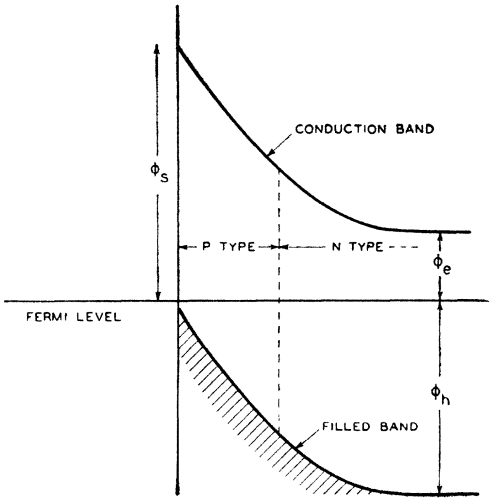

FIG. 2. Schematic energy level diagram of an N-type semi-conductor with a thin layer of P-type conductivity next to the surface.

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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[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 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

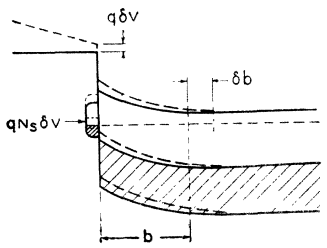

FIG. 1. Energy level diagram showing charge induced in surface states by external field.

$-\rho(L-2b)$ 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	μ cm²/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^{-6}	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 $\ll1$)

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

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).