PRACTICAL DESIGN with Solid State Devices

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To my wife Ruth and my daughter Beverly

PREFACE

Semiconductor solid-state physics is an exceptionally complex subject. Since all transistor circuit characteristics can be derived from the basic science, this has proven to be a valuable and rewarding, although involved and complex, approach to semiconductor circuit design.

The circuit designer, the senior engineer, the junior engineer, and the technician, are seldom if ever interested in the basic science. They are concerned with designing a diode, transistor, thyristor, or integrated circuit (IC), into a practical circuit without "sweating out" the semiconductor physics. The performance of the semiconductor device in a particular application and its operation in a manner that will ensure reliability are the engineer's main considerations. This book is aimed at this type of practical circuit designer. It supplies the technician and creative engineer with enough factual material to complete independent valid circuit designs.

The transistor and other semiconductor devices are treated here only as circuit components exhibiting specific characteristics and limitations. The physics is referred to loosely and only when absolutely required. The discussion centers upon the device and its applications to modern technology.

Derivations of specific formulas are omitted except where continuity of presentation would be disturbed. Equations are derived only when knowledge of the process is useful in circuit designs other than those presented as examples in the text.

As a general rule, the equivalent circuit will be shown or derived and equations for the circuit will be presented. The manipulation of these equations may be omitted in the reading without loss of continuity. An asterisk (*) next to an equation number indicates that this is a particularly significant equation describing a distinct circuit or phenomenon. Examples are presented throughout the text to demonstrate the practical use of the final circuit equation as it is applied to determine specific circuit components and configuration performance. Frequently, equations are presented to allow the designer to use outdated but currently available semiconductor data sheets in modern circuit design.

Although aimed at the technician, the solution to the equations and the various examples can be used as a basis for design by the senior engineer working with semiconductors. Much of the text will serve as a useful handbook to the imaginative and inventive designer.

The discussion in the text starts with devices made of individual semiconductors, leading into a description of the semiconductor diode and its many functions in the modern circuit. Power supplies, filter circuits, and diode characteristics are among the topics. Zener diode regulators, tunnel diodes, and other diodes are also detailed.

In the transistor circuit sections, the dc bias and stabilization conditions for bipolar and field effect transistor (FET) devices are the first consideration. Next, the use of semiconductors in audio and radio-frequency (rf) amplifiers with a varying input signal are discussed. A chapter is devoted to power amplifiers because of the light this discussion throws on all transistor applications. Audio and rf configurations on integrated-circuit chips as well as a description of the different types of microcircuits available, completes our discussion of semiconductor amplifiers.

Several chapters are devoted to pulse and switching circuits. This type of circuit is useful in many transistor applications. Special emphasis is placed on the implications of digital-circuit design along with its many variations. Digital designs using both ICs and discrete components are described.

A complete chapter is spent on power-supply regulators because of their importance to transistor circuitry. This is in addition to the section on zener regulators in earlier chapters.

The final chapter consists of a discussion of silicon-controlled rectifiers and other lesser-known thyristors. Descriptions of the devices, their limitations, and their circuit applications are presented.

A basic knowledge of radio, electronics, and electrical circuits is assumed. Where it is deemed necessary, however, a review of this information is presented in a concise manner. A special section is devoted to boolean algebra, along with methods of applying this type of mathematics to digital designs.

Mannie Horowitz

CONTENTS

CHAPTER 1

SEMICONDUCTORS

Many different types of solid-state devices are made of semiconductor materials. Designs range in complexity from the simple temperature-sensitive resistor, through the conventional transistor, to the microcircuit composed of many semiconductor devices on one structure or substrate. Current flowing through some of these devices may be in the high-ampere ranges. Other devices require only a few microamperes of current to function properly and may be damaged if the low current levels are exceeded.

Semiconductor devices function most frequently in low-voltage and low-current applications. Rather than using large quantities of current, small amounts of current in the milliampere (1/1000 of an ampere) or microampere (1/1,000,000 of an ampere) ranges are used in these devices. To facilitate design calculations, it is necessary to convert readily from, for example, amperes to milliamperes, and back again. Such conversions will be pursued as a matter of course throughout this volume. Exponential notations will be used where convenient. The reader should become familiar with all these common forms of notation.

As for exponential notation, numbers are conveniently expressed as powers of 10. 10^n means 10 multiplied by itself n times.

$$10^2 = 10 \times 10 = 100$$

$$3 \times 10^3 = 3 \times 10 \times 10 \times 10 = 3000$$

$$6.2 \times 10^5 = 6.2 \times 10 \times 10 \times 10 \times 10 \times 10 = 620{,}000$$

10^{-n} denotes a number divided by 10, n times.

$$10^{-2} = 1/(10 \times 10) = 1/100$$

$$50 \times 10^{-3} = 50/(10 \times 10 \times 10) = 50/1000$$

$$3.7 \times 10^{-5} = 3.7/(10 \times 10 \times 10 \times 10 \times 10) = 3.7/100{,}000$$

TABLE 1-1. PREFIXES USED IN THIS BOOK

Prefix	Portion of Basic Unit	Abbreviation for Prefix
milli-	10^{-3} (1/1000)	m
micro-	10^{-6}	μ
nano-	10^{-9}	n
pico-	10^{-12}	p
kilo-	10^{3} (1000)	k
mega-	10^{6}	M
giga-	10^{9}	G

When numbers with exponents are multiplied by each other, the exponents are added. If numbers with exponents are divided one into the other, subtract the exponent in the denominator from the exponent in the numerator.

$$10^2 \times 10^3 = 10^5$$

$$(3\times 10^2)\times(2\times 10^3) = 6\times 10^5$$

$$(8\times 10^3)/(2\times 10) = 4\times 10^2$$

$$(9\times 10^{-3})/(3\times 10^{-1}) = 3\times 10^{-2}$$

Several of the exponents have been given special notations. Prefixes added to the basic unit indicate the multiplier of that unit. This multiplier can be expressed as an exponent of 10. Thus, 1 milliamp $= 10^{-3}$ amps; 7 millivolts $= 7\times 10^{-3}$ volts. Table 1-1 lists the prefixes used in this book.

Since there are 1000 milliamperes (mA) for each ampere, amperes must be multiplied by 10^3 to be converted to milliamperes. Similarly, a millivolt (mV) must be multiplied by 10^3 if it is to be converted to microvolts (μV).

SEMICONDUCTORS

All materials are artificially grouped in categories of conductors, semiconductors, and insulators. Materials that conduct electricity well are copper and silver. These are the most frequently used conductors. Copper has been used as hook-up wire and as the conducting element on printed circuit boards for many years. Silver contacts are commonly used on switches.

Experimenters with static electricity have known for many years about the excellent insulating characteristics of rubber, glass, and amber. Plastic, cotton, and enamel are used as insulators to cover the copper conductor in wires. For all practical purposes, insulating materials resist any flow of electrons.

Semiconductors are in a category somewhere between insulators and good conductors. Germanium and silicon are the two basic elements used in most semiconductor devices, and, although these semiconductor materials are fair insulators at low temperatures, their conduction increases as the temperature rises.

Materials such as arsenic, antimony, or phosphorus (called *impurities*) are normally added to the pure (or intrinsic) semiconductor. More electrons move around freely in the material with these impurities than in intrinsic semiconductor slabs. The process of adding impurities to form the extrinsic crystal is referred to as doping. Material formed when the impurity is added to the silicon or germanium is characterized by a lower resistance than the pure germanium or silicon. It has an excess of negative charge and is referred to as an *n-type* semiconductor.

Similarly, if indium, aluminum, or gallium is added to the basic element, a shortage of electrons (positive charge) exists in the combined material. This shortage of electrons is referred to as an excess of holes and the material is a *p-type* semiconductor.

In most applications, two or more slabs of semiconductor material are combined to form diodes, transistors, silicon-controlled rectifiers, and many other devices. Characteristics exhibited by the individual semiconductors are also frequently taken advantage of. Among their more useful properties are the variations of the semiconductor's resistance with temperature or with the amount of light falling upon it. Voltages generated in the semiconductor due to the presence of a magnetic field while current is flowing in the device (known as the Hall effect) have also been put to good use.

THERMISTORS

A broad but not entirely accurate statement can be made that the resistance of semiconductor materials increases with temperature. Semiconductors can have either a negative or positive temperature coefficient of resistance. The factor determining whether the resistance of a particular semiconductor will decrease or increase as its temperature rises is the material used in the device. Semiconductors designed specifically to exhibit particular resistance variations with temperature are referred to as *thermistors*. Although thermistors ordinarily decrease in resistance as the temperature rises, *sensistors* produced by Texas Instruments and *posistors* produced by Murata are heavily doped semiconductors exhibiting a positive temperature coefficient. Generally, both negative and positive temperature coefficient devices are referred to as thermistors.

Thermistors are made from mixtures of pure oxides of magnesium, nickel, titanium, and cobalt. Because their performances vary widely with the quantity of impurities, germanium and silicon are not used in thermistors. The oxides are milled and mixed in varying proportions to create devices with the desired temperature characteristics. After the elements are sintered (compressed and heated to a high temperature), a binder is added so that all particles cohere, thus forming a hard material. Resistance of the various mixes is determined by the density of the powdered particles, by the size of the device, and by its shape. Lead wires are attached to both ends of the slab as electric contacts and conductors.

Several different shapes or configurations of thermistors are commercially available. They may be made in the shape of beads, rods, bulbs, discs, washers, and so on. Whereas the cold or 25°C resistance of bead thermistors can be anywhere between several hundred ohms and more than 100 megohms, the rod thermistor is limited to resistance values of between 1000 and 200,000 ohms. However, the rod has the distinct advantage over the bead of higher power dissipation capabilities.

In some designs, the bead is mounted in a vacuum or gas-filled glass bulb. In this arrangement, even slight temperature variations caused by the presence of minute amounts of current can readily be sensed. It can also be used to detect extremely small ambient temperature variations.

Like all other devices, the thermistor has maximum voltage, current, power, and temperature operating limits. Recommended body temperatures on specification sheets should never be exceeded. Power dissipation limits at the various temperatures must be observed if the life of the device is not to be terminated prematurely.

USEFUL CHARACTERISTICS

Four characteristics of the thermistor are used in modern circuits.

1. Resistance changes with temperature. For many negative resistance coefficient thermistors, the change can be calculated by multiplying the resistance of the device at 25°C by 0.96 for each degree Celsius that the temperature increases. For these devices, the resistance decreases as the temperature rises. As for the sensistor or posistor (positive temperature coefficient thermistors), multiply the resistance of the device at 25°C by 1.007 for each degree Celsius that the temperature increases. Here, the resistance increases with temperature. These rules assume that the thermistor in question is being heated by external sources only, and that no heat is generated by power being dissipated in the device. Specifications sheets normally indicate the resistance at different temperatures as well as some zero-power resistance ratio. The latter factor indicates the ratio of resistances at two ambient temperatures when no power is being dissipated by the thermistor.
2. There is a time delay for the temperature of the body of the thermistor to change from one value to another. Assume that a high temperature is applied instantaneously or in a step to the thermistor. Its body temperature will not change to its final value at the instant the high temperature is applied. The time it takes for the body temperature to increase to 63.2 percent of its final value is referred to as the *thermal time constant* of the device. Once again, the data specified for this characteristic assumes that no power is being dissipated in the device.
3. When defining the current-time characteristic, it is assumed that a voltage is placed across a series combination involving a thermistor and a fixed resistor, as in Fig. 1-1. Current flowing through the circuit heats the components. As the temperature of the thermistor rises, its resistance

decreases (assuming a negative temperature coefficient device), allowing more current to flow. The temperature of the device increases further because of the added current. Resistance continues to decrease as the current increases through the circuit. This buildup continues until the circuit constants, the voltage and the fixed resistor, limit the amount of current and hence power available to the thermistor. The time required to reach the minimum thermistor resistance and maximum circuit current levels can be used in practical circuits where a time-delay characteristic is essential.

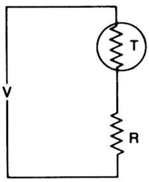

Fig. 1-1. Voltage applied to a thermistor in series with a fixed resistor.

4. Volt-ampere characteristics follow Ohm's law at low voltages. As it increases, the thermistor is heated, its resistance drops, and the voltage across the thermistor decreases as the current increases. The transition point between the Ohm's law portion of the characteristic and the negative resistance portion of the characteristic is referred to as the *self-heating voltage*.

Heat produced from the power dissipated in the thermistor is proportional to the dissipation constant of the device. If, for example, the dissipation constant of a specific thermistor is 0.7 mW/°C indicating that 0.7 milliwatts must be dissipated to increase the body temperature of the semiconductor by 1°C, 7 mW must be dissipated to increase body temperature by 10°C.

ALTERING THE THERMAL CHARACTERISTICS

There are only a select number of cold resistances and temperature characteristics of commercially available thermistors. If the required characteristic in your design differs from that of the standard device, a circuit as in Fig. 1-2A or 1-2B can be ısed. In both circuits, one resistor, R_s, is connected in

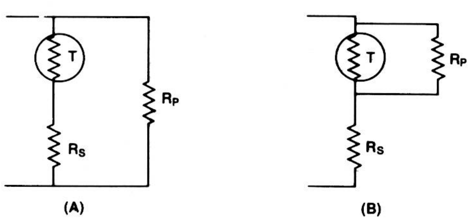

Fig. 1-2. Thermistor in circuit with resistors to establish required resistance-temperature relationship.