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The Theory of *p-n* Junctions in Semiconductors and *p-n* Junction Transistors

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In a single crystal of semiconductor the impurity concentration may vary from *p*-type to *n*-type producing a mechanically continuous rectifying junction. The theory of potential distribution and rectification for *p-n* junctions is developed with emphasis on germanium. The currents across the junction are carried by the diffusion of holes in *n*-type material and electrons in *p*-type material, resulting in an admittance for a simple case varying as $(1 + i\omega\tau_p)^{1/2}$ where τ_p is the lifetime of a hole in the *n*-region. Contact potentials across *p-n* junctions, carrying no current, may develop when hole or electron injection occurs. The principles and theory of a *p-n-p* transistor are described.

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1. INTRODUCTION

AS IS well known, silicon and germanium may be either *n*-type or *p*-type semiconductors, depending on which of the concentrations N_d of donors or N_a of acceptors, is the larger. If, in a single sample, there is a transition from one type to the other, a rectifying photosensitive *p-n* junction is formed.[1] The theory of such junctions is in contrast to those

[1] For a review of work on silicon and germanium during the war see H. C. Torrey and C. A. Whitmer, *Crystal Rectifiers*, McGraw-Hill Book Company, Inc., New York (1948). *P-n* junctions were investigated before the war at Bell Telephone Laboratories by R. S. Ohl. Work on *p-n* junctions in germanium has been published by the group at Purdue

of ordinary rectifying junctions because, on both sides of the junction, both electron flow and hole flow must be considered. In fact, a major portion of the hole current may persist into the n-type region and vice-versa. In later sections we show how this feature has a number of interesting consequences, which we shall describe briefly in this introduction.

A p-n junction may act as an emitter in the transistor sense, since it can inject hole current into n-type material. The a-c. impedance of a p-n junction may exhibit a frequency dependence characterized by this diffusion of holes and of electrons. For high frequencies the admittance varies approximately as $(i\omega)^{1/2}$ and has comparable real and imaginary parts. When a p-n junction makes contact to a piece of n-type material containing a high concentration of injected holes, it acts like a semipermeable membrane and tends to come to a potential which corresponds to the hole concentration.

Although some results can be derived which are valid for all p-n junctions, the diversity of possible situations is so great and the solution of the equations so involved that it is necessary to illustrate them by using a number of special cases as examples. In general we shall consider cases in which the semiconductor may be classified into three parts, as shown in Fig. 1. The meaning of the transition region will become clearer in later sections; in general it extends far enough to either side of the point at which $N_d - N_a = 0$ so that the value of $|N_d - N_a|$ at its boundaries is not much smaller than in the low resistance parts of the specimen. As stated above, appreciable hole currents may flow into the n-region beyond the transition region. For this reason, the rectification process is not restricted to the transition region alone. We shall use the word *junction* to include all the material near the transition region in which significant contributions to the rectification process occur. It has been found that various techniques may be employed to make nonrectifying metallic contacts to the germanium; when this is properly done, the resistance measured between the metal terminals in a suitably proportioned specimen is due almost entirely to the rectifying junction up to current densities of 10^{-4} amp/cm^2.

directed by K. Lark-Horovitz: S. Benzer, *Phys. Rev.* 72, 1267 (1947); M. Becker and H. Y. Fan, *Phys. Rev.* 75, 1631 (1949); and H. Y. Fan, *Phys. Rev.* 75. 1631 (1949). Similar junctions occur in lead sulfide according to L. Sosnowski, J. Starkiewicz and O. Simpson, *Nature* 159, 818 (1947), L. Sosnowski, *Phys. Rev.* 72, 641 (1947), and L. Sosnowski, B. W. Soole and J. Starkiewicz, *Nature* 160, 471 (1947). The theory described here has been discussed in connection with photoelectric effects in p-n junctions by F. S. Goucher, Meeting of the American Physical Society, Cleveland, March 10–12, 1949 and by W. Shockley, G. L. Pearson and M. Sparks. *Phys. Rev.* 76, 180 (1949). For a general review of conductivity in p- and n-type silicon see G. L. Pearson and J. Bardeen, *Phys. Rev.* 75, 865 (1949), and J. H. Scaff, H. C. Theuerer and E. E. Schumacher, *Jl. of Metals*, 185, 383 (1949) and W. G. Pfann and J. H. Scaff, *Jl. of Metals*, 185, 389 (1949). The latter two papers also discuss photo-voltaic barriers. The most recent and thorough theory for frequency effects in metal semiconductor rectifiers is given elsewhere in this issue (J. Bardeen, *Bell Sys. Tech. Jl.*, July 1949).

Even for distributions of impurities as simple as those shown in part (b) there are two distinctly different types of behavior of the electrostatic potential in the transition region, each of which may be either rectifying or nonrectifying. The requirement that the junction be rectifying can be stated in terms of the current distribution, certain cases of which are shown in (c). The total current, from left to right, is I, the hole and electron currents being

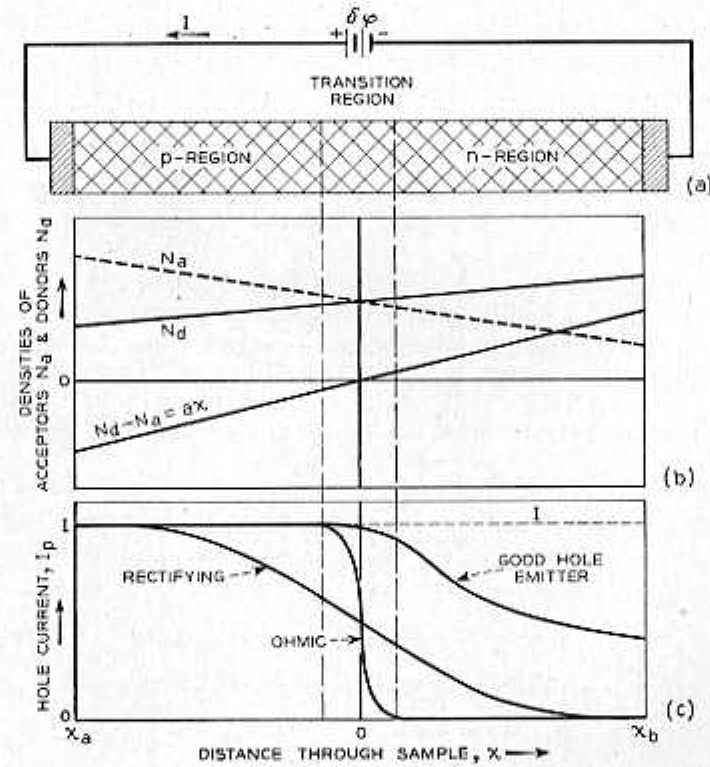

Fig. 1—The p-n junction.
(a) Schematic view of specimen, showing non-rectifying end contacts and convention for polarities of current and voltage.
(b) Distribution of donors and acceptors.
(c) Three possible current distributions.

I_p and I_n, with $I = I_p + I_n$. Well away from the junction in the p-type material, substantially all of the current is carried by holes and $I_p = I$; similarly, deep in the n-type material $I_n = I$ and $I_p = 0$. In general in a nonrectifying junction, the hole current does not penetrate the n-type material appreciably whereas in the rectifying junction it does. Under some conditions the major flow across the junction will consist of holes; such cases are advantageous as emitters in transistor applications using n-type material for the *base*.

Where the hole current flows in relatively low resistance n-type material, it is governed by the diffusion equation and the concentration falls off as $\exp(-x/L_p)$ where L_p is the diffusion length:

$$L = \sqrt{D\tau_p}\,.$$

Here D is the diffusion constant for holes and τ_p their mean lifetime. The lifetime may be controlled either by surface recombination[8] or volume recombination. Surface recombination is important if the specimen has a narrow cross-section.

Under a-c. conditions, the diffusion current acquires a reactive component corresponding to a capacity. In addition, a capacitative current is required to produce the changing potential distribution in the transition region itself.

In the following sections we shall consider the behavior of the junction analytically, treating first the potential distribution in the transition region and the charges required change the voltage across it in a pseudo-equilibrium case. We shall then consider d-c. rectification and a-c. admittance.