

current is larger than the change in emitter current. Furthermore, the collector, being operated in the reverse direction as a rectifier, has a high impedance (10^4 to 10^5 ohms) and may be matched to a high impedance load. A large ratio of output to input voltage, of the same order as the ratio of the reverse to the forward impedance of the point, is obtained. There is a corresponding power amplification of the input signal.

The d.c. characteristics of a typical experimental unit are shown in Fig. 2. There are four variables, two currents and two voltages, with a functional relation between them. If two are specified the other two are determined. In the plot of Fig. 2 the emitter and collector currents I_e and I_c are taken as the independent variables and the corresponding voltages, V_e and V_c , measured relative to the base electrode, as the dependent variables. The conventional directions for the currents are as shown in Fig. 1. In normal operation, I_e , I_c , and V_e are positive, and V_c is negative.

The emitter current, I_e , is simply related to V_e and I_c . To a close approximation:

$$I_e = f(V_e + R_F I_c), \quad (1)$$

where R_F is a constant independent of bias. The interpretation is that the collector current lowers the potential of the surface in the vicinity of the emitter by $R_F I_c$, and thus increases the effective bias voltage on the emitter by an equivalent amount. The term $R_F I_c$ represents a positive feedback, which under some operating conditions is sufficient to cause instability.

The current amplification factor α is defined as

$$\alpha = (\partial I_c / \partial I_e)_{V_c = \text{const.}}$$

This factor depends on the operating biases. For the unit shown in Fig. 2, α lies between one and two if $V_c < -2$.

Using the circuit of Fig. 1, power gains of over 20 db have been obtained. Units have been operated as amplifiers at frequencies up to 10 megacycles.

We wish to acknowledge our debt to W. Shockley for initiating and directing the research program that led to the discovery on which this development is based. We are also indebted to many other of our colleagues at these Laboratories for material assistance and valuable suggestions.

¹ While the effect has been found with both silicon and germanium, we describe only the use of the latter.

² The germanium was furnished by J. H. Scaff and H. C. Theuerer. For methods of preparation and information on the rectifier, see H. C. Torrey and C. A. Whitmer, *Crystal Rectifiers* (McGraw-Hill Book Company, Inc., New York, New York, 1948), Chap. 12.

³ This surface treatment is due to R. B. Gibney, formerly of Bell Telephone Laboratories, now at Los Alamos Scientific Laboratory.

⁴ W. H. Brattain and J. Bardeen, *Phys. Rev.*, this issue.

Nature of the Forward Current in Germanium Point Contacts

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THE forward current in germanium high back-voltage rectifiers¹ is much larger than that estimated from the formula for the spreading resistance, R_s , in a medium

of uniform resistivity, ρ . For a contact of diameter d ,

$$R_s = \rho/2d.$$

Taking as typical values $\rho = 10$ ohm cm and $d = .0025$ cm, the formula gives $R_s = 2000$ ohms. Actually the forward current at one volt may be as large as 5 to 10 ma, and the differential resistance is not more than a few hundred ohms. Bray² has attempted to account for this discrepancy by assuming that the resistivity decreases with increasing field, and has made tests to observe such an effect.

In connection with the development of the semi-conductor triode discussed in the preceding letter,³ the nature of the excess conductivity has been investigated by means of probe measurements of the potential in the vicinity of the point.⁴ Measurements were made on the plane surface of a thick block. Various surface treatments, such as anodizing, oxidizing, and sand blasting were used in different tests, in addition to the etch customarily employed in the preparation of rectifiers.

The potential, $V(r)$, at a distance r from a point carrying a current, I , is measured relative to a large area low resistance contact at the base. In Fig. 1 we have plotted some typical data for a surface prepared by grinding and etching, and then oxidizing in air at 500°C for one hour. The ordinate is $2\pi r V(r)/I$ which for a body of uniform resistivity, ρ , should be a constant equal in magnitude to ρ . Actually it is found that the ratio is much less than ρ at small distances from the point, and increases with r , approaching the value ρ asymptotically at large distances. The departure from the constant value indicates an excess conductivity in the neighborhood of the point.

The manner in which the excess conductivity varies with current indicates that two components are involved. One is ohmic and is represented by the upper curve of Fig. 1 which applies for reverse (negative) currents and for small forward currents. This component is attributed to a thin conducting layer on the surface which is believed to be P -type (i.e., of opposite type to that of the block). A layer with a surface conductivity of .002 mhos is sufficient to account for the departure from the upper curve from a constant value. The second component of the excess conductivity increases with increasing forward current, and

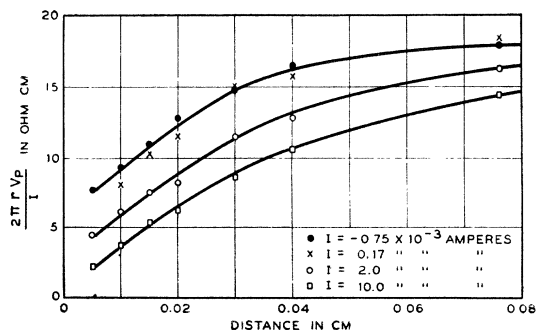


FIG. 1. Measurements of potential, V_p , at a distance r from a point contact through which a current I is flowing into a germanium surface.

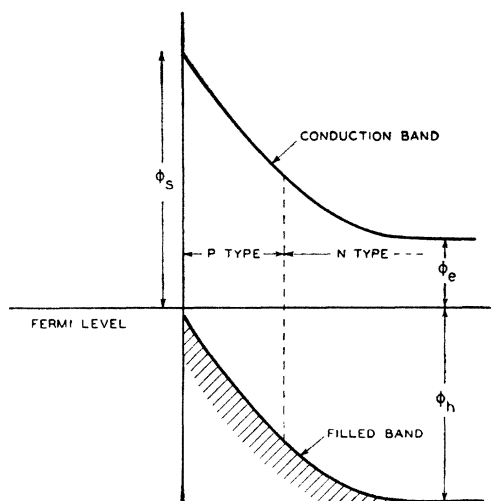


FIG. 2. Schematic energy level diagram of an *N*-type semiconductor with a thin layer of *P*-type conductivity next to the surface.

is attributed to an increase in the concentration of carriers (holes and electrons) in the vicinity of the point with increasing forward bias. The relative as well as the absolute magnitudes of these two components vary with surface treatment. Two different crystal faces on the same block may have different characteristics.

The thin *P*-type conducting layer may result from an excess of acceptor impurities near the surface or from a space charge barrier layer which is sufficient to raise the filled band to a position close to the Fermi level. The latter situation is shown in the energy level diagram of Fig. 2. It is assumed that there is a uniform excess of donor impurities in the interior. The surface states are such as to require the Fermi level to cross the surface near the top of the filled band.⁵ The conductivity in the layer right next to the surface is then *P*-type, and this layer is separated from the normal *N*-type region in the interior by the *P*-*N* rectifying barrier. The energy gap in germanium is about 0.75 eV. Approximate values for the other energies shown on the diagram are: $\phi_e = 0.25$ eV, $\phi_h = 0.50$ eV, $\phi_s = 0.70$ eV. The thickness of the space charge layer is about 10^{-4} cm.

Benzer⁶ has found that the activation energy of the saturation component of the reverse current in a germanium rectifier is almost equal to the energy gap (0.67 eV as compared with 0.75 eV). This is in confirmation of the picture of *P*-type conductivity at the surface.

A large part of the current in both the forward and reverse directions flows *via* the *P*-type conducting layer at the surface. The conditions in the *immediate* vicinity (< 0.01 cm) of the point are complicated by the requirement of conservation of both hole current and electron current. The voltage drop is determined principally by that part of the current (in this case electrons) which encounters the highest resistance. This accounts for the high resistances found for reverse biases and for small

forward biases, in spite of the relatively high conductivity of the surface layer.

¹ H. C. Torrey and C. A. Whitmer, *Crystal Rectifiers* (McGraw-Hill Book Company, Inc., New York, New York, 1948), Chap. 12.

² R. Bray, *Bull. Am. Phys. Soc.* **23**, 21 (1948), Abstract 63 of Washington Meeting, April 29-30, 1948.

³ J. Bardeen and W. H. Brattain, *Phys. Rev.*, this issue.

⁴ The micromanipulator used for this work was designed by W. L. Bond.

⁵ J. Bardeen, *Phys. Rev.* **71**, 717 (1947).

⁶ S. Benzer "Temperature dependence of high voltage germanium rectifier D-C characteristics." NDRC 14-579, Purdue University, October 31, 1945.

Modulation of Conductance of Thin Films of Semi-Conductors by Surface Charges

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WHEN a charge is induced on the free surface of a semiconductor, by making it one plate of a parallel plate condenser for example, some of the charge density δq goes into the surface states and some into the space charge in the barrier layer beneath the surface.¹ Figure 1 shows the energy level diagram for an *N*-type semiconductor under no external field (solid lines) and under the field due to negative voltage on the other plate (dotted). If the applied field produces a change in potential δV on the surface, then δq_s , the increased charge per cm² in the surface states, will be $qN_s\delta V$ where q is the electronic charge and N_s is the number of surface states per unit area per unit voltage. The charge in the interior can be estimated from the Schottky exhaustion layer theory which gives $\delta V = 4\pi\rho\delta b/\epsilon$ where ρ is the net charge density of the impurities, ϵ the dielectric constant, and b the thickness of the exhaustion layer. This gives a charge of $\delta q_b = \rho\delta b = \epsilon\delta V/4\pi b$ per unit area, which is produced by removing conduction electrons. Hence a fraction,

$$\beta = \delta q_b / (\delta q_b + \delta q_s) = (\epsilon/4\pi b) / [qN_s + (\epsilon/4\pi b)],$$

of the total charge induced per unit area on the semiconductor is accounted for by reduced conduction electrons in the interior.

If the semiconductor consists of a thin layer of thickness L with exhaustion layers of thickness b on both sides, then the total charge per unit area of conduction electrons is

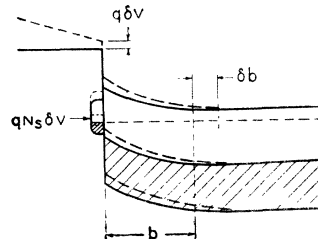


FIG. 1. Energy level diagram showing charge induced in surface states by external field.