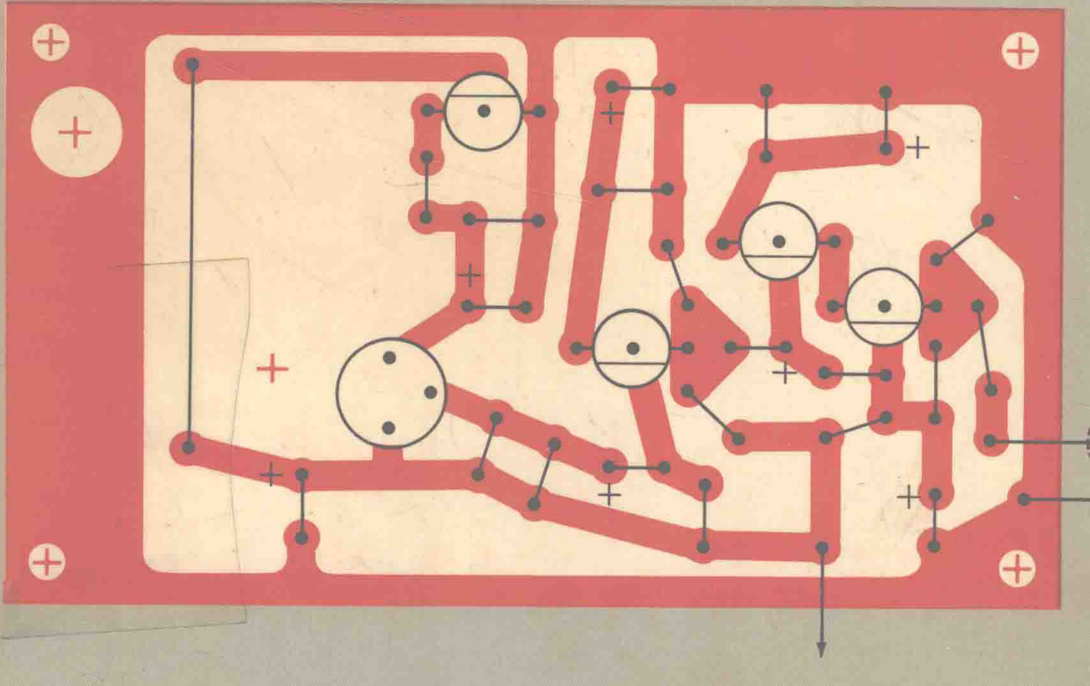
ZUCKER

Electronic Circuits for the Behavioral and Biomedical Sciences

A REFERENCE BOOK OF USEFUL SOLID-STATE CIRCUITS



Electronic Circuits for the Behavioral and Biomedical Sciences

A REFERENCE BOOK OF USEFUL SOLID-STATE CIRCUITS

Mitchell H. Zucker
Electronics Technician, Department of Psychology
University of California, Davis

W. H. FREEMAN AND COMPANY
San Francisco

Printed in the United States of America.

Library of Congress Catalog Card Number: 76-81921

Standard Book Number: 7167 0918-X

Electronic Circuits for the Behavioral and Biomedical Sciences

A series of books in PSYCHOLOGY

Editor: Stanley Coopersmith

Preface

Despite copious publications on the theory and functioning of electronic circuits, the modern researcher in the behavioral and biomedical sciences has had no up-to-date book describing the electronic technology relevant to his particular research needs. Too often the researcher's lack of electronic training has kept him from making adequate adaptations of existing circuitry. The "home-brewed" electronic experiment that turns out to be not only too costly, but also unreliable, is hardly unknown in university research laboratories. This book is written specifically as a reference source for simple, reliable electronic circuits that can be used by the behavioral or biomedical researcher who has had little formal electronic education. It will introduce him to basic semiconductor circuit construction and testing.

The introductory chapters include a discussion of basic semiconductor operation and an explanation of the symbology of circuit diagrams. Particularly important for the novice experimenter are the chapters describing circuit construction techniques and simple, effective troubleshooting procedures. The larger part of the book consists of circuit descriptions, with specific instructions on how to construct them and how to insure that they will operate properly. Three criteria were used in selecting the circuit projects. First, tests must have shown that all the circuits included operate reliably. Second, the circuits must be simple, and demonstrate basic electronic principles. Even though the researcher may have no immediate application for a particular circuit, the description of it may broaden his general electronic understanding. Third, all the circuits must be easily constructed from readily available components. In the few instances where parts for projects are difficult to obtain, addresses have been included to facilitate mail orders. The Appendix includes formulas and tables that may aid in design and construction, and a list of basic relay circuit configurations commonly used in behavioral and biomedical experimentation.

Chapters 5 to 10 constitute a basic inventory of circuit descriptions. By combining various designs, the experimenter can create new circuit configurations suitable for his particular research. For example, should an experimenter need a sensitive photocell detector coupled to an electronic pulse-forming ntework, he could construct such a device after reading the descriptions of the photocell amplifiers and monostable multivibrator. The ability to work creatively with circuits is less likely to come from studying theoretical discussions than from "playing" with actual circuits. The experimenter who modifies circuits and then tries to explain the resulting circuit function in terms of the individual component performance is learning by the best method, by doing.

Although the book was not intended as a textbook, it will be useful for an introductory survey course in electronics, particularly where the intent of the course is to familiarize the student with the circuits and the construction techniques used in electronic apparatus.

I wish to acknowledge the kindness of the General Electric Company and the publishers of *Popular Electronics*, *Electronics World*, and *Radio Electronics*, who have permitted me to include in this book circuit descriptions and diagrams that originally appeared in their publications. To Vincent Polidora and Henry Veatch I would like to express my gratitude for their penetrating criticisms and helpful corrections. For the many photographs in this book, I am grateful to Ronald R. Peck, Davis, Calif. Various portions of the text have been read and criticized by Allan Wegner and Carl Klein. To both these gentlemen, and the rest of the staff of Night Flight Enterprises, I express my deep thanks and appreciation.

Finally, I wish to especially thank my wife, Rosalie, for her assistance in reviewing and typing the manuscript.

January 1969 Mitchell Zucker
Davis, California

Electronic Circuits for the Behavioral and Biomedical Sciences

Contents

Chapter 1 Introduction to Semiconductor Operation 1

Semiconductor materials 1
Rectifier operation 3
Rectifier operating characteristics 5
The transistor 6
Transistor biasing 8
Silicon-controlled rectifier 15
Other semiconductor devices 17
Integrated circuits 17

Chapter 2 Understanding Circuit Diagrams 19

Schematic diagram 19
Pictorial diagram 22
Exploded-view diagram 22
Block diagram 22
Circuit components and symbols 22
Wiring conventions 23
Ground and chassis symbols 23
Connections to voltage sources 25
Cable wiring symbols 26
From schematic to completed circuit 26

Chapter 3 Construction Techniques 29

Printed circuits 30
Printed-circuit construction 30
Breadboard circuit kits 32
Point-to-point wiring 35
Circuit-board wiring 35
Techniques of soldering 38
  Selection of a soldering tool 39
  Selection of solder 40
  Soldered connections 40
  Soldering printed circuits 41
  Soldering semiconductor devices 41
Semiconductor component mounting 43
Mounting components to heat sinks 43
Lead-mounted semiconductors 45
Safety precautions 46

Chapter 4 Troubleshooting Transistor Circuits 47

Rectifier testing 49
Transistor testing 49
  Front-to-back testing, base to emitter 50
  Transistor cut-off ability 51
  Transistor saturation test 51
In-circuit transistor testing 52
  In-circuit voltage testing 53
  Open-circuit tests 54
  Shorted transistor testing 55
  Transistor conduction tests 55
  Testing components other than transistors 55

Chapter 5 Power-Supply Circuits 57

Power-supply circuits 58
Regulated power supply (9-volt) 62
Variable low-voltage power supply (0.5-ampere) 64
Variable low-voltage power supply (2-ampere) 66
General-purpose power supply (24-volt) 68
Simple relay power source (28-volt) 70
High-voltage D.C. laboratory power supply 72
D.C.-to-D.C. high-voltage converter 75
D.C.-to-A.C. inverter (12 volts D.C. to 120 volts A.C.) 77
Voltage doublers 79
Regulated storage-battery charger 82

Chapter 6 Sensing Circuits 85

Sensors 86
Initial control stage circuitry 87
Electric thermistor thermometers 90
Sensitive light meter 94
Simple photoelectric relay 98
Sensitive photoelectric relay 100
Body-capacitor proximity relay 102
Ultrasonic proximity detector 105
Magnetic proximity dry-reed switches 110
Schmitt trigger 113
Pulse former, monostable multivibrator 115
SCR sensor control circuits 117

Chapter 7 Control Circuits 121

Control amplifiers 121
Regulator circuits 124
Remote-control device 125
Control oscillators 125
Electronic relay control amplifier 127
Basic differential amplifier (null indicator) 132
Variable A.C. control 135
Temperature regulator 137
Remote-control switch 141
Basic relay pulse generators and pulse shapers 144
Astable multivibrator oscillator 148
Pulse generator 151

Chapter 8 Programming Circuits 153

Basic logic-gating circuits 154
Bistable multivibrator (flip-flop) 165
Lamp and relay drivers 170
Integrated-circuit logic gates 174

Chapter 9 Time-Delay Circuits 179

Basic time-delay relay 180
Timing capacitors 181
Basic unijunction transistor time-delay relay 183
Unijunction transistor solid state time delay 184
Silicon-controlled rectifier, 117-volt A.C. time-delay relay 185
Thermistor time-delay relay 186
Further information 187

Chapter 10 Audio Circuits 189

Amplifier characteristics 190
Basic three-transistor audio amplifier 194
Audio mixer 196
White-noise generator 198
Metronome 200
Voice-activated relay 202
Integrated circuit audio amplifier 205

Appendixes 209

A Schematic symbols used in circuit diagrams 211
B Resistor and capacitor color codes 214
C Common electronic formulas 217
D Table of standard annealed bare copper wire 220
E Basic relay circuits 222

Selected Bibliography 233

Index 237

1

Introduction to Semiconductor Operation

This chapter is intended for those who want a rudimentary knowledge of semiconductors and how they function. Although the reader need not know the theory of semiconductor operation to build the circuits in this book, he will better understand the circuits he builds if first he has gained some insight into how they work.

The information in this chapter will not enable the experimenter to design his own circuits, for which far more information than can be presented here would be required. However, there are many books and courses of instruction on semiconductor technology for both novice and advanced experimenters. A bibliography listing several of these sources is at the end of this book.

SEMICONDUCTOR MATERIALS

The category of semiconductor devices includes diode rectifiers, silicon-controlled rectifiers, and transistors. These devices are characterized by the materials used in their construction, namely, semiconductor compounds or elements. A semiconductor is any material that displays conductive characteristics intermediate between metals (good electrical conductors) and insulators. Silicon, selenium, and germanium are the elements most commonly used in semiconductor devices. To understand how semiconductor devices are developed and how they function, we must look at the atomic and molecular structure of the semiconducting elements.

An atom of the element germanium, a typical semiconductor used in the manufacture of transistors, has four valence electrons. Atoms of germanium form covalent bonds with other germanium atoms, resulting in a crystal lattice molecular structure. If a very small quantity of arsenic, which has five valence electrons, is added to pure germanium, four of arsenic's valence electrons form covalent bonds with germanium electrons; the fifth arsenic electron is held fairly weakly (see Figure 1.1). The altered germa-

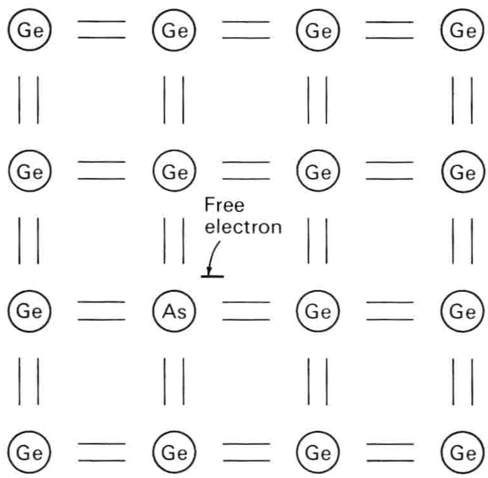


Figure 1.1
Valence electron bonds in germanium, with an arsenic atom replacing a germanium atom.

nium is then said to have a few "free" electrons within its crystal structure. The name given to the germanium crystal containing donor arsenic atoms is N-type (for negative-type) germanium.

If a small amount of a substance having three valence electrons, such as boron or indium, is added to germanium, the resulting crystal structure is that diagrammed in Figure 1.2. The formation of a four-electron bond between an indium atom and germanium crystal creates a "hole" in a germanium atom. The altered germanium crystal is known as P-type (for positive-type) germanium.

When P-type and N-type materials are fused or joined together by a special manufacturing process, a P-N junction is formed. The result is a useful semiconductor device known as a rectifier or diode.

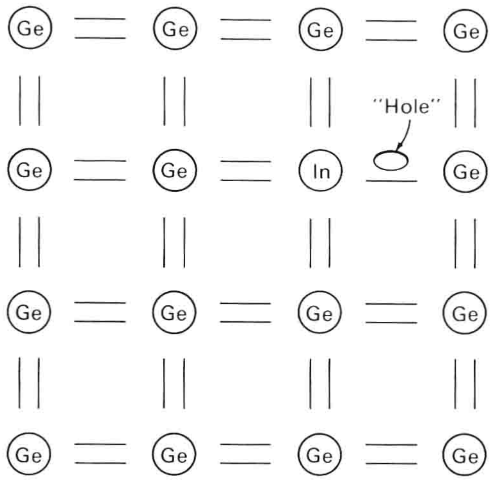


Figure 1.2
Valence electron bonds in germanium, with an indium atom replacing a germanium atom. The "hole" indicates an electron absent from a covalent bond, a site readily occupied by a free electron.

RECTIFIER OPERATION

Figure 1.3 shows a simple circuit composed of a battery, a resistor, and a silicon rectifier made of fused N-type and P-type silicon wafers. At the junction of the two wafers, where the N-type and P-type materials meet, current can flow from the P region to the N region, but cannot effectively flow in the reverse direction. (Note that in this and all subsequent discussions, the standard current-flow convention is used; current is described as flowing from positive to negative.) If the rectifier is reversed (see Figure 1.4), no current can flow, except for a very small current in the microampere range, commonly called leakage current, which for the most part can be ignored. When a voltage source is connected in this manner, the rectifier is described as being reverse-biased.

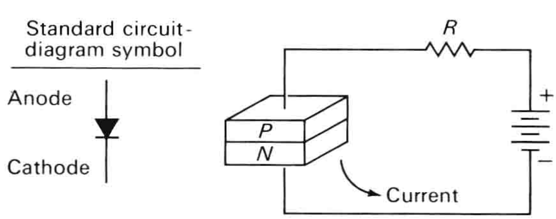


Figure 1.3
Current flow through a silicon rectifier.

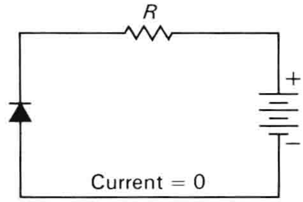


Figure 1.4
No current flow through a silicon rectifier; reverse bias.

If the rectifier is connected in series with a source of alternating current (see Figure 1.5), the rectifier will conduct electricity only when the positive-going half-cycle is applied to the rectifier's anode or positive lead, since the rectifier is effectively reverse-biased when the negative-going half-cycle

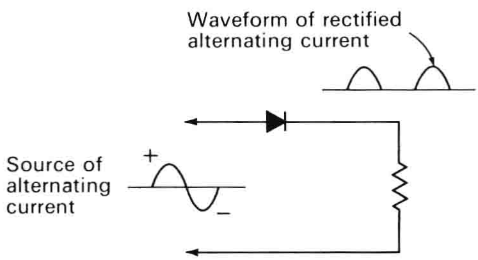


Figure 1.5
Alternating current flow through a rectifier.

is applied to the rectifier anode. In this circuit, the alternating current is said to have been changed to pulsating direct current or to have been half-wave rectified.

A useful circuit using alternating current and a rectifier is shown in Figure 1.6. In this circuit a switch is used to connect either a rectifier in

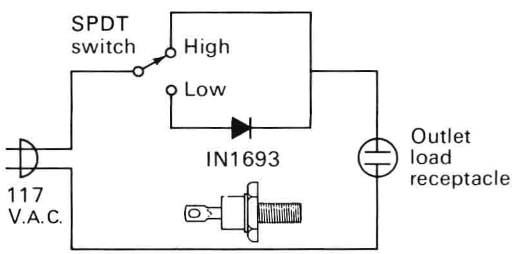


Figure 1.6
High-low switch, showing in outline the IN1693 rectifier diode, oriented in the same direction as its symbol in the diagram.

series with a load or the load directly to a source of power. In the switch position shown, the power is delivered directly to the output receptacle. When the switch is thrown to its other position, the rectifier is connected in series with the output receptacle and will block half the half-cycles from the source of power. As a result, the load will be presented with only the half-cycles of the line frequency that are passed by the rectifier. Since the total power applied to the load may be expressed as the product of the applied voltage and the current flowing through the load, inserting a rectifier in series with the load reduces power by about half. There is a slight voltage drop across the rectifier when it is conducting in the forward direction, but this drop is quite small compared to the voltage drop in the reverse or blocking direction. By switching from the high position to the low position, one may dim a light, or reduce a heater's output or a motor's speed.[1] With the particular rectifier shown in Figure 1.6, it is possible to control up to 130 watts of power; that is, the rectifier may be placed in series with a 130-watt load without being damaged. Other rectifiers can control loads as great as 1,000 watts.

RECTIFIER OPERATING CHARACTERISTICS

Figure 1.7 is the characteristic curve or operation curve for a typical rectifier. It is plotted by measuring the voltage across the rectifier and the current flowing through it when it is biased in the forward and in the reverse directions. It can be seen in the right half of Figure 1.7 that a forward-biased rectifier has a relatively small forward voltage (V_F) measured across it when conducting a relatively large current (I_F). That is, useful voltage is lost within the rectifier structure and creates heat. The product of V_F and I_F gives the power loss within the rectifier. This power loss and the consequent heating can destroy the rectifier, and must be considered when designing rectifier circuits. This heating is why metal plates, called "heat sinks," are used in some stud-mounted rectifier circuits, since the heat sink helps dissipate heat that would otherwise adversely affect the current rating of the rectifier. The current-handling capabilities of a rectifier are determined by temperature; excess heat must be removed from the rectifier to prevent it from being destroyed.

When the rectifier is reverse-biased (left half of Figure 1.7), a large reverse voltage will cause a relatively small flow of current. There is a certain point, however, at which increases of reverse-bias voltage will cause a very large reverse current flow. The voltage at this point is known as the peak reverse voltage (PRV), and most rectifiers will be destroyed when the PRV is exceeded (Point A in Figure 1.7).

[1] Certain loads, such as fluorescent lamp ballasts and transformers, will not operate properly when connected to the rectifier circuit shown in Figure 1.6.