TRANSISTOR ELECTRONICS

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半導體放大器綫路

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PREFACE

In the few years since its invention, the transistor has become firmly established as a most important member of the rapidly increasing family of electronic devices. Indeed, the transistor is already competitive and promises to surpass the vacuum tube in many applications in the electronic industry.

To one interested in becoming familiar with the field of transistors and associated devices, certain questions naturally arise. How well is the operation of the transistor understood? Is the design of transistor circuits more complex than the design of vacuum tube circuits? Is an understanding of vacuum tube circuits of direct benefit in the application of transistors? These questions and their answers may logically preface a book on transistor electronics.

With reference to the first question, it may be said that the theory of operation of the transistor has been brought to a remarkable state of advancement, considering the relatively short time the transistor has been known. Theoretical expressions describing the behavior of the transistor agree well with experimentally observed behavior, especially for transistors of relatively simple geometrical construction.

A clear-cut answer cannot be given to our second question, since factors which complicate the design of certain circuits may be of little consequence in the design of other circuits. The transistor, in contrast with the vacuum tube, for example, may often have to be considered a bilateral device even at low frequencies. Analysis of certain linear continuous-wave transistor circuits may thereby be more complicated. On the other hand, large signal characteristics of the transistor approach those of a perfect switching device. Switching circuits utilizing transistors may therefore be simpler in design and structure than vacuum tube circuits which perform the same function.

Knowledge of vacuum tube circuits may be beneficial in applying the transistor to circuits if reasonable care is exercised. In view of the very different mechanisms of operation of transistors and vacuum tubes, it is surprising when certain similarities in their circuit behavior are recognized. However, too rigorous an attempt to develop parallels between vacuum tube and transistor circuits, as for example, literally following the principles of direct analogy or of duality, may obscure unique circuit possibilities of the transistor.

Emphasis is placed here on a basic understanding of the circuit aspects of the transistor, and description and analysis of circuits are directed to the principles governing operation of these circuits. In addition, intelligent use of the transistor is facilitated by knowledge of the physical principles governing transistor operation, so that discussion of these principles is included.

Chapter 1 of this volume treats qualitatively the fundamental concepts of transistor physics. Chapters 2 and 3 introduce the operating characteristics and the general properties of the transistor as a circuit element. Stabilization of the d-c operating point, important in transistor circuits, is described in Chapter 4. Chapters 5 and 6 offer a treatment of low-frequency amplifiers, including the principles of complementary symmetry as applied to these circuits. Chapters 7 and 8 introduce the reader to high-frequency operation of transistors including high-frequency equivalent circuits. Chapter 8, in particular, treats the various physical phenomena of transistor action in the light of their effect on equivalent circuits. This is followed by a study of high-frequency amplifiers in Chapter 9. Chapters 10, 11, and 12 deal with nonlinear operation of the transistor; oscillators are treated in Chapter 10, modulation and demodulation are treated in Chapter 11, and pulse circuits are studied in Chapter 12.

This book is written for advanced undergraduate or graduate students in electrical engineering and associated fields, and as a reference work for the electronics engineer. The sections on circuit design should provide an effective guide for the design engineer, covering many fields from amplifiers to digital computers. Parallels and contrasts between transistor and vacuum tube circuits are included where it is believed they may properly add perspective.

The symbols and notations used in this book conform, in the main, to the I.R.E. standards. A particular deviation is the use of V and v to represent voltages, while the letters E and e are reserved to designate the emitter of the transistor. Since no graphical symbol has become standard for the transistor at this time of writing, the authors have found it desirable to adopt a symbol for the junction transistor for better functional representation and to distinguish it from the point contact transistor. It should be noted that this symbol is of the "building block" type, as recommended by the I.R.E.

The authors wish to acknowledge the helpful cooperation of the Radio Corporation of America. They are indebted to many of their colleagues for valuable suggestions and criticisms, as well as for technical contributions which have been adapted and acknowledged in this volume. In particular, the authors wish to thank T. P. Bothwell, D. E. Deuitch, H. Johnson, H. C. Lin, A. Moore, and W. M. Webster, for their kind assistance.

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Chapter 1

PHYSICAL CONCEPTS

1.1 Introduction

In the application of the transistor to electronic circuits one needs only to treat the transistor as a circuit element whose behavior is defined by its operating characteristics. However, if one is to realize the greatest possible facility in using the transistor, a knowledge of the fundamental principles governing the operation of the device is essential.

Basically, the electron-tube operates by virtue of the flow of electrons in vacuum between the electrodes; the two fundamental problems involved are the liberation of electrons from a solid and the control of these electrons in a vacuum. In transistors, as well as in other related solid-state electronic devices, operation depends upon a flow of electric charge carriers within the solid; here the essential problems are the generation and control of these carriers within the solid. This chapter presents a summary of the physical concepts governing the operation of transistors, phototransistors, and rectifiers in a descriptive and qualitative form without entering into detailed and rigorous discussion of solid-state physics. However, in some specific instances, where circuit analysis requires a more thorough understanding of transistor physics, adequate quantitative treatment of the physical concepts involved is provided in those chapters where such subjects are considered. In particular, Chapters 7 and 8 will discuss the physics of high-frequency operation in detail.

It is practically impossible to review the physics of the transistor without reference to the works of Shockley and others,[1] whose treatments of this subject are adopted in this chapter. The reader is urged to study these references where a more thorough grasp of fundamentals is desired.

1.2 Germanium crystal

Germanium is the material used in most transistors and crystal rectifiers available at present. Some other semiconductors, such as

[1] See references at the end of this chapter.

silicon are also presently being used. Purified germanium usually is in the polycrystalline form, though it is possible and often desirable to prepare a specimen of germanium which is a single crystal. In such a single crystal, the germanium atoms arrange themselves in a regular pattern known as the *lattice structure*. As shown in the symbolic diagram of Fig. 1-1; each atom is bonded to four neighboring atoms in such a manner that the distance between any two neighboring atoms is the same. Each germanium atom consists of a nucleus and 32 electrons. The nucleus and 28 of the electrons form an inert core of net charge of +4 units of the charge of an electron. The inert cores,

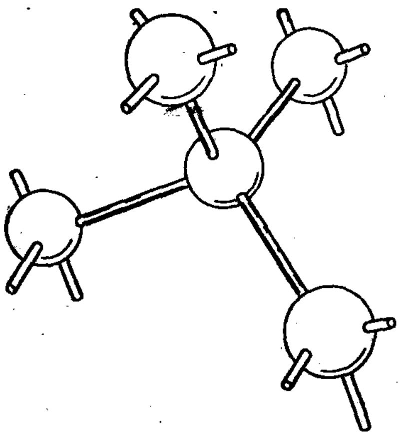

Fig. 1-1. Germanium crystal structure.

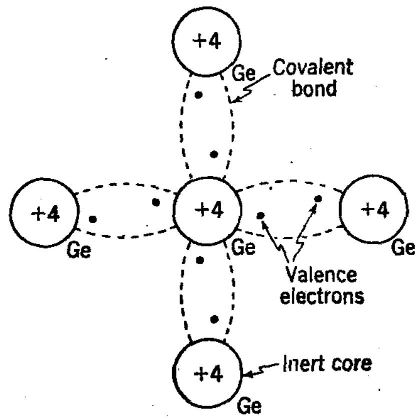

Fig. 1-2. Symbolic crystal structure of perfect* germanium.

represented by the spheres in the figure, comprise the essential mass of the solid but do not contribute directly to the chemical and electrical properties of the element. The remaining 4 electrons, which constitute the bonds between the atoms (represented by the rods in Fig. 1-1), are the valence electrons and are responsible for the chemical and electrical properties. Two valence electrons, one from each of two neighboring atoms, by virtue of their relative motion cause a binding force to exist between the two atoms. This binding force and the force of electrostatic repulsion of the positively charged cores are in equilibrium, resulting in the specific arrangement of the atoms within the crystal. The electron-pair bonds are referred to as *covalent bonds*.

For a clearer conception of this arrangement, the lattice structure is reproduced symbolically in the two-dimensional picture shown in

Fig. 1-2. In the absence of external disturbances, the covalent bonds are stable and the motion of the valence electrons is restricted to their individual bonds. Although there are enormous numbers of electrons in a germanium crystal, these electrons are bound, either in the cores or in the covalent bonds, and are not free to move from one point to another in the crystal under the influence of an electric field. Thus the germanium crystal behaves like an insulator with a high dielectric constant. This discussion is limited to the ideal case of a perfect crystal in which there is no imperfection whatever in the lattice structure. It will be shown later that the operation of transistors and crystal rectifiers depends on controlled imperfections in the crystal. For the sake of simplicity, in the rest of the book the term "electron," unless specified otherwise, will be reserved for electrons that contribute to the conduction of electricity in the crystal, and will not include electrons in the covalent bonds or in the cores.

1.3 The behavior of an electron in the perfect germanium crystal

Suppose that by some means an electron is injected into a perfect germanium crystal. Since this *excess electron* is situated in an environment of perfect periodicity of electric potential, wave mechanics predicts that the electron will not be affected by the fluctuating electric field inside the crystal. This implies that the electron should either remain at rest or it should move with constant velocity through the crystal. In practice, however, this is not the case. The presence of thermal energy in the crystal, which we can never entirely avoid unless the crystal is kept at absolute zero temperature, causes lattice vibration. This lattice vibration excites the electrons into motion. The mechanism of thermal excitation of electrons may be illustrated by adopting the concept of the *phonon*. In much the same manner that light energy may be considered to be composed of discrete quanta, *photons*, the energy of lattice vibration may be considered as composed of particles of quantized energy, known as the *phonons*. We may consider phonons to be uncharged elastic masses moving with random thermal energies. Successive collisions between the phonons and the electron cause the electron to describe a random zigzag motion as represented in Fig. 1–3a. The random zigzag motion does not create a net displacement of the electron in any one direction; and thus does not contribute to the conduction of electricity in the solid.

A net displacement of electrons in a solid may happen as the result of *drift* or *diffusion*. When an electric field is applied to the solid, the random motion of the excess electron is modified to show a net drift in the direction of the field (Fig. 1-3b). The drift of the electron constitutes an electron current or, in other words, the conduction of electricity in the crystal. The resultant motion is the superimposition of the motion due to the electric field and the random zigzag motion of diffusion. Within the limit that the drift velocity of the electron is small compared with the thermal velocity of the phonon, the drift

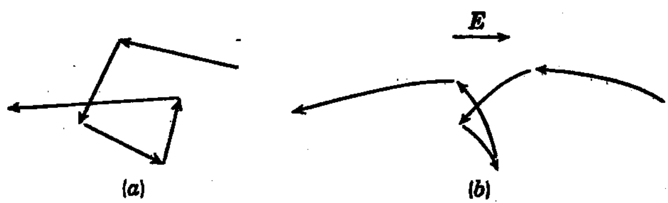

Fig. 1-3. Motion of an electron in a crystal: (a) random motion under no electric field; (b) motion under an electric field E.

velocity is directly proportional to the potential gradient (in other words, the electric field) in the relation,

$$v = \mu E$$

where v is the drift velocity, E is the applied electric field, and μ is the *mobility constant*, which is different in different solids. Consider the example of a solid of uniform cross section with a length l and a potential difference V applied across this length. If there are N electrons per unit length of the solid, the current in the solid is

$$i = Nqv = Nq\mu E = Nq\mu(V/l)$$

where q is the charge of an electron. This implies that the relation between voltage and current in a crystalline solid obeys Ohm's law. This relation, however, no longer holds when the applied electric field is too strong.

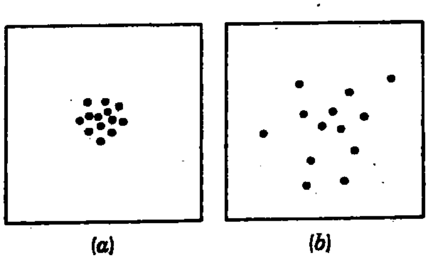

Fig. 1-4. Spreading of electrons by diffusion in a crystal: (a) before diffusion; (b) after diffusion.

When a concentration of electrons is injected at a point in the crystal, in the absence of an externally applied electric field, the random motion of the electrons results in spreading the electrons in all directions (Fig. 1-4). This spreading of electrons, being the result of thermal excitation in the crystal, is referred to as *diffusion*. Consider a sample of unit cross section area in which there is a uniform linear density gradient along the specimen. The diffusion current is

$$i = qD(dp/dx)$$

where q is the charge of an electron, dp/dx is the density gradient, and D is the *diffusion constant* of the solid.

The diffusion constant and the mobility of electrons in a crystal are related by the expression, known as Einstein's relationship,

$$D/\mu = kT/q \tag{1-1}$$

where k is Boltzmann's constant, T is the absolute temperature, and q is the charge of an electron. At room temperature the diffusion constant and mobility of electrons in germanium are approximately $\mu = 3600$ cm/sec per volt/cm, and $D = 93$ cm^2/sec.

1.4 Imperfections in the crystal

Up to this point we have been considering the properties of a perfect crystal whose structure suffers no imperfection. A small number of electrons injected into the crystal does not disturb the crystal structure nor does it appreciably affect the distribution of the electric field in the crystal. However, as far as transistor electronics is concerned, the perfect crystal is but an idealized model. The operation of transistors and crystal rectifiers actually depends on controlled imperfections in the crystal. Imperfections in the crystal provide the electric charge carriers in the solid and also contribute to the control of flow of these carriers. The three main causes of imperfections are radiation energy, chemical impurities, and disordered atomic arrangements. (The term imperfection is used here in the broad sense to include not only atomic imperfections such as atomic dislocations and impurity atoms but also energy imperfections which result from a disturbance of the normal energy state of the crystal.)

1.5 Imperfection by radiation energy

The electrical properties of germanium may change considerably when the element is exposed to light. The incident light is composed