Junction Fieldistors*

O. M. STUETZER†, ASSOCIATE, IRE

Summary—A high-impedance, input-low impedance output amplifying device which utilizes surface conductivity control in the neighborhood of a *p-n* junction is described. The transconductances of the order of 1,000 micromhos can be reproduced at very low frequencies.

Introduction

A SCHEMATIC DIAGRAM (Fig. 1) shows the essentials of the experimental device we shall discuss. A *p-n* junction is biased in the reverse direction by a current I_a. A control electrode is attached in close proximity to the junction. The distance d is of the order of a few microns, the breadth B, of the order of 100 microns for practical devices. An ac signal can be applied to the control electrode on top of a variable dc bias $\pm U_g$. The circuit is balanced to keep the center of the junction electrically on zero and to measure all potentials versus this zero. For practical applications this is, of course, not necessary. Fig. 2 shows experimental models.

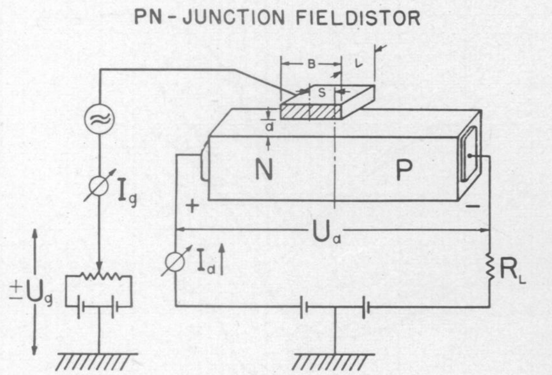


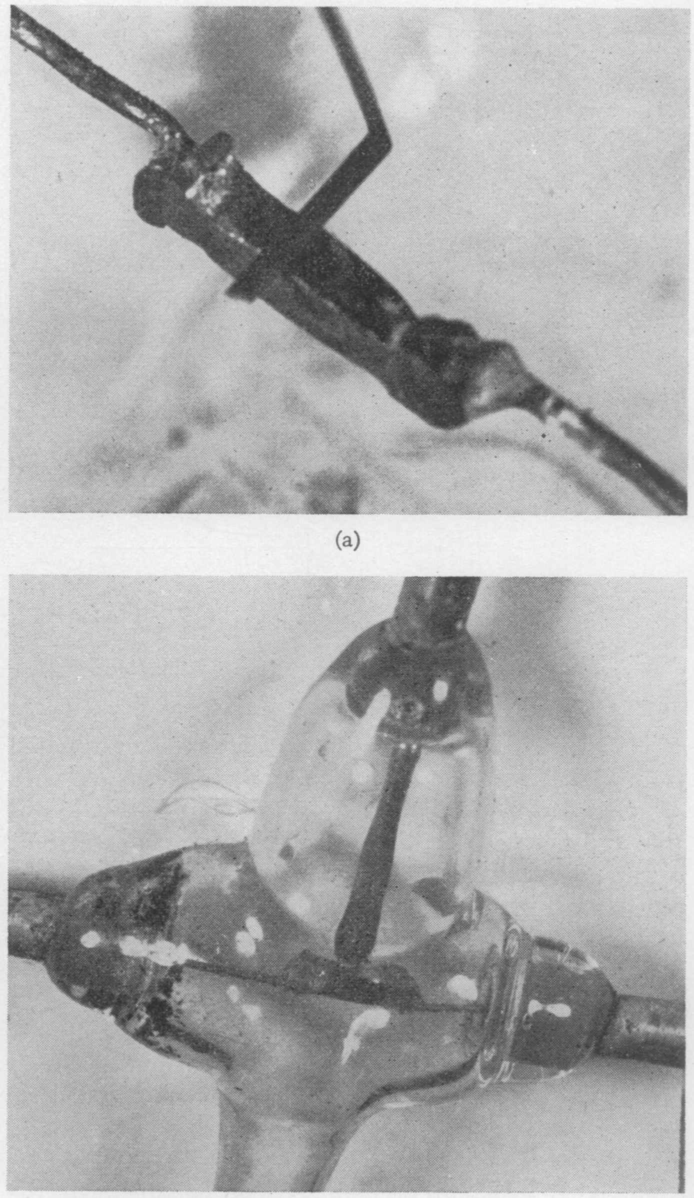
Fig. 1—Schematic diagram of arrangement.

The arrangement is very similar to the point- or line-contact "fieldistor" described previously.[1] The voltage U_g exerts a controlling effect on the current I_a. As a quality figure for the device, we will choose the transconductance $G_m = (\partial I_a / \partial U_g)_{U_a}$.

The controlling effects depend on the state of the surface. The experiments to be reported were carried out with Ge junctions (Diodes M1470 and M1728, Bell Telephone Laboratories). They were cleaned with alcohol only; the surface, which comes heavily treated, was not changed.

In the arrangement of Fig. 1, this material produces devices with a G_m of several micromhos and a flat frequency response up to several hundred kc. Liquid dielectrics between control electrode and surface (f.i. water free oils) increases the effect roughly in proportion with their dielectric constant.

However, if we introduce between surface and control electrode a liquid with a reasonably high polar moment, G_m changes sign and increases drastically. The output impedance of the device $\partial I_a / \partial U_a$ decreases and the frequency response shows a cutoff in the audio-frequency range. Devices of this kind, which are easy to reproduce and measure, shall be the subject of our discussion.



(a)

(b)

Fig. 2—Experimental models: (a) open, (b) sealed. Actual size of crystal: $0.3 \times 0.08 \times 0.08$ cm³.

The DC Characteristic

The sign of G_m depends on the position S (see Fig. 1) of the control electrode. Fig. 3 illustrates the experi-

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† Components and Systems Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Dayton, Ohio.

mental evidence. If the control electrode F is on the n-side of the junction, I_a increases pronouncedly if U_g becomes more negative. Positive increments of U_g are needed to produce a current increase if F is on the p-side of the junction. If F is positioned directly above the center, the two effects superimpose and a characteristic with a minimum occurs, as often observed with point-contact fieldistors.[1]

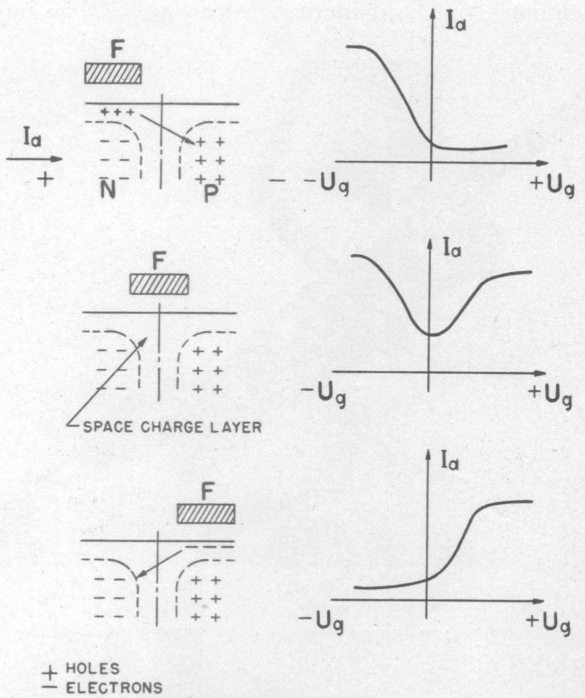

Fig. 3—Controlling action versus position of field electrode F.

The order of magnitude of the effect can be estimated from Fig. 4, a semilogarithmic plot of I_a versus U_g, with U_a as a parameter. The figure shows that for high positive and negative control voltages, I_a reaches different saturation values. These and the minimum current are plotted in Fig. 5 for a similar fieldistor in the form of a logarithmic I_a-U_a diagram. It shows that the dc impedance of the device can be changed by more than one order of magnitude.

The optimum G_m is directly proportional to the linear length L of the junction. The model measured in Fig. 4 gives four times the G_m values when, instead of a control electrode on one side ($L=0.08$ cm), a ribbon extending around the crystal block ($L=0.32$ cm) is used.

G_m is approximately inversely proportional to the electrode distance d. (See the low-frequency values in Fig. 8, which will be discussed later.) This means that the controlling effect is proportional to the controlling fieldstrength ("fieldistor").

G_m, furthermore, depends on the polar moment of the liquid introduced. In general, G_m is the larger, and the output (and input) impedance the smaller, the higher the polar moment of the liquid (see Figs. 6, 7, to be discussed later).

From Fig. 4 a considerable hysteresis effect becomes apparent, which is not surprising for a mechanism in which the orientation of polar molecules close to a surface with "surface states" and "traps" plays a role. I_a decreases more rapidly with decreasing control voltages than it increases with increasing control voltages.

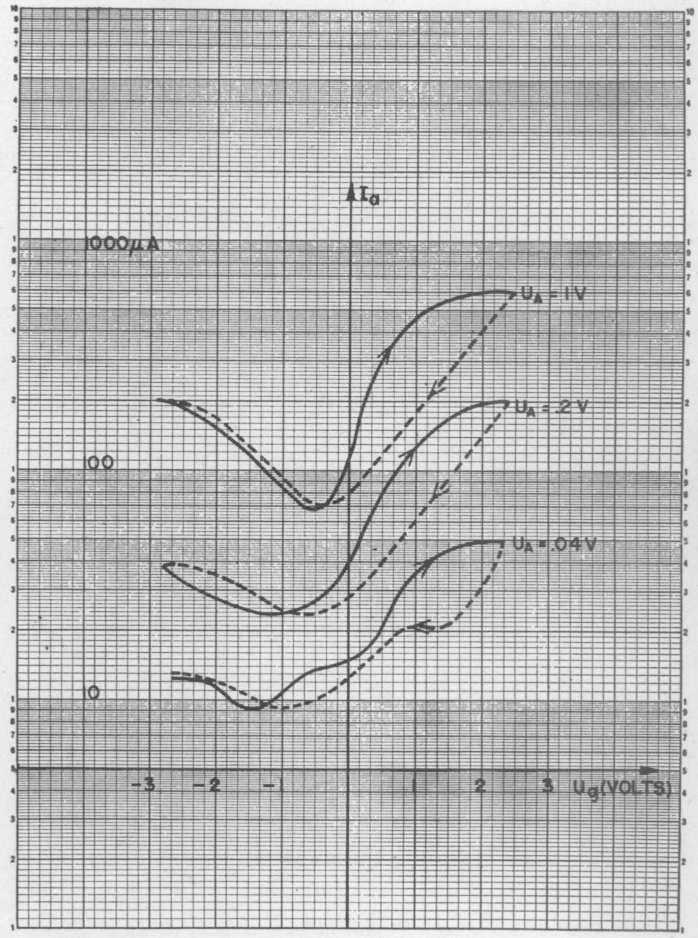

Fig. 4—I_a versus U_g diagrams for various "anode" voltages U_a($L=0.08$, $B=0.003$ cm; $d=0.0005$ cm).

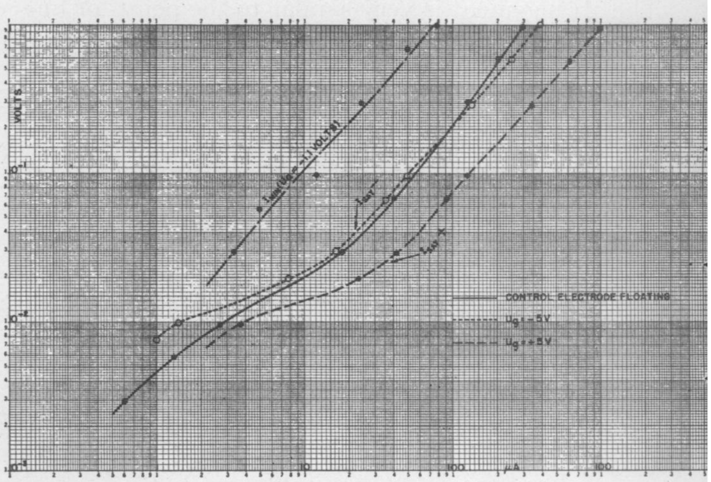

Fig. 5—Junction voltage U_a versus junction current I_a, showing saturation values I_{sat+} for large positive and I_{sat-} for large negative biases as well as minimum current I_{min}.

[1] O. M. Stuetzer, "A crystal amplifier with high input impedance," Proc. I.R.E., vol. 38, pp. 868–871; August, 1950.

For high controlling (and driving) voltages, electrolytic action which causes irreproducible changes occurs. If all voltages are kept below 1.5 volts, however, carefully manufactured devices stay constant within ± 15 per cent over months.

In a junction without any control electrode attached, each part has just the potential of the right sign to produce a current increase in the other part ("self-fieldistoring"). This results in marked changes of the back characteristic (see Fig. 6). The plot indicates how important complete absence of polar surface molecules is for high back-voltage rectifiers.

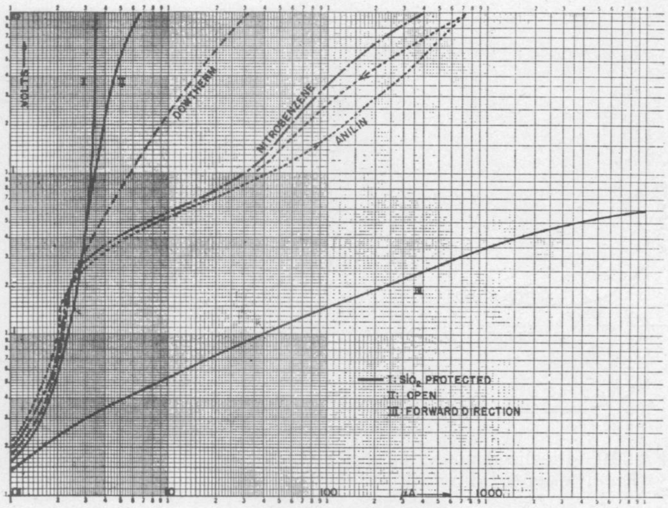

Fig. 6—Deterioration of rectifying junction characteristics due to fieldistor effect.

AC Behavior

With a suitable model the frequency response for an ac signal over the dc bias was measured for various dielectric liquids (Fig. 7). The curves could be reproduced within 15 per cent after one month. The frequency response depends, to a certain degree, on the dc bias applied, as is indicated for n-butyl-phthalate.

Fig. 8 shows the frequency response for a nitrobenzene activated fieldistor with the distance d as a parameter. Figs. 7 and 8 are for measuring models only; in actual devices L was larger, leading to transconductance values of several thousand μmhos at low frequencies.

The observed frequency behavior is reminiscent of that of two RC combinations in series (see Fig. 9). That the cutoff curves shown in Figs. 7 and 8 do not slope off exactly inversely proportional to frequency can be explained by the fact that in reality we will have to assume many of such combinations in parallel.

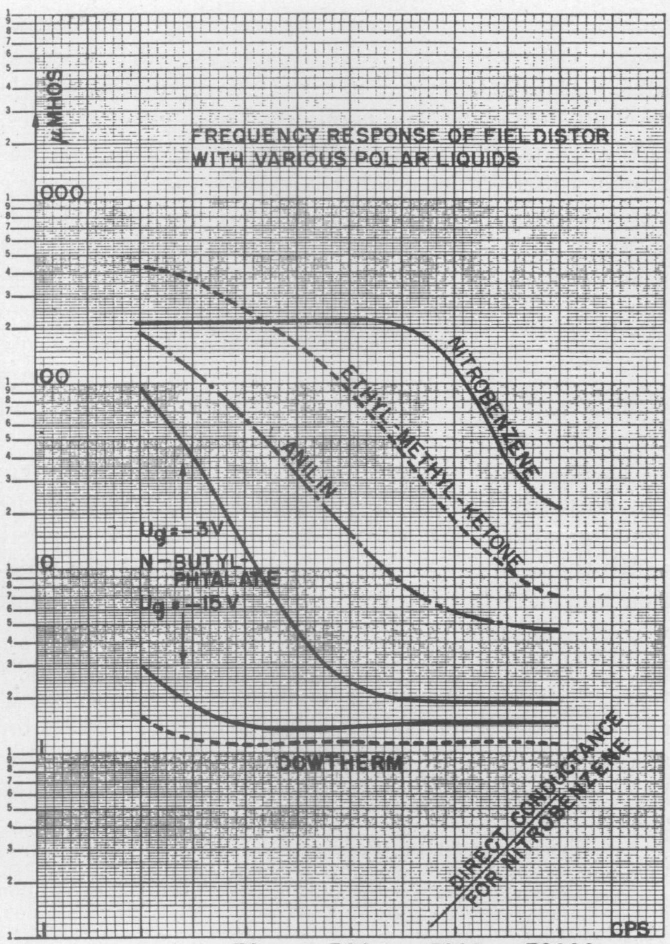

Fig. 7—Dependence of G_m on frequency for fieldistor model ($L=0.12$, $B=0.003$, $d=0.0002$ cm, for various polar liquids.

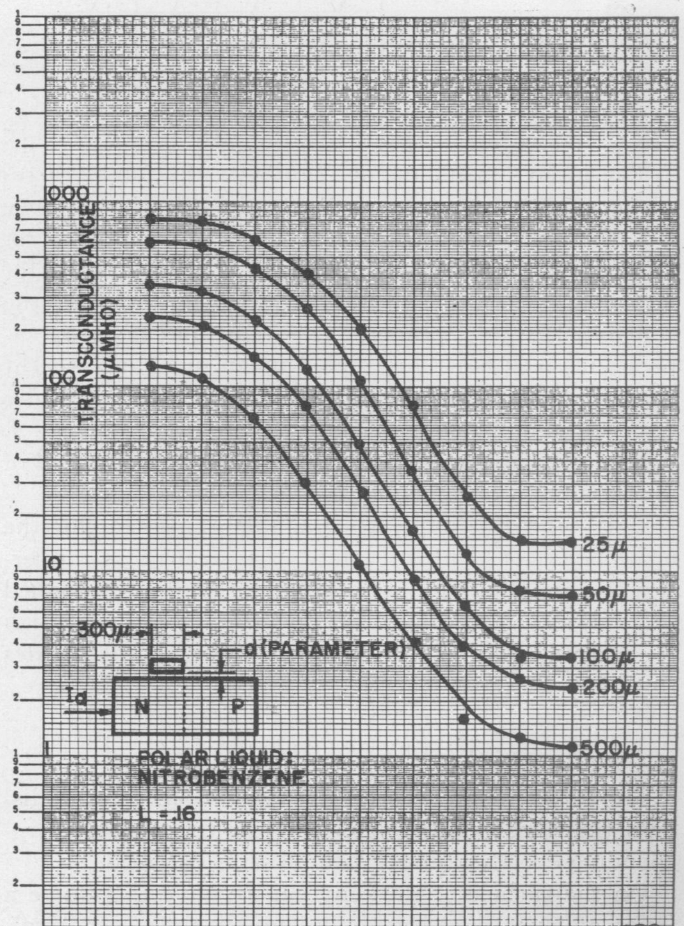

Fig. 8—Frequency response versus distance d.

The output impedance of the device is naturally dependent on the bias (compare Fig. 5). At points of maximum G_m, several thousand ohms are found with liquids of high polarity, several ten thousand with liquids of lower polar moment (compare Fig. 6).

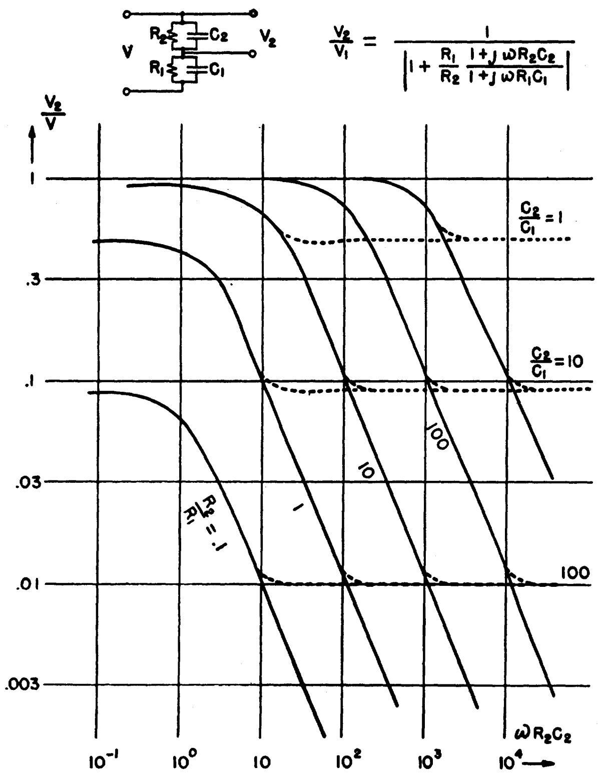

Fig. 9—Frequency characteristics of two RC combinations in series.

The input impedance of the devices is roughly a resistance of about 10 megohms paralleled by capacitance $\epsilon BL/d$, which turns out to be of the order of a few micromicrofarads. (See plot of "direct conductivity" for nitrobenzene sample in Fig. 7.) Leakages around the controlling system proper, and circuit and build-up capacitances, are mostly of higher magnitude, unless great care is taken. Input impedance is discussed more fully later in connection with the interpretation of Fig. 9.

Using the above figures, a power gain $R_{in}R_{out}G_m^2/4$ of about 40 db is obtained for low frequencies.

Only tentative data are available at present for the noise behavior. Unfortunately, the ideal noise properties of a junction are lost when a polar liquid is applied to its surface. Noise figures at operation points with high G_m are very similar to those of the point-contact diodes (60 to 80 db at 1000 cps.).

Theory of Operation

For a sketch of a theoretical explanation, we shall discuss the n-side of the junction. On the p-side, corresponding events happen, with all signs reversed.

On the surface of the junction we have to assume a layer of surface charges, (in our example, negative), which is counterbalanced by a space-charge layer of ionized donors of about 10^{-4} cm depth. The left diagram in Fig. 10 represents that configuration and gives a rough plot of the electron energy ϕ_e in the conduction band and the hole energy ϕ_h in the filled band. The number of carriers present varies inversely to exp ϕ/kT.

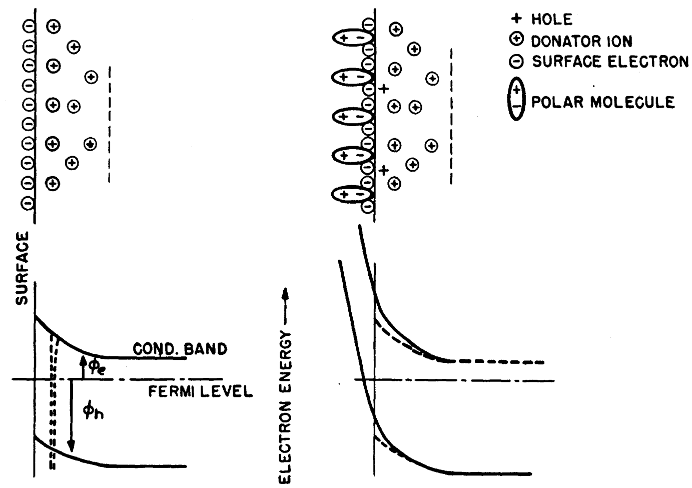

Fig. 10—Idealized model of surface on n-side of junction, with and without oriented dipole layer, showing electron and hole energies.

If a positive charge is induced into the system, that is, if the control electrode F (see Fig. 3) is negatively biased, the conduction electrons are repelled, the space-charge layer increased, and the energy bands raised a little.[2] A slight decrease in conductivity of the sample should be expected, and is observed with clean surfaces.

With a polar liquid present, however, a rather pronounced increase of conductivity is the case. We have to assume that the outside field raises the energy bands so much that, close to the surface, ϕ_h becomes smaller than ϕ_e, leading to the creation of excess holes. (Fig. 10 right.) The underlying physical mechanism is the repelling forces of the negative surface charges tearing valence electrons out of the lattice atoms. Experiments similar to the one described by Shockley, Pearson, and Haynes[3] indicate minority carrier conduction.

It is essential for our effect that the minority carriers originating in this way be produced on that side of the junction where the existing fields in the junction underneath the surface (see Fig. 3) help them cross the junction barrier. That is one reason why the arrangement works rather effectively.

Fig. 10 (right, top) shows a layer of oriented dipole molecules on a surface. The average potential rise in such a dipole layer is several volts[4] (about 5 volts for nitrobenzene). Close to one of the charged molecules, however, much higher rises are present, similar to the

[2] W. Shockley and G. L. Pearson, "Modulation of conduction of thin films of semiconductors," *Phys. Rev.*, vol. 74, p. 232; July, 1948.

[3] W. Shockley, G. L. Pearson, and J. R. Haynes, "Hole injection in germanium," *Bell Sys. Tech. Jour.*, vol. XXVIII, pp. 344–366; July, 1949.

[4] J. H. DeBoer, "Electron Emission and Adsorption Phenomena," Macmillan Co., New York, N. Y., p. 50, ff.; 1935.

potential fall indicated for a donor ion on the left side of Fig. 10. It is no surprise that the interaction with the surface atoms of the high fields creating these potentials raises the average potential close to the surface inside the crystal by a few tenths of a volt. (Potential rises of the order of magnitude were indicated in experiments by using a suitable probe arrangement and a high impedance electrometer.)

Fig. 11 shows the customary energy diagram for the junction in equilibrium. The carrier densities associated with the energies are plotted on the left side. It can be seen that a few tenths of potential rise brings substantial minority carrier density on both surfaces.

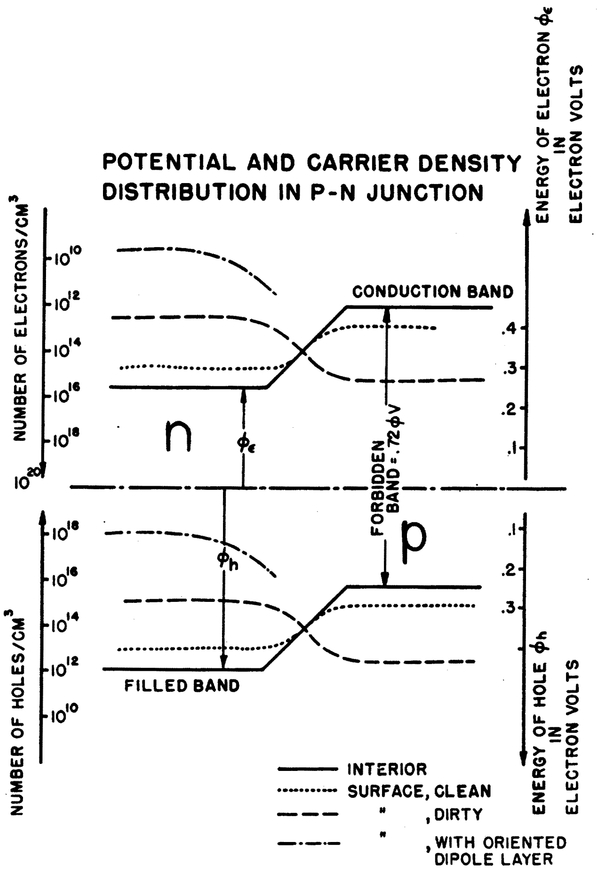

Fig. 11—Electron energy and carrier density distribution along junction. (Interior curves for conductivity of about 2 ohm^{-1} cm^{-1}.)

The detailed theoretical description of the surface layer will be rather complex. The potential in perpendicular to the surface no longer varies parabolically, but increases much faster (until degeneracy occurs). The potential along the axis of the device can not be assumed to be independent of the distance from the surface. The layer of high generation and high recombination will affect the mobility close to the surface.

Roughly, a density of 10^{18}/cm^3 directly on the surface, leading with an approximated potential distribution to an area density of 10^{12}/cm^2, can be assumed. With a mobility of 10^3 cm^2/volt sec and an accelerating field of 10 v/cm, the order of magnitude of the effect can be explained.

The high current densities (10^3 amp/cm^2) on the surface will be partly responsible for the high noise of the device.

We can explain the saturation properties of the device (see Figs. 4 and 5) by assuming that all the microdipoles are then oriented.

To analyze the frequency behavior of the device, we shall use the circuit model of Fig. 9. V_2 is that part of the (ac) control voltage V, which induces the surface changes necessary for our control effect. Analysis shows that we have to attribute to C_2 a value of the order of 10^{-10} F. This points to the existence of a high capacitance layer on the surface—probably a gas layer similar to the one in electrolytic condensers—with a capacity of about $10^{-8}F$/cm^2. C_1, which is one to two orders of magnitude smaller, then represents the capacitance of the control electrode (in series with the capacitance of the conductive surface layer). R_2 in this picture would be the very big (several megohms) resistance of the (gas) layer and R_1 the resistance of the control liquid in series with that of the conductive surface layer. R_1 will certainly change with bias, and C_2 may very well do so. This explains the dependence of the frequency characteristic on dc bias.

Conclusions

A crystal amplifier with about 10-megohms input and several thousand ohms output impedance, a transconductance of about a thousand micromhos, and a noise figure of the order of 70 db was described. A frequency cutoff in the audio range will severely limit the application of the present form of the device.

The investigations add to our knowledge of surface phenomena. They explain why the presence of molecules with a polar moment on the surface of a diode damages its back voltage properties.

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