MONOGRAPH B-1574

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TECHNICAL PUBLICATIONS

The transistor and related experiments

by

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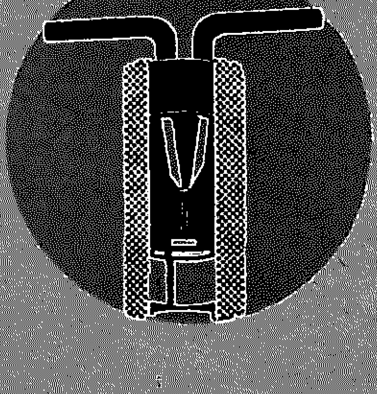

Published in

THE PHYSICAL REVIEW

Vol. 74, pp. 230-233, July 15, 1948

Printed in the UNITED STATES OF AMERICA

The Transistor,
A Semi-Conductor Triode

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June 25, 1948

A THREE-ELEMENT electronic device which utilizes a newly discovered principle involving a semiconductor 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 $\sim$.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 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.

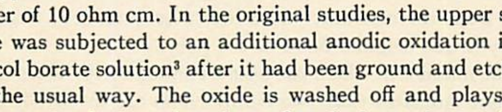

Fig. 1. Schematic of semi-conductor triode.

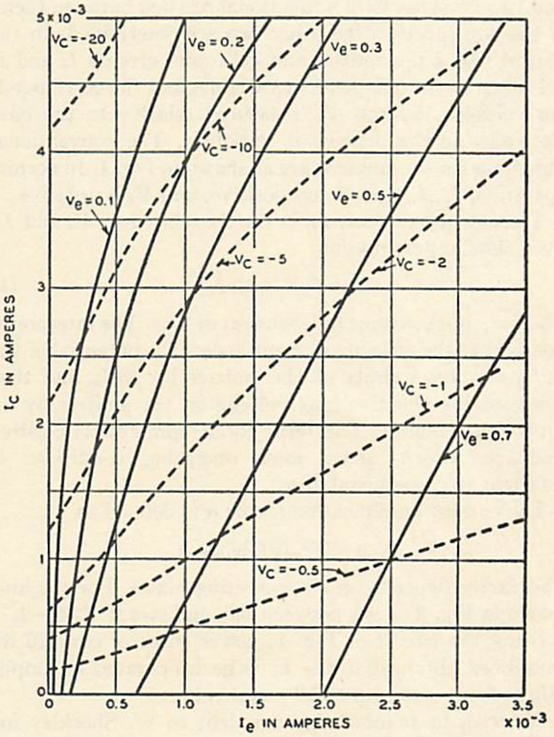

Fig. 2. D.c. characteristics of an experimental semi-conductor triode. The currents and voltages are as indicated in Fig. 1.

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

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

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.

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[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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June 25, 1948

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

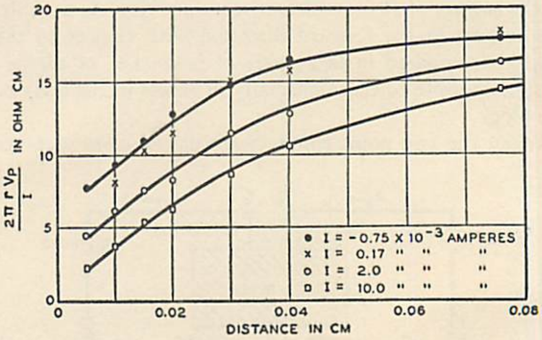

FIG. 1. Measurements of potential, V_p, at a distance r from a point contact through which a current I is flowing into a germanium surface.

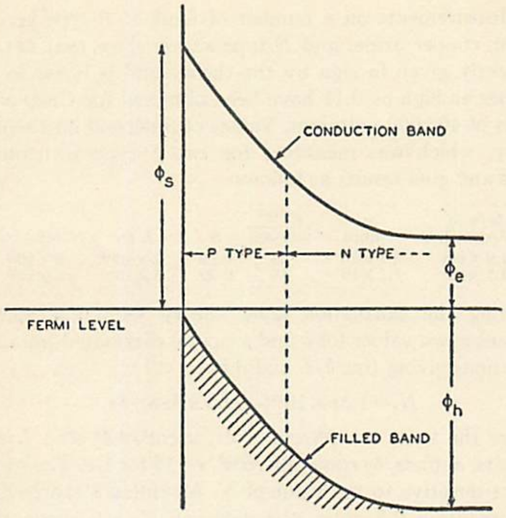

FIG. 2. Schematic energy level diagram of an N-type semi-conductor with a thin layer of P-type conductivity next to the surface.

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: $\varphi_e=0.25$ ev, $\varphi_h=0.50$ ev, $\varphi_s=0.70$ ev. The thickness of the space charge layer is about 10^{-4} cm.

Benzer[6] 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 (<.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.

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[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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June 25, 1948

WHEN a charge is induced on the free surface of a semi-conductor, 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 cm^2 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 $\delta V=4\pi\rho b\delta b/\epsilon$ 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 semi-conductor 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

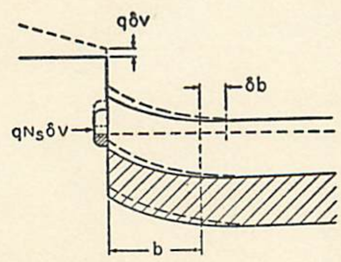

FIG. 1. Energy level diagram showing charge induced in surface states by external field.

$-\rho(L-2b)$ and the conductance parallel to the layer is $\sigma=\rho(L-2b)\mu$ where μ is the mobility. The applied field changes the charge by $\delta q_b=\beta\delta q$ and, therefore, changes the conductance of the layer by

$$\delta\sigma/\sigma=\pm\beta\delta q/\rho(L-2b)=\pm\beta\delta q\mu/\sigma,$$

where the minus sign holds for N-type material (i.e., when $\delta q_b>0$, there are less electrons and $\delta\sigma<0$) and plus for P-type.

The charge δq on the surface is induced by using the semi-conductor as one plate of a parallel plate condenser, and the change in conductance is simultaneously determined for current flow parallel to the plate. The experimental arrangement consists of a condenser with rectangular plates about 1×2 cm of gold and semi-conductor evaporated on opposite sides of a slab of fused quartz 0.003 inch thick. The current used to measure the change in conductance flows between two additional gold electrodes evaporated on the two ends of the semi-conductor. According to the above theory, the capacity of this unit is that of the quartz C_q in series with $C_s=qN_s$ and $C_b=\epsilon/4\pi b$ in parallel, and is thus chiefly determined by C_q. The value δq is determined directly from the measured capacity per unit area and the applied voltage. (Experiments to check the equivalent circuit for the unit, including relaxation effects, will be communicated later.)

Measurements on a number of films of P-type germanium, copper oxide, and N-type silicon show that $\delta\sigma/\sigma$ is correctly given in sign by the theory and is linear in $\delta\sigma$. Values as high as 0.11 have been obtained for Cu_2O with fields of 400,000 volts/cm. Values of β depend on the mobility, which was measured for two P-type germanium films and give results as follows:

$\delta\sigma/\sigma\,\delta q$ cm²/coulomb	σ mhos	$\frac{\mu\ \text{cm}^2}{\text{volt-sec.}}$	β	L cm	N_s/cm² volt
1.0×10^4	3.1×10^{-4}	33	0.10	2×10^{-5}	6×10^{12}
5.5×10^3	7.7×10^{-4}	49	0.09	5×10^{-5}	5×10^{13}

Using the exhaustion layer theory with $V=2\pi\rho b^2/\epsilon$, the unknown values for b and ρ can be eliminated from the equations giving (for b/L and β both $\ll 1$)

$$N_s=1.31\times10^{12}(\epsilon\mu/LV\sigma)^{\frac{1}{2}}\sigma\delta q/\delta\sigma,$$

where the units are N_s/cm² volt, μ cm²/volt-sec., L cm, V volts, σ mhos, δq coulombs/cm², $\epsilon=19$ for Ge. The result is not sensitive to the value of V. Assuming a representative value of 0.5 volts, the value of N_s was computed. This value is comparable with that previously obtained for silicon by another method.[2]

We are indebted to many of our colleagues for discussions and advice and to R. B. Gibney, J. R. Haynes, and M. Sparks for preparation of the films.

[1] J. Bardeen, Phys. Rev. 71, 717 (1947).
[2] W. H. Brattain and W. Shockley, Phys. Rev. 72, 345 (1947).

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