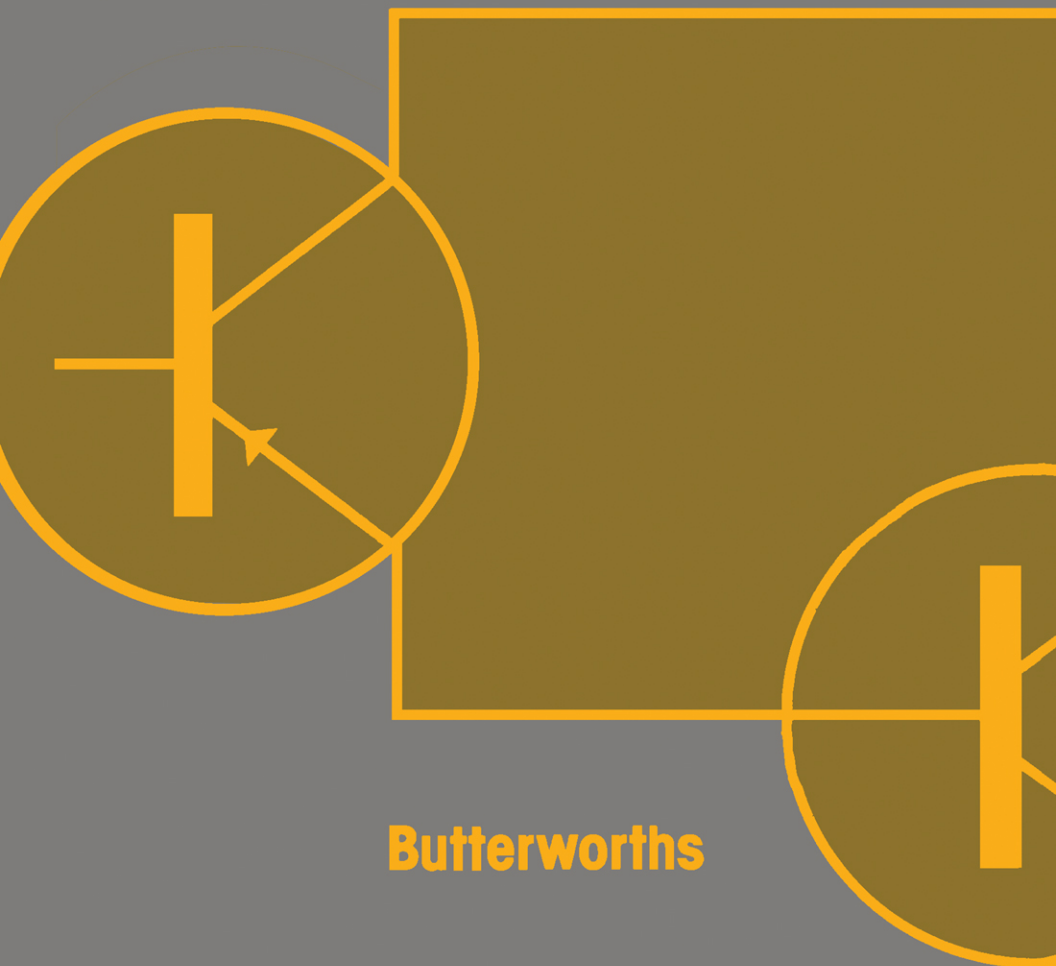


**Sixth
Edition**

S W Amos

Principles of Transistor Circuits

**Introduction to the design of
amplifiers, receivers and
digital circuits**



Butterworths

Principles of Transistor Circuits

SIXTH EDITION

This page intentionally left blank

Principles of Transistor Circuits

SIXTH EDITION

INTRODUCTION TO THE DESIGN OF
AMPLIFIERS, RECEIVERS AND DIGITAL CIRCUITS

S W AMOS, BSc, CEng, MIEE

*formerly Head of Technical Publications Section,
Engineering Training Department,
British Broadcasting Corporation*

BUTTERWORTHS

London Boston Sydney Wellington Durban
Toronto

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, including photocopying and recording, without the written permission of the copyright holder, application for which should be addressed to the Publishers. Such written permission must also be obtained before any part of this publication is stored in a retrieval system of any nature.

This book is sold subject to the Standard Conditions of Sale of Net Books and may not be re-sold in the UK below the net price given by the Publishers in their current price list.

First published for *Wireless World* by Iliffe Books Ltd, 1959

Second edition 1961

Third edition 1965

Fourth edition 1969

Reprinted 1972

Fifth edition by Newnes-Butterworths, 1975

Reprinted 1976

Reprinted 1978

Sixth edition by Butterworths, 1981

© S. W. Amos, 1981

Amos, S. W.

Principles of transistor circuits. – 6th ed.

1. Transistor circuits

2. Electronic circuit design

I. Title

621.3815'30422 TK7871.9

ISBN 0-408-01106-8

ISBN 0-408-00599-8 Pbk

Printed in Great Britain by The Whitefriars Press Ltd.,
London and Tonbridge

Preface

The most significant development in electronics since the fifth edition was published in 1975 has been the more widespread use of integrated circuits. Their application to remote control of television receivers, in digital watches and in microprocessors are three obvious examples. Accordingly some changes and additions have been made in Chapter 15 on Digital Techniques to update the information and to improve the clarity of presentation. The author would like to record his gratitude to John Scotland of the BBC Engineering Training Department who checked the accuracy of this chapter and made a number of valuable suggestions for its improvement.

The section on a.m. detectors has been enlarged to include an account of the shunt-diode circuit, and the description of f.m. detectors has been rewritten to give a detailed explanation of the ratio detector and to include new information on the balanced quadrature type included in integrated circuits.

The account of regulated power supplies has been expanded to include up-to-date circuits, and the section on thyristors has been revised to give more information on modern types.

A number of minor changes have been made to eliminate dated information or to simplify or clarify the text.

Finally, all the circuit diagrams have been redrawn so that the graphical symbols conform with the most recent recommendations of the British Standards Institution as published in BS 3939.

S. W. Amos
Broadway, Worcs.

Acknowledgments

The author is grateful to his former employers, the British Broadcasting Corporation, for permission to use the circuit diagrams of two BBC-designed amplifiers. Thanks are also due to Thorn-A.E.I. Radio Valves & Tubes Ltd. who provided valuable information on the design of i.f. amplifiers (particularly those using silicon transistors) and to Mullard Ltd. for information on bipolar and field-effect transistors, the design of video and colour-difference amplifiers and on electric-motor control by thyristors. The information on monolithic amplifiers is used by kind permission of Motorola Semiconductor Products Inc. and on the u.h.f. tuner by permission of Rank-Bush-Murphy Ltd.

The following organisations also provided useful information:

General Electric Co. Ltd.

Ferguson Radio Corporation Ltd.

Philips Electrical Ltd.

Texas Instruments Ltd.

S.G.S. Fairchild Ltd.

The author also gratefully acknowledges the help of Dr. J. R. Tillman who made useful comments on Appendix A.

Contents

1 Semiconductors and Junction Diodes	1
2 Basic Principles of Transistors	20
3 Common-base and Common-gate Amplifiers	41
4 Common-emitter and Common-source Amplifiers	53
5 Common-collector and Common-drain Amplifiers (Emitter and Source Followers)	65
6 Bias and D.C. Stabilisation	77
7 Small-signal A.F. Amplifiers	99
8 Large-signal A.F. Amplifiers	120
9 D.C. and Pulse Amplifiers	141
10 I.F. Amplifiers	162
11 Sinusoidal Oscillators	189
12 Detectors, Frequency Changers and Receivers	200
13 Pulse Generators	219
14 Sawtooth Generators	243
15 Digital Circuits	252
16 Further Applications of Transistors and other Semiconductor Devices	281
Appendix A The Manufacture of Transistors and Integrated Circuits	306
Appendix B Transistor Parameters	318
Appendix C The Stability of a Transistor Tuned Amplifier	324
Index	327

This page intentionally left blank

Semiconductors and Junction Diodes

INTRODUCTION

The most significant development in electronics since the Second World War has been the introduction of the transistor. This minute semiconductor device can amplify, oscillate and be used for switching and other purposes. In all its applications it has an efficiency much greater than that of a thermionic valve. Moreover the transistor has a longer life than a valve, is non-microphonic and is much cheaper than a valve.

It is not surprising that transistors have superseded valves in most categories of electronic equipment. They will probably supplant valves completely in all except high-power applications.

Early germanium transistors had limited output power and operated satisfactorily only up to a few MHz: moreover they had appreciable leakage currents which caused difficulties at high ambient temperatures. Later developments particularly the introduction of the silicon epitaxial planar transistor eliminated these limitations. Modern transistors can give more than 25 W output; they operate satisfactorily up to frequencies above 1,000 MHz, and leakage currents are no longer troublesome. The characteristics are however dependent on temperature and precautions are necessary to ensure stability of operating conditions and gain.

By its physical structure the bipolar transistor is a current-controlled device, that is to say its output current is linearly related to the input current. The input resistance is low (and dependent on signal amplitude) and the output resistance is high. The associated circuits must be designed to operate with such resistances

2 Principles of Transistor Circuits

and thus differ from those used with valves. On the other hand the properties of the field-effect transistor are very similar to those of the valve. It is the purpose of this book to give the fundamental principles of the design of circuits for both types of transistor.

To explain the origin of the properties of transistors it is useful to begin with an account of the physics of semiconductors.

DEFINITION OF A SEMICONDUCTOR

The heart of a transistor consists of semiconducting material, e.g. germanium or silicon and the behaviour of the transistor largely depends on the properties of this material. As the name suggests a semiconducting material is one with a conductivity lying between that of an insulator and that of a conductor: that is to say one for which the resistivity lies between, say $10^{12} \Omega\text{-cm}$ (a value typical of glass) and $10^{-6} \Omega\text{-cm}$ (approximately the value for copper). Typical values for the resistivity of a semiconducting material lie between 1 and $100 \Omega\text{-cm}$.

Such a value of resistivity could, of course, be obtained by mixing a conductor and an insulator in suitable proportions but the resulting material would not be a semiconductor. Another essential feature of a semiconducting material is that its electrical resistance

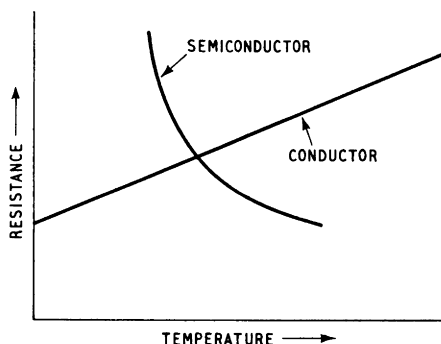


Fig. 1.1. Resistance-temperature relationship for a conductor and a semiconductor

decreases with increase in temperature over a particular temperature range which is characteristic of the semiconductor. This behaviour contrasts with that of elemental metallic conductors for which the resistance increases with rise in temperature. This is illustrated in Fig. 1.1, which gives curves for a conductor and a semiconductor. The resistance of the conductor increases linearly,

whereas that of the semiconductor decreases exponentially, as temperature rises. Over the significant temperature range the relationship between resistance and temperature for a semiconductor could be written

$$R_t = ae^{b/T}$$

where R_t is the resistance at an absolute temperature T , a and b are constants characteristic of the semiconductor material and e is the base of the natural logarithms, i.e. 2.81828... The two curves in Fig. 1.1 are not to the same vertical scale of resistance.

All semiconducting materials exhibit the temperature dependence discussed in the paragraphs above in the pure state: the addition of impurities raises the temperature at which the material exhibits this behaviour, i.e. the region of negative temperature coefficient.

Germanium in its pure state is a poor conductor, the resistivity being $46 \Omega\text{-cm}$ at 27°C , and is of little direct use in transistor manufacture. However, by the addition of a very small but definite amount of a particular type of impurity, the resistivity can be reduced and the material made suitable for transistors. Germanium and silicon so treated are extensively employed in the manufacture of transistors.

The behaviour of semiconductors can be explained in terms of atomic theory. The atom is assumed to have a central nucleus which carries most of the mass of the atom and has a positive charge. A number of electrons carrying a negative charge revolve around the nucleus. The total number of electrons revolving around a

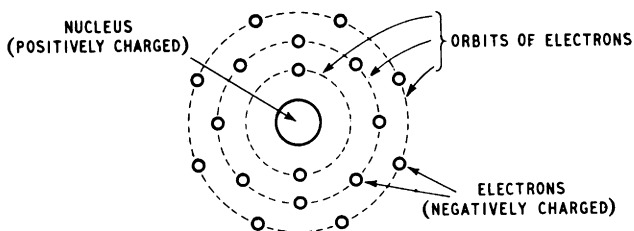


Fig. 1.2. Simplified diagram of structure of atom: for simplicity, electron orbits are shown as circular and co-planar

particular nucleus is sufficient to offset the positive nuclear charge, leaving the atom electrically neutral. The number of electrons associated with a given nucleus is equal to the atomic number of the element. The electrons revolve in a number of orbits and, for the purpose of this discussion, the orbits may be regarded as concentric, the nucleus being at the centre, as shown in Fig. 1.2.

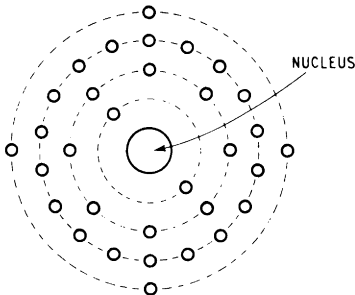
4 Principles of Transistor Circuits

This diagram is greatly simplified ; the orbits are in practice neither concentric nor co-planar.

The first orbit (sometimes called a ring or a shell) is complete when it contains 2 electrons, and an atom with a single complete shell is that of the inert gas, helium. The second ring is complete when it has 8 electrons, and the atom with the first 2 rings complete is that of the inert gas, neon. The third ring is stable when it has 8 or 18 electrons, and the atom having 2, 8 and 8 electrons in the 1st, 2nd and 3rd rings is that of the inert gas, argon. All the inert gases have their outermost shells stable. It is difficult to remove any electrons from a stable ring or to insert others into it. Atoms combine by virtue of the electrons in the outermost rings: for example an atom with one electron in the outermost ring will willingly combine with another whose outermost ring requires one electron for completion.

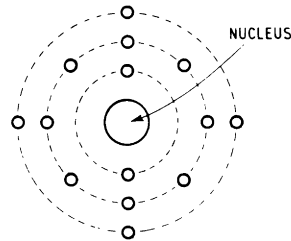
The inert gases, having their outer shells stable, cannot combine with other atoms or with each other. The number of electrons in the outermost ring or the number of electrons required to make the outermost ring complete has a bearing on the chemical valency of the element and the outermost ring is often called the *valence ring*.

Now consider the copper atom: it has 4 rings of electrons, the



1 st	RING	2	ELECTRONS
2 nd	"	8	"
3 rd	"	18	"
4 th	"	4	"

Fig. 1.3 Structure of germanium atom



1 st	RING	2	ELECTRONS
2 nd	"	8	"
3 rd	"	4	"

Fig. 1.4. Structure of silicon atom

first 3 being complete and the 4th containing 1 electron, compared with the 32 needed for completion. Similarly the silver atom has 5 rings, 4 stable and the 5th also containing 1 out of 50 needed for completion. The atoms of both elements thus contain a single electron and this is loosely bound to the nucleus. It can be removed with little effort and is termed a *free electron*. A small e.m.f. applied

to a collection of these atoms can set up a stream of free electrons, i.e. an electric current through the metal. Elements in which such free electrons are available are good electrical conductors.

It might be thought that an atom with 17 electrons in the outermost orbit would be an even better conductor, but this is not so. If one electron is added to such an orbit it becomes complete and a great effort is needed to remove it again.

The arrangement of orbital electrons in a germanium atom is pictured in Fig. 1.3. There are 4 rings, the first containing 2 electrons, the second 8, the third 18, and the fourth (final) 4. The total number of electrons is 32, the atomic number of germanium. The corresponding diagram for the silicon atom is given in Fig. 1.4, the three rings containing 2, 8 and 4 electrons respectively. The total number of electrons per atom is 14, the atomic number for silicon. A significant feature of these two atomic structures is that the outermost ring contains 4 electrons: both elements belong to Group IV of the Periodic Table.

Covalent Bonds

It might be thought that some of the 4 electrons in the valence ring of the germanium or silicon atom could easily be displaced and that these elements would therefore be good conductors. In fact, crystals of pure germanium and pure silicon are very poor conductors. To understand this we must consider the relationships between the valence electrons of neighbouring atoms when these are arranged in a regular geometric pattern as in a crystal. The valence electrons of each atom form bonds, termed *covalent bonds*, with those of neighbouring atoms as suggested in Fig. 1.5. It is difficult to portray a three-dimensional phenomenon in a two-dimensional diagram, but the diagram does show the valence electrons oscillating between two neighbouring atoms. The atoms behave in some respects as though each outer ring had 8 electrons and was stable. There are no free electrons and such a crystal is therefore an insulator: this is true of pure germanium and pure silicon at a very low temperature.

At room temperatures, however, germanium and silicon crystals do have a small conductivity even when they are as pure as modern chemical methods can make them. This is partly due to the presence of minute traces of impurities (the way in which these increase conductivity is explained below) and partly because thermal agitation enables some valence electrons to escape from their covalent bonds and thus become available as charge carriers. They

6 Principles of Transistor Circuits

are able to do this by virtue of their kinetic energy which, at normal temperatures, is sufficient to allow a very small number to break these bonds. If their kinetic energy is increased by the addition of light or by increase in temperature, more valence electrons escape and the conductivity increases. When the temperature of germanium is raised to 100°C , the conductivity is so great that it swamps

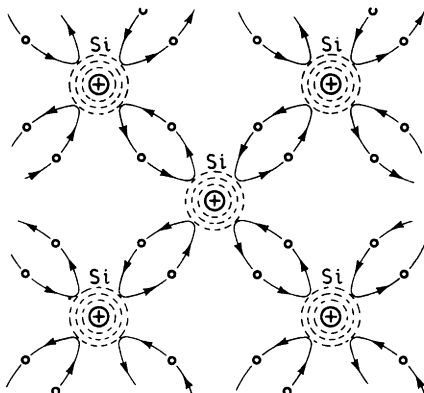


Fig. 1.5. Illustrating covalent bonds in a crystal of pure silicon: for simplicity only electrons in the valence rings are shown

normal transistor action. Moreover, if a reasonable life is required, it is recommended that germanium transistors should not be operated above say 80°C . The life of a germanium transistor is shortened if it is operated above this temperature but a silicon transistor will give a satisfactory life even when operated at 150°C .

Donor Impurities

Suppose an atom of a Group-V element such as arsenic is introduced into a crystal of pure silicon. The atom enters into the lattice structure, taking the place of a silicon atom. Now the arsenic atom has 5 electrons in its outermost orbit and 4 of these form covalent bonds with the electrons of neighbouring atoms as shown in Fig. 1.6. The remaining (5th) electron is left unattached; it is a free electron which can be made to move through the crystal by an e.m.f., leaving a positively-charged ion. These added electrons give the crystal much better conductivity than pure silicon and the added element is termed a *donor* because it gives free electrons to the crystal. Silicon so treated with a Group-V element is termed *n-type* because negatively-charged particles are available to carry

charge through the crystal. It is significant that the addition of the arsenic or some other Group-V element was necessary to give this improvement in conductivity. The added element is often called an impurity and in the language of the chemist it undoubtedly is. However, the word is unfortunate in this context because it suggests that the pentavalent element is unwanted; in fact, it is essential.

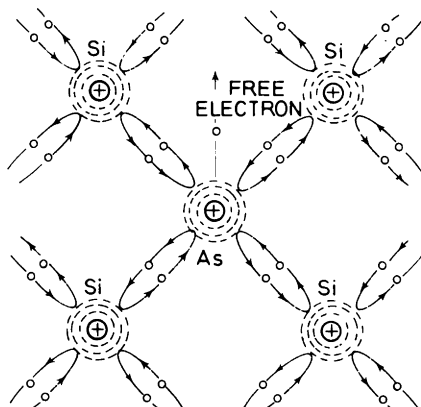


Fig. 1.6. Illustrating covalent bonds in the neighbourhood of an atom of a Group-V element introduced into a crystal of pure silicon. For simplicity only electrons in the valence rings are shown

When a battery is connected across a crystal of n-type semiconductor the free electrons are attracted towards the battery positive terminal and repelled from the negative terminal. These forces cause a drift of electrons through the crystal from the negative to the positive terminal: for every electron leaving the crystal to enter the positive terminal another must be liberated from the negative terminal to enter the crystal. The stream of electrons through the crystal constitutes an electric current. If the voltage applied to the crystal is varied the current varies also in direct proportion, and if the battery connections are reversed the direction of the current through the crystal also reverses but it does not change in amplitude; that is to say the crystal is a *linear* conductor.

Acceptor Impurities

Now suppose an atom of a Group-III element such as boron is introduced into a crystal of pure silicon. It enters the lattice

8 Principles of Transistor Circuits

structure, taking the place of a silicon atom, and the 3 electrons in the valence ring of the boron atom form covalent bonds with the valence electrons of the neighbouring silicon atoms. To make up the number of covalent bonds to 4, each boron atom competes with a neighbouring atom and may leave this deficient of one electron as shown in Fig. 1.7. A group of covalent bonds, which is deficient

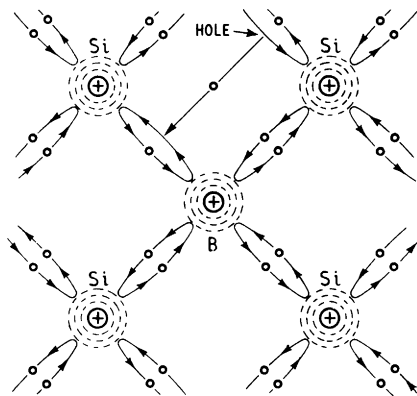


Fig. 1.7. Illustrating covalent bonds in the neighbourhood of an atom of a Group-III element, introduced into a crystal of pure silicon. For simplicity, only electrons in the valence rings are shown

of one electron, behaves in much the same way as a positively-charged particle with a charge equal in magnitude to that of an electron. Such a particle is called a *hole* in semi-conductor theory, and we may say that the introduction of the Group-III impurity gives rise to holes in a crystal of pure silicon. These can carry charge through the crystal and, because these charge-carriers have a positive sign, silicon treated with a Group-III impurity is termed p-type. Such an impurity is termed an *acceptor* impurity because it takes electrons from the silicon atoms. Thus the introduction of the Group-III element into a crystal lattice of pure silicon also increases the conductivity considerably and, when a battery is connected across a crystal of p-type silicon, a current can flow through it in the following manner.

The holes have an effective positive charge, and are therefore attracted towards the negative terminal of the battery and repulsed by the positive terminal. They therefore drift through the crystal from the positive to the negative terminal. Each time a hole reaches