to have a positive dn/dT and is considered to have large homopolar bonding, similar reasoning predicts that $dn/d\rho$ is positive; i.e., $\lambda_0 > 1$. In crystals containing radicals and in many glasses, positive dn/dT values are frequently obtained although their $dn/d\rho$ values are negative. In these materials there are effects within the radical which contribute mainly to dn/dT and only slightly to $dn/d\rho$. A more complete treatment of these subjects will be presented in a forthcoming paper.

[1] H. Mueller, Phys. Rev. **47**, 947 (1935).
[2] Burstein, Smith, and Henvis, Bull. Am. Phys. Soc. **23** (2), 33 (1948).
[3] G. N. Ramachandran, Proc. Ind. Acad. Sci. **A25**, 266 (1947).
[4] S. Bhagavantam and S. Suryanarayana, Proc. Ind. Acad. Sci. **A26**, 97 (1947).
[5] C. D. West and J. Makas, Chem. Phys. **16**, 427 (1948) reported $+(p_{11}-p_{12})$ for two mixed thallium halides in agreement with our results. Their data also gives a $+(p_{11}-p_{12})$ and $-p_{44}$, for AgCl in agreement with Mueller's prediction for NaCl structures with small ratio of negative to positive ion polarizibilities. We do not agree with West and Makas concerning the sign of the diamond constants and believe them to be correct as given by Ramachandran.[3]

The Transistor, A Semi-Conductor Triode

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A THREE-ELEMENT electronic device which utilizes a newly discovered principle involving a semi-conductor as the basic element is described. It may be employed as an amplifier, oscillator, and for other purposes for which vacuum tubes are ordinarily used. The device consists of three electrodes placed on a block of germanium[1] as shown schematically in Fig. 1. Two, called the emitter and collector, are of the point-contact rectifier type and are placed in close proximity (separation ~.005 to .025 cm) on the upper surface. The third is a large area low resistance contact on the base.

The germanium is prepared in the same way as that used for high back-voltage rectifiers.[2] In this form it is an N-type or excess semi-conductor with a resistivity of the order of 10 ohm cm. In the original studies, the upper surface was subjected to an additional anodic oxidation in a glycol borate solution[3] after it had been ground and etched in the usual way. The oxide is washed off and plays no direct role. It has since been found that other surface treatments are equally effective. Both tungsten and phosphor bronze points have been used. The collector point may be electrically formed by passing large currents in the reverse direction.

Each point, when connected separately with the base electrode, has characteristics similar to those of the high

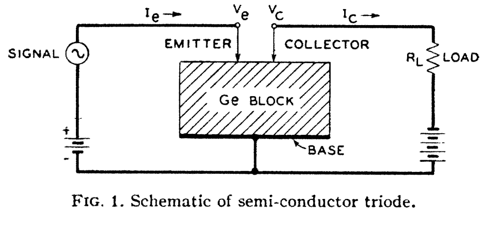

FIG. 1. Schematic of semi-conductor triode.

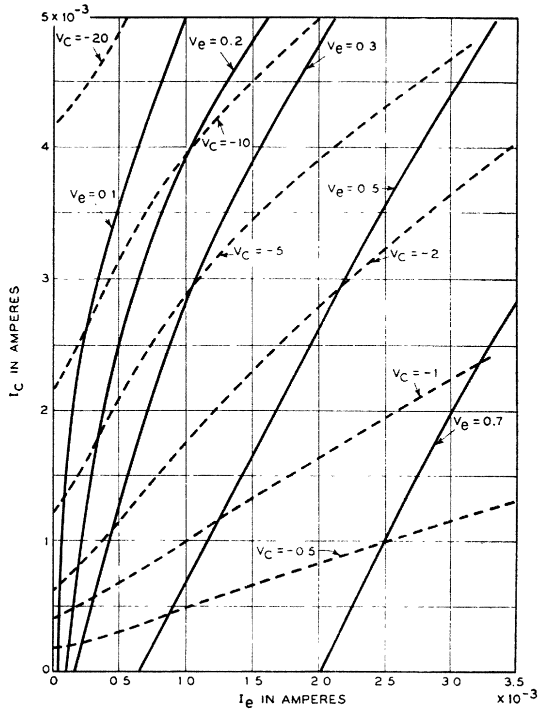

FIG. 2. d.c. characteristics of an experimental semi-conductor triode The currents and voltages are as indicated in Fig. 1.

back-voltage rectifier. Of critical importance for the operation of the device is the nature of the current in the forward direction. We believe, for reasons discussed in detail in the accompanying letter,[4] that there is a thin layer next to the surface of P-type (defect) conductivity. As a result, the current in the forward direction with respect to the block is composed in large part of holes, i.e., of carriers of sign opposite to those normally in excess in the body of the block.

When the two point contacts are placed close together on the surface and d.c. bias potentials are applied, there is a mutual influence which makes it possible to use the device to amplify a.c. signals. A circuit by which this may be accomplished in shown in Fig. 1. There is a small forward (positive) bias on the emitter, which causes a current of a few milliamperes to flow into the surface. A reverse (negative) bias is applied to the collector, large enough to make the collector current of the same order or greater than the emitter current. The sign of the collector bias is such as to attract the holes which flow from the emitter so that a large part of the emitter current flows to and enters the collector. While the collector has a high impedance for flow of electrons into the semi-conductor, there is little impediment to the flow of holes into the point. If now the emitter current is varied by a signal voltage, there will be a corresponding variation in collector current. It has been found that the flow of holes from the emitter into the collector may alter the normal current flow from the base to the collector in such a way that the change in collector 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:

$$I_e = f(V_e + R_F I_c), \tag{1}$$

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 rectifiers[1] 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. Bray[2] 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 of the upper curve from a constant value. The second component of the excess conductivity increases with increasing forward current, and

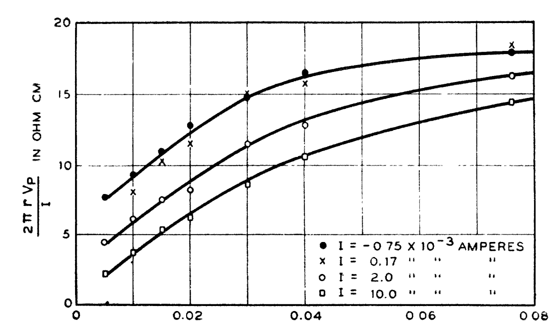

FIG. 1. Measurements of potential, V_p, at a distance r from a point contact through which a current I is flowing into a germanium surface.