HOW TO DESIGN AND BUILD AUDIO AMPLIFIERS,

including digital circuits - 2nd Edition

Designing and building audio circuits for ALL electronics applications.
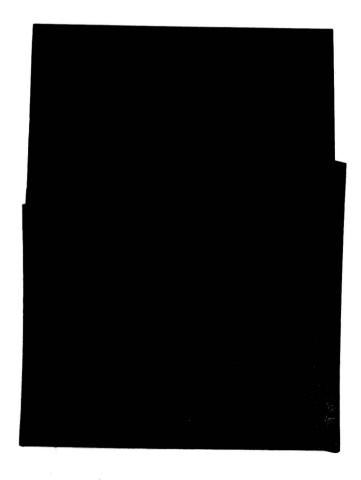
by MANNIE HOROWITZ

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Preface

Scientists perform experiments and then generate theories in an attempt to explain their observations. Some of these theories are supported by evidence gathered over the years; others are simply disproved and discarded as so much nonsense.

This is what happened in the engineering field regarding transistors and transistor circuits. Many engineers have tried to explain the various phenomena they observed, especially in the case of audio power amplifiers. Many of these explanations held up well while others had to be disposed of as invalid. To one degree or another every engineer was guilty of this weakness. I was no exception. In this book I made every attempt to avoid theory unless it was required to do actual practical design work. It is my goal here to provide the tools necessary to design solid-state audio circuits successfully. As you proceed through the book, you will find some sections covering elementary topics. I am certain that most readers know the information covered. But the basic facts are included primarily to help anyone who is not too familiar with the topic discussed and secondarily to present a complete discussion of organized knowledge.

Circuit design is a science based primarily on fact, and to an even greater degree, on trial and error. Before reaching the trial-and-error stage, a circuit should be designed on paper. Design requires mathematics—mostly simple arithmetic. Some basic knowledge of algebra is assumed, as is the ability to convert to different units such as from amperes to milliamperes to microamperes, or from ohms to kilohms to megohms and so on. This

information is readily available in various textbooks. Also assumed is a fundamental knowledge of electric circuits and a familiarity with basic hardware such as capacitors, resistors and inductors. Everyone reading this is probably as familiar with voltage, current, impedance and reactance, as he is with his postal ZIP code number; however, much of this will be reiterated throughout the book just for the sake of clarifying a more involved point.

The technical discussion must be initiated by describing two basic conventions concerned with the direction of current flow. In the heyday of vacuum tubes it was taken for granted that current flows from the negative terminal of a battery through the load and back to the positive terminal. This is the actual direction in which electrons flow. With tubes it is significant only because electrons flow from the heated cathode in the electron tube to the plate.
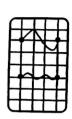
When talking about circuits involving semiconductors it is much easier to use conventional current flow as the standard. Here, current starts to flow from the positive terminal of the power supply, through the load, and back to the negative terminal. This direction is just the reverse of electron flow. The arrow in diode and transistor symbols indicates the direction of current—not electron flow. It is a great help when describing transistor circuits to remember that current flow is in the direction of the arrow drawn in the symbol of the particular semiconductor.

Basic circuit commonly used in hi-fi and other audio equipment are described in detail in the text. New developments using VFETs (Vertical Field-Effect Transistors) and pulse circuits in audio applications are likewise discussed. Microcircuits have also been integrated into audio equipment. Integrated circuits are introduced in Chapter 14 along with applications of these chips as well as applications using discrete components.

Digital circuits have found their way into many otherwise linear configurations. Chapter 13 is devoted to introducing the audio expert to concepts required in understanding and designing these circuits. Among the topics covered are binary numbers, logic circuits, BCD (Binary /Coded Decimal) notation, registers and digital readouts. As many of these arrangements are available as integrated circuits, unnecessary theory is avoided.

I would like to thank the editor of *Radio-Electronics*, Larry Steckler, Gernsback Publications and M. Harvey Gernsback, the editor and publisher, for permission to use the material previously published in the magazine as the basis of this book.

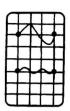<div align="right">Mannie Horowitz</div>

Contents

Chapter 1

Fundamentals of
Semiconductor Devices

Every experimenter is familiar with electrical conductors. Ordinary copper hookup wire used to connect two components in a piece of electronic equipment is a common example of a conductor. The chassis used to support the components of an audio amplifier is frequently used as a conductor.

Insulators are just as important in audio work as are the conductors. Air resists the flow of electricity at the most used voltage levels, and is thus an excellent insulator. Plastic, cotton, or enamel coverings over hookup wire are important insulators. These insulators are frequently rated by the amount of voltage they can safely withstand before they break down and start conducting.

Semiconductors, as the name implies, are materials that fall somewhere between conductors and insulators in their ability to conduct electricity. Although germanium and silicon are fair insulators in their pure state, the addition of impurities changes all this. Impure germanium and silicon are the basic materials of most semiconductors currently in use.

Characteristics of the semiconductor materials are determined by the impurities added. While one type of impurity will cause an excess of electrons to float around in the semiconductor material, a second type will provide a material lacking in electrons and is positive in nature. These materials are assigned names: N-type material contains an excess of electrons while P-type material is lacking in electrons.

JUNCTION DIODES

An independent piece of N-type or P-type material is of value as a component such as a thermistor, a varistor, a hall-effect generator and so on. If an N-type semiconductor is joined to a P-type semiconductor, the practical value of the resulting device is
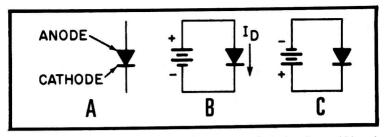
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Fig. 1-1. Junction diode symbol (A). A diode can conduct when forward-biased (B) and cannot conduct when reverse-biased (C).

without bounds. This is the geometry of the PN junction diode. Depending upon the application and specific design, it may be called a silicon rectifier, a zener diode, a noise diode, a signal diode, a switching diode, as well as by many other designations.

The symbol of the junction diode is shown in Fig. 1-1A. The terminal with the arrow is made of P-type material and is referred to as the anode. The straight line is the cathode and is made of an N-type slab. Figures 1-1B and 1-1C indicate what happens if a battery is connected across the diode. Do not try this experimentally unless you include a resistor in series with the circuit to limit diode current to a safe value.

A diode will conduct (Fig. 1-1B) when the voltage supplied at the anode is positive with respect to that at the cathode. In other words the P-type material must be positive with respect to the N-type material if the diode is to conduct. This is an important fact to remember. It is also important to notice the direction in which the current will flow. It is indicated by the arrow next to and in the diode symbol. Current flows from the positive battery terminal, through the diode, to the negative terminal. In Fig. 1-1C the battery is connected in the reverse direction. Theoretically no current will flow. This last statement will be modified to some degree later.

Now let us turn our attention to the forward-biased diode. In this arrangement it conducts current. There is no intention of implying that a diode will conduct if a supply voltage is connected as shown in Fig. 1-1B; other conditions could prevent conduction. However, the voltage must be applied with the polarity shown if the diode is to conduct in the forward direction.

The amount of current a diode conducts depends on the circuit, the applied voltage and the characteristics of the particular diode. A typical forward-biased diode curve is shown in Fig. 1-2A. The solid line indicates the relationship between the current the diode passes and the voltage across the diode.

It is simple to determine from the curve just how much current will flow when a specific voltage is placed across the diode. Just draw a vertical line from the voltage axis (horizontal axis) in Fig. 1-2B, starting at a point equalling the voltage (V₁) across the diode. Extend the line until it touches the solid line diode characteristic curve. Now draw a horizontal line from the point where the diode curve and the vertical line just drawn intersect. Extend this line to the vertical current axis and read the current at the point where this line touches the vertical axis. Current I₁ flows through the diode when voltage V₁ is present across the diode.

Returning to Fig. 1-2A you will notice that at low voltages very little or no current flows. As the voltage is increased the amount of current that flows increases rapidly. This can be seen in a more instructive way in Fig. 1-3. Here the diode is in a circuit with a resistor and variable voltage power supply. Assume that voltage E is increased to very large values. Current that can flow will be
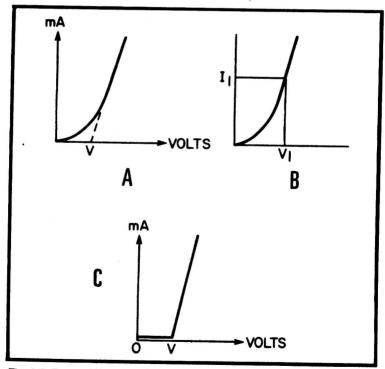

Fig. 1-2. Forward-biased diode curves. Curve A represents a forward-biased diode. Curve B shows the method of determining diode current. Curve C approximates a diode's characteristics.
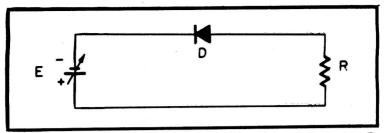
limited by resistance R. Regardless of the current flowing the voltage across the diode will rise very slowly after voltage V has been exceeded. The bulk of voltage E will be developed across resistance R. Voltage across the diode will increase only somewhat above V in Fig. 1-2A.

It is interesting to stop here for a moment to see just what is happening. Input voltage E rises rapidly and the current flowing through the circuit increases rapidly. Yet the voltage across the diode remains at about V and rises only slightly above V. Voltage across a load in parallel with the diode will remain quite constant at V despite supply voltage variations. This is the basis of a voltage regulator.

Voltage V in Fig. 1-2A is quite important and is a basic factor in the approximate characteristic curve of the diode. Value V is determined by assuming that the straight portion of the curve is extended to the zero current axis. The total approximate curve for the forward-biased diode is shown in Fig. 1-2C. From 0 to V no current flows. Therefore, it can be assumed that no current flows when the voltage across the diode is less than V. As soon as the voltage across the diode is increased to, or is even slightly above V, current will flow; the voltage across the diode will remain at about V volts or rise slightly. The amount of current flowing through the circuit in Fig. 1-3 will be relatively independent of the diode; instead, it will depend primarily upon E and R.

Two important numbers should be remembered. For germanium diodes V ranges from 0.2 to 0.4 volt. For silicon devices it is about 0.6 or 0.7 volt. We use these approximations throughout this book. It should also be noted that these voltages are relatively accurate at room temperatures, 25° C. They decrease at about 2.5 millivolts (0.0025 volt) for each degree Celsius rise in temperature. The effect of this change in temperature moves the entire curve in Fig. 1-2A slightly to the left.

The diode is also characterized by its forward resistance. Figure 1-4 is a drawing of curves representing the forward characteristics of two different diodes. Curve A could be that of a silicon power rectifier, while curve B may have the curve of a point-contact germanium signal diode. The DC resistance of the diode is

$$r_{DC} = V/I$$

at any point on the curve. It is different at different points on each curve. As an example determine the DC resistance at 0.5 volt for both rectifiers. For power rectifier A the current flowing is 0.05 ampere and the DC resistance is

$$
\begin{aligned}
r_{DC} &= V/I \\
&= 0.5/0.05 \\
&= 10
\end{aligned}
$$

where r_{DC} is in ohms. For diode B the current flowing is 0.1 ampere and the DC resistance is

$$
\begin{aligned}
r_{DC} &= V/I \\
&= 0.5/0.1 \\
&= 5
\end{aligned}
$$

where r_{DC} is in ohms.

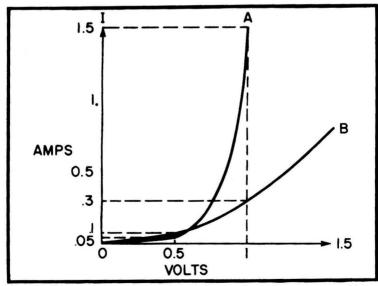In this region the power rectifier has a higher DC resistance than the signal diode.

Fig. 1-4. Curves for two different types of diodes. Curve A represents a silicon power rectifier, while B may be the curve of a point- contact germanium type.
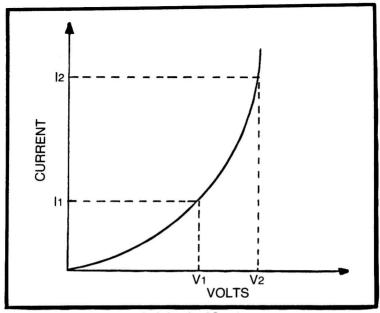
Fig. 1-5. Curves useful in calculating the AC resistance of a diode.

Now consider the DC resistance at 1 volt. Current flowing through the signal diode is 0.3 ampere and that flowing through the power rectifier is 1.5 amperes. The DC resistance of the signal diode is then

$$r_{DC} = V/I$$
$$= 1/0.3$$
$$= 3.33$$

where r_{DC} is in ohms. And the DC resistance of the power rectifier is

$$r_{DC} = V/I$$
$$= 1/1.5$$
$$= 0.67$$

where r_{DC} is in ohms.

This is the usual situation that exists under normal operating conditions. Power rectifiers have a lower resistance than point-contact germanium signal diodes. (Note that point-contact signal diodes have few, if any, audio applications; therefore, they are not discussed here. Point-contact diodes are used primarily in RF work. The structure does not consist of a junction of dissimilar semiconductors. It is introduced here only because of the distinct difference of the curve when compared with junction diode curves.) It will also

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be found that the resistance of junction signal diodes is lower than that of point-contact devices, but is usually larger than that of power rectifiers.

A more important diode characteristic is the AC resistance. In the discussion above it was assumed that only direct current flows through the diode. In the more usual case the current is AC. The AC resistance can be readily and accurately determined from the diode curve. The procedure is described with the help of Fig. 1-5.

As you know as AC waveform is basically sinusoidal, varying over the 360 cycle. Assume an AC voltage is applied to the diode. When the AC signal is at a minimum the voltage across the diode is V_1, while at the maximum it is V_2. At these instants in the cycle the currents flowing through the diode are I_1 and I_2, respectively. The AC resistance, determined from the slope of the curve, is

$$r_{AC} = \frac{V_2 - V_1}{I_2 - I_1}$$

This is the actual resistance the sine wave sees. It will be found that the relative AC resistances of the various types of diodes are like the DC resistances in that power rectifiers exhibit the lowest resistances. Point-contact diodes have the highest resistances and silicon junction signal devices fall somewhere between the two, but close to the magnitude of the AC resistance of power rectifiers.

A convenient formula to remember for all junction diodes (not point-contact types) is

$$r_{AC} = 26/I_F \qquad (1\text{-}1)$$

where I_F is the average forward current flowing through the diode when this current is expressed in milliamperes mA (0.001 ampere). I_F is frequently midway between I_1 and I_2. At room temperature this formula will provide AC resistances close in value to those determined from the curves.

The complete equivalent circuit of a forward-biased diode can now be drawn as in Fig. 1-6. The arrow-line symbol represents the
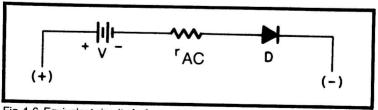

Fig. 1-6. Equivalent circuit of a forward-biased diode. The diode conducts when the applied voltage exceeds V.

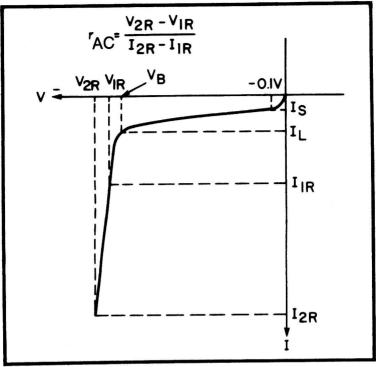$$r_{AC} = \frac{V_{2R} - V_{IR}}{I_{2R} - I_{IR}}$$

Fig. 1-7. Characteristics of reverse-biased diode.

ideal diode showing that current will flow only if the anode (arrow) is positive with respect to the cathode. For the ideal diode V in Fig. 1-2A is zero; however, V is not forgotten in the equivalent circuit. Battery V represents this cut-in voltage encountered in the description of Fig. 1-2A. It is assumed that a positive voltage greater than V must be applied at the terminal marked plus (+) in the equivalent circuit (or at the anode of a real diode) before the diode will conduct. Value r_{AC} in the equivalent circuit is the AC diode resistance discussed above and is drawn as a resistor in the equivalent circuit.

We now turn our attention to the reverse-bias characteristic. It is drawn graphically in Fig. 1-7. It was stated earlier, with reservations, that current will not flow through the diode when it is reverse biased. Actually, current will flow. When the reverse voltage is about 0.1 volt a saturation current flows. This current increases only with temperature. It doubles for every 10° C rise in temperature when the diode is made of germanium material. For silicon devices the current is assumed to double for every 6° C rise in

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