiconductors are the elements germanium and silicon and the compounds indium antimonide, indium arsenide and copper oxide. Their chief properties can be discussed successfully by reference to their atomic structure and the forces which are acting at intermolecular levels. The energy associated with the electrons can be illustrated in energy level diagrams and by using the band theory of solids. A brief treatment of conduction in semiconductors is given in this chapter.

It is known that the electrons in an isolated atomic structure can only have certain definite energy levels, transitions being made from one energy level to another accompanied by the emission or absorption of energy. Electrons possessing little energy orbit close to the nucleus, due to their high binding energy, while energy received due to, say, ultra-violet light, increases the orbit by discrete steps and not by a continuously variable amount. Alternatively, it may remove a high energy electron in an outer orbit completely from its atomic site.

The definite energy levels in the case of individual atoms, not influenced by interatomic forces, become a series of energy bands when applied to the regular structure of a crystal lattice. The lowest energy levels are all filled. One important energy band, corresponding to electrons furthest from the nucleus in the unexcited state, is the valence band. An electron when given energy is said to be excited. It may then leave the valence band by temporarily jumping to a conduction band at yet higher energy. Such bands are often empty or only partly filled. This is illustrated in Fig. 1.1. Conduction electrons, being far from the nucleus, may be easily made to drift

under the action of a field. This drift is commonly known as a conduction current.

Conduction of electrons takes place, as might be expected, in the conduction bands and so the gap between the top of the valence

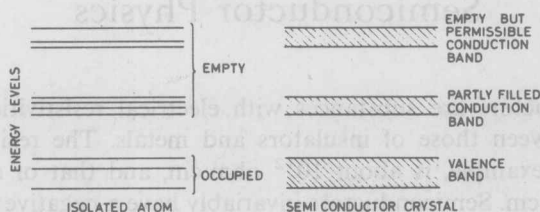


FIG. 1.1

band and the lowest energy level in the conduction band is an important characteristic of a substance. This band-gap is the minimum energy necessary to make a valence electron mobile within the crystal. Also the binding energy and the melting point of the crystal are related to the crystal structure, so that a high binding energy gives rise to a wide band-gap. Some examples are quoted in Table 1.1.

Table 1.1

substance	melting point (°C)	energy gap (eV)	mobilities (cm sec <sup>-1</sup> /V cm <sup>-1</sup> )	
			electrons	holes
Gallium arsenide	1,233	1.5	4,000	400
Silicon	1,420	1.1	1,300	500
Germanium	937	0.65	3,800	1,800
Indium arsenide	940	0.36	20,000	250
Indium antimonide	525	0.2	78,000	4,000

### Fermi Level

As shown in Fig. 1.1, the energy of an electron in a crystal may take one of a number of closely spaced values within these bands, and it may not take any value which lies within the non-permitted bands between them. At 0°K the lowest energy levels are filled by the electrons, so that these levels are completely occupied up to a certain level, and completely unoccupied above it. At higher temperatures, the thermal energies which the electrons possess lift

them to higher energy levels. By using Fermi-Dirac statistics it is possible to calculate the fraction,  $\varepsilon$ , of possible levels at any energy  $E$  which is occupied at a temperature  $T$ :

$$\varepsilon = \frac{1}{\exp (E-E_F) / k T + 1}$$

This relationship involves the Fermi level,  $E_F$ , which is such that, at any temperature, the number of electrons with greater energy than the Fermi energy is equal to the number of unoccupied energy levels lower than this. The permitted energy band immediately above the Fermi level is the conduction band and that below it is the valence band. In conductors, the Fermi level occurs in a permitted band and, in insulators, it is in the centre of a large forbidden band. In semiconductors, the Fermi level lies in the relatively small energy gap.

### Mobility

Electrical conductivity depends both on the number of charge carriers in the conduction bands and on the rate at which these charges move under the influence of an electric field. The velocity with which a charge moves in unit field is called its *mobility*. In semiconductors, the carrier concentration is often dependent on impurities present. This is particularly true where there is a large band-gap or the substance is at a low temperature. If an energy band has empty levels, it may hold electrons which may then take part in conduction. Such levels occur, for example, in the highest energy bands. Electrons entering a vacant level in the conduction band leave behind a gap or "hole" in the valence band. This permits other electrons to move up into the valence band leaving holes at a low energy level. Because of this it is convenient to consider two types of conduction. In one case the charge,  $-e$ , is said to be carried by an electron, and in the other the absence of an electron, due to its elevation to another band, is said to constitute a hole or a positive carrier, carrying a charge,  $+e$ . Thus, the free conduction electrons, moving under the action of an e.m.f., may be viewed as the movement of electric charge by negative carriers, whilst the corresponding movement of holes constitutes the motion of a charge by positive carriers.

In a pure semiconductor, conduction takes place by electron and

hole pairs, since each electron that is excited leaves a hole at a lower energy level. The mobilities of these positive and negative carriers are shown in Table 1.1. Their differing mobilities are due to the fact that they are at different energy levels and travel under the action of different forces. A carrier's mobility,  $\mu$ , is stated in unit field, and so is often expressed in  $\text{cm sec}^{-1}/\text{V cm}^{-1}$ , that is, in  $\text{cm}^2\text{V}^{-1}\text{sec}^{-1}$ .

### Intrinsic Conduction

For the purposes of transistor manufacture two important materials are germanium and silicon. These elements are tetravalent, that is, they appear in group IV of the periodic table. They have a tetrahedral crystal structure similar to that of diamond, in which adjacent atoms are bound by sharing the outer valence electrons forming covalent bonds. Figure 1.2 illustrates this in one plane.

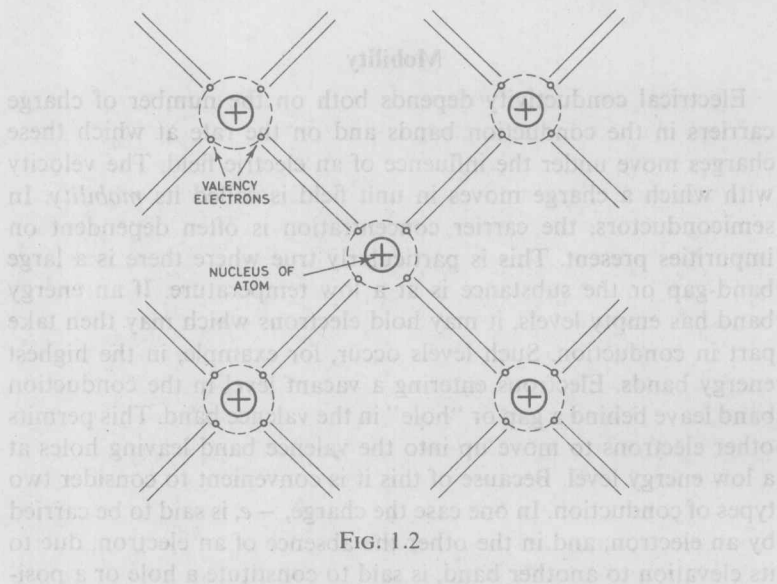


FIG. 1.2

Industrial preparation of germanium can reduce impurities to the order of one part in  $10^{10}$ . This is largely due to the technique of zone refining, in which a liquid zone is formed in a solid ingot, and this zone is made to move along the bar of material sweeping the impurities with it. The purification of silicon is more difficult, but in the last few years much progress has been made.

Conduction in this intrinsic material is small and is made possible by the thermal energies of the electrons. Under the action of a field  $E$ , a resultant drift velocity is produced against the direction of the applied field. We can express this as:

$$v = \mu E \quad (1.1)$$

where  $\mu$ , the mobility of the carriers, is the drift velocity in unit field.

Since, as shown previously, electron mobility,  $\mu_n$ , and hole mobility,  $\mu_p$ , are not identical, the total current,  $I$ , flowing in an intrinsic semiconductor is given by:

$$I = I_p + I_n \quad (1.2)$$

where  $I_p$  is the hole current and  $I_n$  is the electron current. Therefore from equations (1.1) and (1.2)

$$J = eE(n\mu_n + p\mu_p)$$

where  $en$  and  $ep$  are the respective charge densities and  $J$  is the current density. Thus the conductivity,  $\sigma = J/E$  and we put  $\rho = 1/\sigma$

Therefore 
$$\sigma = e(n\mu_n + p\mu_p) \quad (1.3)$$

But Fowler (1936) has shown that for the thermal formation of electron-hole pairs in an intrinsic semiconductor

$$n = p = 2 \frac{(2\pi mkT)^{3/2}}{h^3} \exp\left(\frac{W}{2kT}\right) \quad (1.4)$$

(where  $m$  is the electron mass,  $k$  is Boltzmann's constant,  $T$  is the absolute temperature,  $h$  is Planck's constant and  $W$  is the energy for the formation of electron-hole pairs).

This shows the resistivity,  $\rho$ , of the material is a function of temperature. This temperature dependence of the current which flows in the semiconductor is of great practical importance. Some typical resistivities are given in Table 1.2.

Table 1.2

substance	resistivity at 300°K (ohm cm)
Germanium	65
Silicon-typical refined	250
Silicon-high purity	100,000

### Extrinsic Conduction\*

The electrical properties of intrinsic semiconductors can be considerably modified by the intentional addition of trace impurities in concentrations of the order of one part in  $10^8$ . Important cases arise when the valency of the impurity is 3 or 5, causing the electrical properties of the semiconductor to be modified. *Extrinsic conduction* due to the impurity is then said to take place. This does not mean that intrinsic conduction does not also occur, but, unless the temperature is high, its effect is small compared with that due to the conduction which is due to the presence of the impurities.

A trace of impurity of group V, say arsenic, may be incorporated into the germanium lattice, each atom replacing an atom of germanium. Each arsenic atom may be considered as being completely surrounded by germanium atoms. The covalent bonds are completed with this isolated atom, an extra electron becoming available

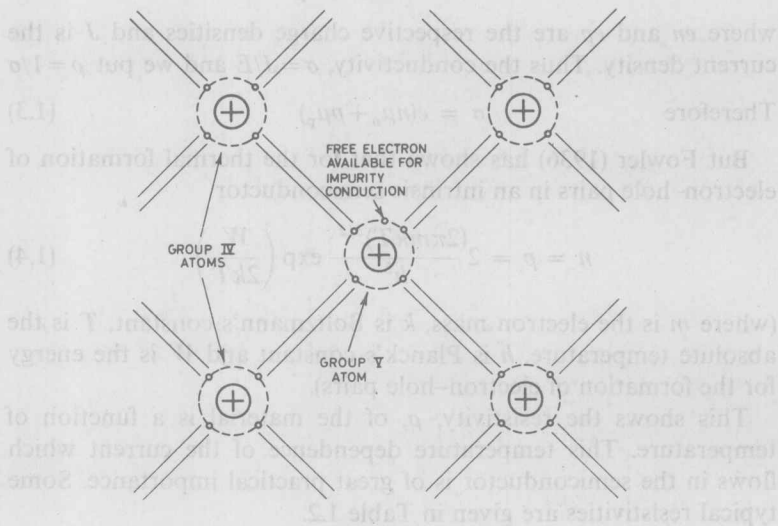


FIG. 1.3

for each atom of impurity. Impurities of this kind also include phosphorus and antimony and are called "donor" types, providing additional electrons or *n*-carriers. This technique of adding impurities to molten semiconductors in carefully controlled amounts

\* Also known as "impurity conduction".

is known as "doping". Due to extrinsic conduction, doped semiconductors have reduced resistivities compared with the intrinsic materials.

At temperatures near the absolute zero, the free electrons illustrated in Fig. 1.3 remain closely bound to their own nuclei. They have a fixed energy level associated with them. It is above the valence band and below the bottom of the first conduction band of the intrinsic material. However, above temperatures of the order of  $40^\circ\text{K}$ , the excess donor electrons' orbits cover several atomic distances and all these isolated donor atoms may be considered to be ionized. Under the action of an applied e.m.f. they drift in a direction imposed by the applied field. The positive nuclei left behind are static and do not drift as holes drift in intrinsic conduction. Since intrinsic conduction is taking place as well, a few holes, formed in this process, will move. Thus electrons are the majority carriers and holes are the minority carriers.

Let  $n$  be the density of free carriers and the impurity density be  $n_0$ . Then, as the temperature is raised the number of free carriers due to intrinsic conduction increases, and that due to extrinsic conduction remains substantially constant. In the case of germanium raised to  $150^\circ\text{C}$ , the number of free intrinsic carriers has risen to equal the number of extrinsic carriers with normal impurity concentration. This is illustrated in Fig. 1.4.

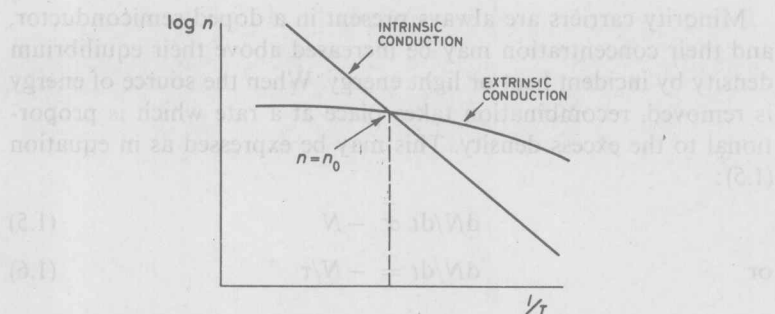


FIG. 1.4

At this temperature the semiconductor is said to become intrinsic (this may be seen from equation (1.4)), and it is nearly always necessary to operate below these temperatures. Silicon becomes intrinsic



at 300°C. When the temperature of the semiconductor is lowered through this point, the material is said to become extrinsic.

Boron, aluminium and indium are examples of group III, and when these exist as impurities the lattice has one bond incomplete. This bond is filled by an electron from a neighbouring atom. This process, often repeated, may be regarded as the movement of a hole. This hole moves through several atomic distances, and, under the action of an e.m.f., becomes the majority carrier in this acceptor- or *p*-type material. In this case the holes or *p*-carriers move and the negatively charged sites are left behind.

The impurity level in the case of a group III impurity in germanium is of the order of 0.01 eV above the valence band, and for group V it is 0.01 eV below the lowest conduction level. This should be contrasted with the band-gap of about 0.65 eV.

The presence of a trace impurity of group V and its associated impurity level has the effect of raising the Fermi level above the position it normally occupies in the band-gap. Similarly, the presence of a group III impurity results in the Fermi level being lowered. Since the impurity concentration is relatively small the extent by which the Fermi level is shifted is also small. It still lies within the band-gap but displaced from its original position.

### Lifetime

Minority carriers are always present in a doped semiconductor, and their concentration may be increased above their equilibrium density by incident heat or light energy. When the source of energy is removed, recombination takes place at a rate which is proportional to the excess density. This may be expressed as in equation (1.5):

$$dN/dt \propto -N \quad (1.5)$$

or

$$dN/dt = -N/\tau \quad (1.6)$$

where  $\tau$  is a constant depending on the semiconductor material.

One solution of this is:

$$N = N_0 \exp(-t/\tau) \quad (1.7)$$

where  $N_0$  is the initial density when the energy source is removed.  $\tau$  is the minority carrier lifetime of the material and may be regarded