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Effect of Variations in Surface Potential on Junction Characteristics

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A filamentary structure has been used to compare the electrical properties of a germanium surface with those of an adjacent *p-n* junction intersecting the same surface. Surface charge is varied by field effect plates in the isolated portion of the filament and near the junction. An orderly relation can be found between surface potential variations and changes in the reverse currents across the junction. At low bias, the junction current varies with surface recombination velocity, and for bias near breakdown, the breakdown voltage varies with induced charge at the surface. For inverted surfaces, the low bias current varies rapidly as expected from channel length variations. With inverted surfaces, channel growth leads to large reverse current variations with surface potential, but breakdown voltage becomes independent of surface charge. These variations are considered in terms of simple theory, and device implications are discussed.

I. INTRODUCTION

PROPERTIES of semiconductor surfaces have been the subject of numerous investigations.[1,2] Of interest here are studies of semiconductor device surfaces which can be divided into two categories: physical studies of surface structure on a single conductivity semiconductor and studies of surface problems related to device characteristics and their stability. In general, these two kinds of study have been carried out separately; for example, changes in surface potential have been inferred from changes in *p-n* junction characteristics, and changes in junction characteristics have been predicted from single conductivity filamentary measurements.

It is the purpose of this paper to describe experiments which utilize a filamentary structure for direct comparison of the electrical characteristics of a *p-n* junction with physical properties of the semiconductor surface intersecting the junction. In this way, the two kinds of study mentioned above can be carried out simultaneously with the same material and surface preparation.

In these experiments, a single filamentary germanium specimen is employed. The specimen consists of an extended single conductivity (*p*-type) portion, with an n^+ region grown on one end to form an n^+-p junction. Using an ac field effect technique,[3] surface conductance[4] and surface recombination velocity[5] are determined as functions of surface charge on the single conductivity portion of the specimen. Using the ac field effect technique to vary the surface charge at the surface intersecting the n^+-p junction, the nature and magnitude of the reverse bias junction current has been investigated for corresponding values of surface charge.

At low junction bias, the reverse current variations are calculable in terms of the measured changes in surface recombination velocity, provided the surface conductivity type remains the same as that of the body. For inverted surfaces, an additional current appears, which is approximately calculable in terms of channel growth.[6,7]

At higher bias voltages (with noninverted surfaces), surface avalanche breakdown[8,9] is found to be an additional source of reverse current. The junction breakdown voltage increases with increasing magnitude of negative surface charge, reaching the body value soon after the surface becomes inverted. This measured variation of breakdown voltage with surface charge is not calculable on the basis of simple theory.[9]

The expected relations between an n^+-p junction characteristic and the surface properties of the low conductivity side of the junction are discussed in more detail in the following section.

II. RELATIONS BETWEEN n^+-p JUNCTION CHARACTERISTICS AND PHYSICAL PROPERTIES OF SURFACES

A. Physical Properties of Surfaces

Some of the properties of semiconductor surfaces have been successfully interpreted in terms of electronic energy level diagrams similar to the one in Fig. 1 which represents an idealized equilibrium situation at a semiconductor surface boundary. E_c and E_v represent the lowest energy in the conduction band and the highest energy in the valence band, respectively. E_i represents the Fermi energy for an intrinsic semiconductor and E_f represents the Fermi energy in a *p*-type specimen. A quantity φ may be defined by

$$q\varphi = E_f - E_i, \qquad (1)$$

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[1] R. H. Kingston, J. Appl. Phys. **27**, 101 (1956).

[2] R. H. Kingston, editor, *Semiconductor Surface Physics* (University of Pennsylvania Press, Philadelphia, Pennsylvania, 1956).

[3] W. L. Brown and H. C. Montgomery, Phys. Rev. **98**, 1565(A) (1955).

[4] W. L. Brown, Phys. Rev. **100**, 590 (1955).

[5] C. G. B. Garrett and W. H. Brattain, Bell System Tech. J. **35**, 1019 (1955).

[6] W. L. Brown, Phys. Rev. **91**, 518 (1953).

[7] A. L. McWhorter and R. H. Kingston, Proc. Inst. Radio Engrs. **42**, 1376 (1954).

[8] A. J. Wahl and J. J. Kleimack, Proc. Inst. Radio Engrs. **44**, 494 (1956).

[9] C. G. B. Garrett and W. H. Brattain, J. Appl. Phys. **27**, 299 (1956).

where q is the electronic charge. Referring to Fig. 1, φ varies from a value φ_b in the semiconductor to a value φ_s at the surface. The corresponding hole and electron densities vary from p_b and n_b to p_s and n_s, and are given by

$$p=n_i e^{-\beta\varphi}, \tag{2}$$

$$n=n_i e^{\beta\varphi}. \tag{3}$$

The density of holes and electrons in the space charge region is a unique function of φ_s and φ_b.[4] If we assume the surface carrier mobilities[10] are the same as the bulk mobilities (i.e., small magnitudes of φ_s), then the surface conductance is a unique function of φ_s and φ_b. As the carrier concentration at the surface varies, the conductance of the semiconductor will vary. This conductance change is given by

$$\Delta G=q(\mu_p\Delta P+\mu_n\Delta N). \tag{4}$$

ΔP and ΔN are the changes in the hole and electron concentration per unit surface area summed over the region in the filament where $\varphi\neq\varphi_b$. The ΔP and ΔN are functions of φ_s and φ_b and have been tabulated by Kingston and Neustadter[11] and by Garrett and Brattain.[12]

Brown[4] has shown that measurements of changes in ΔG produced by changes in an applied field directed normal to the surface can be used to determine the values of φ_s, provided that the ΔG range includes the minimum value of surface conductance.

The surface recombination rate of excess minority carriers is defined as

$$S=J/\Delta n, \tag{5}$$

where J is the recombination current and Δn is the excess minority carrier concentration near the surface, but far enough inside the semiconductor so that $\varphi=\varphi_b$.

Recombination at surfaces has been considered by Brattain and Bardeen[13] in terms of intermediate states in the gap (fast surface states), in an analogous manner to the bulk recombination process considered by Shockley and Read.[14] Using this kind of analysis, considering states at one discrete energy, Stevenson and Keyes[15] have arrived at the following expression for S:

$$S=N_tC_pC_n(p_b+n_b)/C_n(n_s+n_{s1})+C_p(p_s+p_{s1}), \tag{6}$$

where N_t = the density of recombination centers (per unit area of surface), and C_p = the capture probability per center per unit time for holes if all centers are filled, C_n = capture probability per center per unit time for electrons if all centers are empty, p_{s1} = hole density at the surface if $E_f=E_t$, where E_t is the effective energy level of the center, and n_{s1} = the electron density at the surface if $E_f=E_t$.

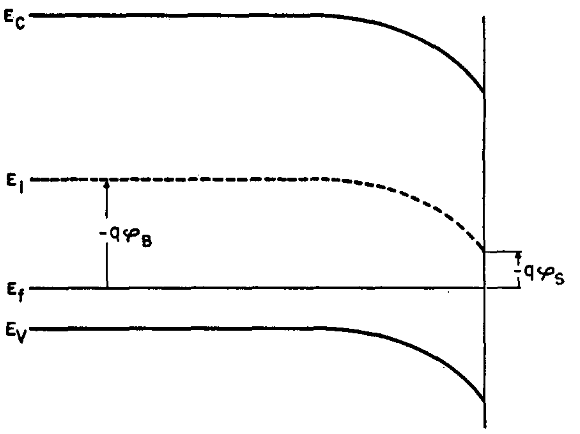

FIG. 1. Energy level diagram for a p-type semiconductor.

According to this model, S has a maximum value, S_M, at a value of $\beta\varphi_M$ given by $\beta\varphi_M=\frac{1}{2}\log C_p/C_n$ and is symmetrical in φ about φ_M.

Thus, for a ratio of C_p/C_n close to l, S generally increases, goes through a maximum, and decreases as φ_s is varied from negative to positive values.[16]

B. Low Bias Reverse Junction Current

The term "low bias" is used here to denote reverse bias values low enough to preclude avalanche multiplication effects at the junction (to be discussed in the following section), but substantially large compared to $1/\beta$.

The current across a p-n junction at low reverse bias depends on the minority carrier generation on both sides of the junction.[17] For a junction between heavily doped n type and lightly doped p type, i.e., an n^+-p junction, most of the reverse current is carried by electrons generated in the body and at the surface of the p-type material. For a rectangular geometry, in which surface generated carriers are appreciable, the current density is given by

$$j=qn_b\left(\frac{D}{\tau_E}\right)^{\frac{1}{2}}(e^{\beta V}-1), \tag{7}$$

where V is the applied voltage, D is the diffusion constant for electrons in the p-type semiconductor and τ_E is an effective lifetime given by

$$1/\tau_E=\frac{2S}{l}+\frac{1}{\tau_b}. \tag{8}$$

Here l is the thickness of the filament and τ_b is the body lifetime. This expression applies for rectangular fila-

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[10] J. R. Schrieffer, Phys. Rev. **97**, 641 (1955).

[11] R. H. Kingston and J. F. Neustadter, J. Appl. Phys. **26**, 718 (1955).

[12] C. G. B. Garrett and W. H. Brattain, Phys. Rev. **99**, 376 (1955).

[13] W. H. Brattain and J. Bardeen, Bell System Tech. J. **32**, 1 (1953).

[14] W. Shockley and W. T. Read, Phys. Rev. **87**, 835 (1952).

[15] D. T. Stevenson and R. J. Keyes, Physica **20**, 1041 (1954).

[16] Many, Harnik, and Margoninski in reference 2, page 89.

[17] W. Shockley, Bell Syst. Tech. J. **28**, 346 (1949).

ments for which t is small compared to width and length and is valid for $St/D \ll 1$. It is to be expected that the reverse current will be related to changes in φ_s near the junction, since S is related to φ_s by a function similar to the one given in Eq. (6). Variations in the saturation current of p-n junctions attributed to variations of S with φ_s have been reported.[8,18]

In the case of $2S/t \gg 1/\tau_b$ the reverse junction current primarily results from surface generation. According to Eqs. (6), (7), and (8), the low bias current increases as $\beta\varphi_s$ is varied from negative towards positive values, reaching a maximum near $\beta\varphi_s = 0$ if $C_p/C_n \simeq 1$.

However, when $\beta\varphi_s$ becomes positive, the surface becomes n type, and the inversion layer, or channel, tends to increase the area of the junction effective in collecting minority carriers. Thus, although for sufficiently positive $\beta\varphi_s$ Eq. (6) indicates a decrease in S, Eqs. (7) and (8) are not expected to apply for $\beta\varphi_s > 0$, and the junction current continues to increase with $\beta\varphi_s$. An approximate expression for the channel current[7] as a function of $\beta\varphi_s$ is given in Sec. B of the Appendix.

C. Breakdown Voltage

Wahl and Kleimack[8] have shown that changes in φ_s may produce large changes in the collector breakdown voltage of alloy junction transistors. Garrett and Brattain[9] have carried out a more detailed study of the breakdown of reverse biased germanium alloy junctions. Their experiments indicate that reverse biased p-n junctions can exhibit a multiplicative breakdown near the surface at considerably lower bias values than those necessary to produce a multiplicative breakdown in the body of the semiconductor. Thus the observed breakdown voltage of a p-n junction, V_{BO}, can be less than or equal to the body value, V_B. The magnitude of the change in breakdown voltage, ΔV_B, defined as $|V_B - V_{BO}|$ is found to be a function of the fixed charge covering the surface in the vicinity of the junction. The value of ΔV_B for p-n junctions in which the doping is substantially greater on one side (i.e., n^+-p or p^+-n junctions) is sensitive to the surface charge on the higher resistivity side of the junction. If this charge is of that sign which tends to induce a channel on the high resistivity side of the junction ΔV_B is essentially zero. If the surface charge is of opposite sign, and sufficiently large, ΔV_B becomes appreciable.

Using the simplified model proposed by Garrett and Brattain, the value of ΔV_B has been calculated as a function of $\beta\varphi_s$ for the particular case of an n^+-p germanium step junction with a resistivity value of 2.5 ohm-cm on the p-type side of the junction. This variation of ΔV_B is indicated in Fig. 2. Indicated on the lower horizontal scale are values of Q_s, (the surface charge density required to neutralize the charge density just inside the semiconductor surface, neglecting charge in "fast" surface states) corresponding to indicated values on the $\beta\varphi_s$ scale.

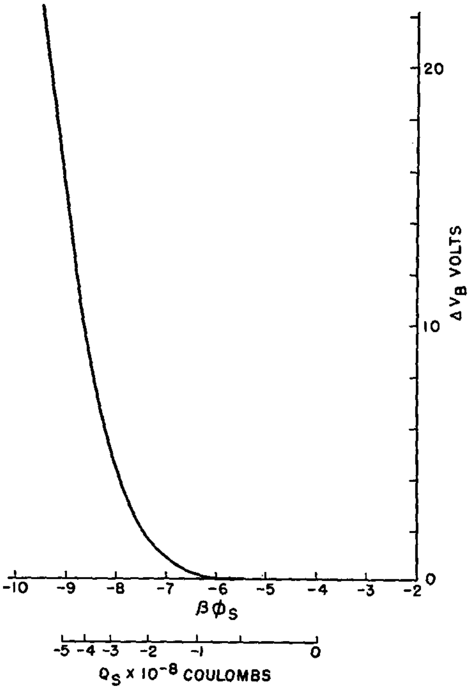

FIG. 2. Change in V_{BO} as a function of surface charge.

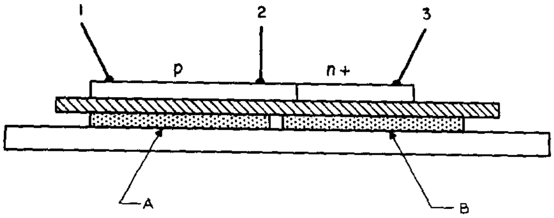

FIG. 3. Experimental filamentary germanium diode.

As indicated in the figure, the theory predicts that at small positive values of $\beta\varphi_s$, the junction should exhibit body breakdown, and should do so until $\beta\varphi_s$ reaches negative values large enough in magnitude that a substantial enrichment layer has begun to develop. Then breakdown begins at the surface, and the observed ΔV_B increases rapidly as $-\beta\varphi_s$ increases.

III. EXPERIMENTAL

The brief discussion of surface and junction properties indicates that the junction saturation current and breakdown voltage should be uniquely related to φ_s. In order to investigate such relationships, the experimental structure described below can be used.

Referring to Fig. 3, the filamentary grown junction germanium diode is placed on a thin mica spacer, supported by two similar flat metal plates cemented to a glass microscope slide. Electrodes 1 and 2 permit longitudinal flow of current through the p-type side of the junction and electrodes 1 and 3 permit current

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[18] J. E. Thomas and R. H. Rediker, Phys. Rev. **101**, 984 (1956).

flow across the n^+-p junction. One of the plates at A, extending only along the p-type filament, serves to apply a field directed along the normal to the surface of the p-type material, and the other plate, at B, serves to apply a field in the same direction but at one of the surfaces where the junction current is generated. It is assumed that the effect of the field at the n^+ surface produces changes which are unimportant compared to those produced at the high resistivity side of the junction.

Electrical measurements are made with the circuit shown in Fig. 4. By passing direct current down the filament by means of electrodes 1 and 2, and modulating with an ac voltage on the field effect plate A, a measurement of the ac field effect can be made in the manner described by Montgomery and Brown.[3,19] After proper balancing out of the capacitive currents in the plate circuit by adjustment of R_1, changes in surface conductance (as changes in voltage across R_c) appear on the oscilloscope against changes in plate voltage. Using electrodes 1 and 3, a reverse dc bias is applied to the junction. The plate B is used to modulate the surface potential near the junction, and the effect on the reverse current of the junction is observed as a function of the plate voltage. This provides a plot of I_J, the reverse junction current change against Q_T, the charge per unit area on the field effect electrode.

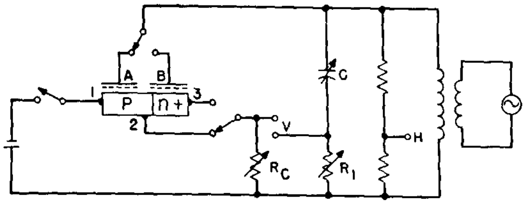

FIG. 4. Large signal field effect measurement circuit.

By increasing the bias sufficiently, the junction may be biased to breakdown voltage, defined as the voltage at 50-μamp reverse current. The current may be held constant at this value by increasing R_c. The voltage changes induced across R_c by the modulating plate voltage are essentially changes in breakdown voltage, and these changes are plotted against plate voltage on the oscilloscope. Thus, a plot of ΔV_B against Q_T may be obtained.

In theory, for sufficient applied fields, this equipment allows a determination of the variation in φ_s and Q_T on the single conductivity p-type portion of the specimen, for direct comparison with variations in I_J and ΔV_B at the junction. Such a comparison should be a valid one, since the whole specimen has been subjected to the same surface preparation and is exposed to the same ambient.

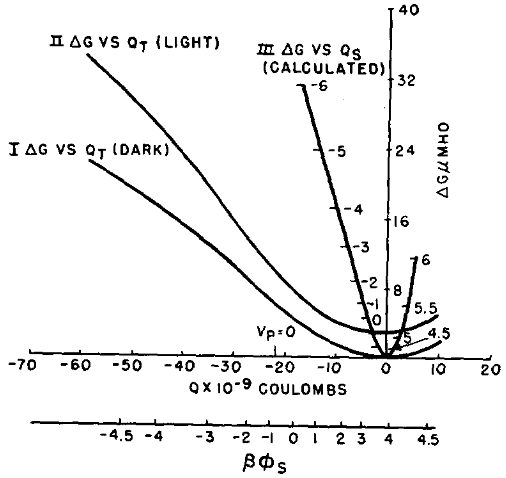

FIG. 5. Surface conductance as a function of surface charge (2.5 ohm-cm p-type germanium).

IV. FIELD PRODUCED VARIATIONS IN φ_s AND S

In the interest of brevity, the single conductivity p-type portion of the specimen between the electrodes 1 and 2 will be referred to as the "filament," and measurements made on this portion of the specimen as "filamentary measurements." In this section, the data from a typical filamentary measurement is presented. The specimen was etched in CP-8, and during the course of the experiment, was exposed to a dry oxygen ambient.

A plot of the experimental ΔG as a function of Q_T is indicated in Fig. 5 (curve I). The zero values for the ΔG and Q_T scales are arbitrarily taken at the position of the conductance minimum. The frequency applied to the field effect plate was 80 cycles per second (the trace was insensitive to frequency in the range of 60 to 500 cycles per second). The total excursion in plate voltage, V_p, is about 400 volts which represents peak to peak fields on the order of 10^6 volts per centimeter. Curve II represents ΔG as a function of Q_T during illumination by chopped light.

The separation of these curves, after a correction has been made to account for the fact that the plate modulates S on only one side of the filament, is proportional to $1/S^5$. The data are obtained in a dry oxygen ambient. Ambient cycling is not necessary since the voltage sweep in the large signal field effect contains the conductance minimum. Then it is not necessary to make the assumption that changes in ambient will vary the surface charge but not the nature of the surface states.† A calculated curve of ΔG as a function of Q_s is superimposed on the experimental dark curve so that the minima coincide. (Curve III, Fig. 5.)

From these three curves, the position of the energy bands at the surface,[4,19] φ_s, and the variation of surface recombination velocity[5] can be determined as functions

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[19] H. C. Montgomery and W. L. Brown, Phys. Rev. 103, 865 (1956).

† In several experiments we have observed that ozone apparently changes the nature of the surface states as well as the surface charge.

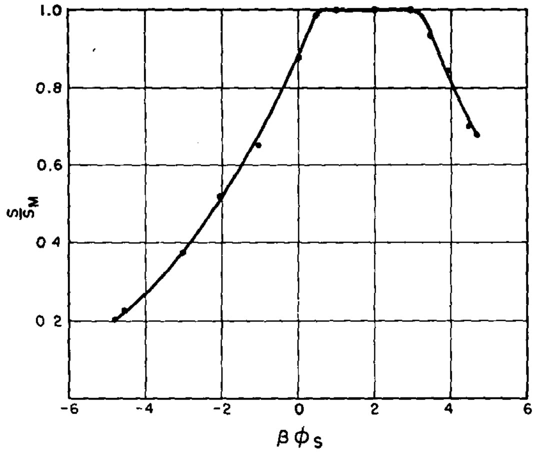

FIG. 6. Surface recombination velocity as a function of $\beta\varphi_s$.

of Q_T. The values of $\beta\varphi_s$, corresponding to values of Q_T are indicated on the lower horizontal scale. The relative surface recombination velocity, S/S_M, where S_M is the maximum value observed, is plotted as a function of $\beta\varphi_s$ in Fig. 6. S has its maximum value at $\beta\varphi_s$ near 2. These filamentary data are qualitatively similar to those observed by other workers.[20,21]

These quantities will be used in later sections in the analysis of the characteristics of the filamentary diode as a function of the same values of surface charge.

V. FIELD PRODUCED VARIATIONS IN JUNCTION CHARACTERISTICS

A. Small Signal Variations

The reverse junction current, I_J, is observed to be sensitive to modulation by voltage changes on the field plate. For a given surface preparation and ambient, these effects are reproducible. In ambients favoring surface breakdown, the direction and magnitude of the changes in I_J produced by a given change in plate voltage are found to depend on the dc bias applied to the junction.

The field produced change in reverse current and the dc reverse junction current are compared for increasing bias on the junction in Fig. 7. While these measurements were made, the specimen was exposed to an ozone ambient. Curve I is a plot of the junction current as a function of the dc bias on the junction, V_J. Curve II represents $\Delta I_J{}^+$ as a function of V_J where $\Delta I_J{}^+$ is the reverse current change produced by a positive change in the field plate voltage, ΔV_p. Curve III represents $\Delta I_J{}^-$ as a function of V_J, where $\Delta I_J{}^-$ is the reverse current change produced by applying $-\Delta V_p$ to the plate. It is apparent that $\Delta I_J{}^+$ and $\Delta I_J{}^-$ are independent of V_J until the reverse characteristic begins to soften (i.e., for V_J near 60 volts). If we assume that the current collected at the junction at low bias results from the generation of carriers at the surface, then $\Delta I_J{}^+$ and $\Delta I_J{}^-$ should be independent of bias. For voltages approaching the surface breakdown voltage, the effect of the plate is to modulate the multiplication factor, which is in itself bias sensitive. Therefore, at these voltages the $\Delta I_J{}^+$ and $\Delta I_J{}^-$ are bias sensitive.

Field effect conductance measurements on the single conductivity end of the specimen in this ambient indicate that for the surface conditions maintained during this experiment (tending in the direction of an enrichment layer on p-type material), S increases with increasing positive charge on the field effect plate. Thus the $\Delta I_J{}^+$ and $\Delta I_J{}^-$ at low V_J values have the signs expected if the junction current is supplied by surface recombination. The fact that $\Delta I_J{}^-$ and $\Delta I_J{}^+$ increase rapidly and change sign as V_J is increased toward breakdown voltage is in qualitative agreement with the trends discussed by Garrett and Brattain.[9] A positive increase in V_p produces a more n-type surface, a decrease in the surface multiplication factor, and a decrease in current. The filamentary field effect measurement indicates that the sign of the equilibrium value of $\beta\varphi_s$ favors surface breakdown. Photoconductance measurements indicate the current at large V_J is multiplicative and ambient variations of measured breakdown voltage indicate surface breakdown.

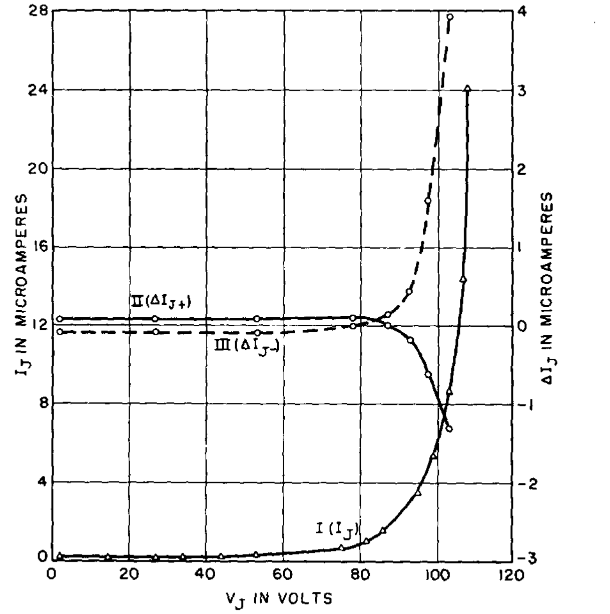

FIG. 7. Comparison of field produced current changes with dc junction characteristics.

These data therefore indicate that the field produced changes in junction current are related to the dc junction characteristic in a qualitatively appropriate manner if it is assumed that the junction current at low bias values arises from surface generation of minority carriers, and at higher bias values, can arise from multiplicative surface breakdown.

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[20] Many, Harnik, and Margoninski in reference 2, p. 85.

[21] Garrett, Brattain, Brown, and Montgomery in reference 2, p. 126.

Larger signal variations in the low and high bias junction currents will be discussed more quantitatively in the following two sections.

B. Low Bias Reverse Current Variations

Field produced junction current changes are shown in Fig. 8 for the low bias case. Experimental conditions are the same as those described in Sec. IV. The lower solid curve (I) is the experimentally determined dark reverse current as a function of Q_T. The upper curve (II) is the reverse current as a function of Q_T measured with the filament illuminated.

The relative junction current as a function of Q_T is obtained by using the field effect plate on the junction side of the specimen as described in Sec. III. The absolute value of reverse current is determined by dc measurement with $V_P=0$. The field effect plates are identical and experimental conditions are the same at the junction as they are at the filament. If the surface conditions near the junction are the same as on the filament, then the abscissa of Fig. 5 is the same as that of Fig. 8. The junction current for all values of Q_T is relatively insensitive to junction bias up to values near the breakdown voltage.

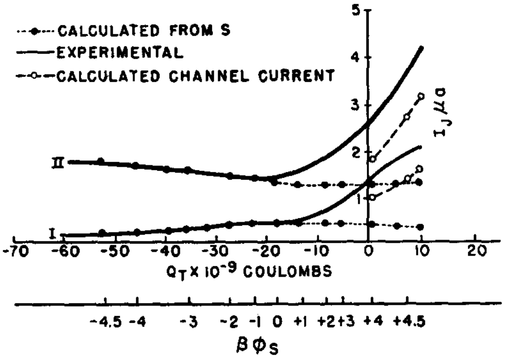

FIG. 8. Field produced current changes for an n^+-p junction.

For a filamentary junction of the dimensions used (see Appendix), with equal S on both sides, the dark reverse current density is given by Eq. (7). However, the field effect plate can modulate S on one side only. The variation of the dark current with S changing on one side only is given by Eq. (14) derived in the appendix. The solid points shown on curve I, Fig. 8, are calculated from Eq. (14), using the values of S given in Fig. 6 corresponding to the appropriate values of φ_s. The points on curve II are calculated from Eq. (19) in the Appendix, using the same values of S, after normalizing one theoretical point to fit the data at $V_p=0$.

Both light and dark curves agree well with theory for φ_s less than 0. When φ_s becomes positive, an inversion layer begins to form at the surface, and the collecting area of the junction increases. Thus, for $\varphi_s>0$ it is expected that I_J no longer depends simply on S. Curves I and II should begin to diverge from the calculated values as they are observed to do.

The lower set of open points indicate values of the excess dark channel current, calculated using Eq. (25) in the Appendix. The upper set of open points represent the illuminated channel current, calculated from Eq. (26), using an experimental value of the light current L obtained with the help of Eq. (27). It is evident that the excess current at the large values of $\beta\varphi_s$ is of the order expected from channel formation. Since the experiment is performed in a dry ambient with a field induced channel,[22] ionic surface currents,[23] and anomalous channel conductances of the kind considered by Statz and associates[24] are not encountered.

C. Breakdown Voltage Variations

Figure 9 shows the field produced variations in breakdown voltage. These data were obtained under the same experimental conditions as used in obtaining the data in Figs. 5 and 8. ΔV_B is the magnitude of the change in breakdown voltage produced by a charge Q_T on the field effect electrode. ΔV_B is small for positive values of φ_s and increases as φ_s decreases. Thus, as indicated in Sec. II C on breakdown voltage, a decrease in surface breakdown is favored by a negative surface potential. However, for this junction the theoretical plot of Fig. 2 indicates no substantial increase in the magnitude of ΔV_B until $\beta\varphi_s$ is near -4.5. Therefore, the observed values of ΔV_B for $\beta\varphi_s>-4.5$ are inconsistent with the theory of Garrett and Brattain. This trend has previously been inferred by these authors from measurements on alloy junction transistors.

VI. DISCUSSION OF EXPERIMENTAL RESULTS

The dual specimen has permitted direct examination of the variations in surface potential in the single conductivity portion for use in calculating variations in junction characteristics. Variation of $\beta\varphi_s$ from about -4.5 to $+4.8$ on this part of the specimen produces a regular change in S with φ_s and a maximum near $\beta\varphi_s=2$.

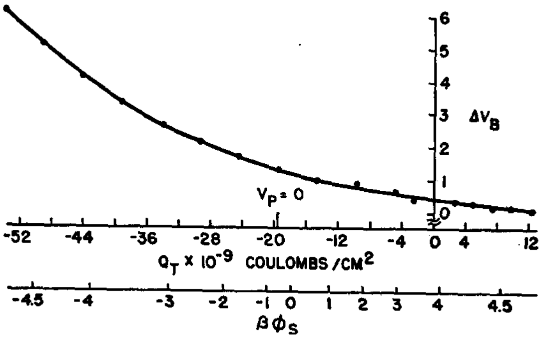

FIG. 9. Field produced variations in breakdown voltage.

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[22] Field induced channels have been studied under dc conditions by E. N. Clarke, Phys. Rev. **99**, 1899 (1955).

[23] J. T. Law, Proc. Inst. Radio Engrs. **42**, 1367 (1954).

[24] Statz, deMars, Davis, and Adams in reference 2, p. 139.

This variation does not contradict the assumption of a recombination center at an energy level roughly $5kT$ above the center of the gap.[17] Our data are insufficient to confirm this unambigously. Comparison of the two curves, ΔG as a function of Q_T and ΔG as a function of Q_s, indicates a buildup of the density of fast states from values of about 10^{10} cm^{-2} near the middle of the gap to values on the order of 10^{11} cm^{-2} at energies about $\pm 5kT$ from the center of the gap.[24,25] Thus, our filamentary measurements indicate a regular variation of φ_s and S with surface charge corresponding to a unique system of fast surface states with similar properties to those observed by other experimenters on higher resistivity germanium.

The junction measurements indicate that in principle the properties of this system can be used to calculate the variation in junction current with φ_s.

In a range of interest for practical device design, variations in low bias junction current are calculated in terms of variations in S for $\beta\varphi_s<0$. For $\beta\varphi_s>0$, variations are on the order expected for channel currents dependent on the rate of surface generation. The reverse current at high bias, although varying reproducibly with φ_s, is in qualitative, but not quantitative agreement with the assumption of multiplicative surface breakdown.

If nonuniform surface conditions exist near the junction (patches), they would have a tendency to be averaged out in the measurement for the low bias case. However, the same conditions would produce appreciable effects in the measurement of surface breakdown, acting to reduce the observed breakdown voltage. The high dc bias voltages and the accompanying high field across the body junction subject the breakdown voltage measurement to another possible source of error. This is the shift in φ_s near the junction (for $V_p=0$) produced by the application of dc bias to the junction. The "clamping" of φ_s by slow surface states (observed by deMars *et al.*[26] and Kingston[27]) tends to suppress this effect, provided time is allowed for stabilization of the surface before the ac measurement is made. In any event, this effect tends to shift φ_s (on the p-type side of the junction) in the direction of positive increase, the wrong direction to account for observed values of ΔV_B for $\beta\varphi_s>-4.5$.

VII. DEVICE IMPLICATIONS

The results discussed above provide a basis for prediction of surface dependent properties of junction devices. Device parameters of importance are reverse currents, breakdown voltage, and transistor current gain (α). The data indicate that these parameters can be discussed in terms of a single parameter φ_s. Referring to Fig. 8, the low bias reverse current can be relatively small for $\beta\varphi_s<0$. However, as shown in Fig. 9, breakdown voltage decreases as φ_s decreases, and in fact, if body breakdown is desirable, φ_s must be positive. The drop in V_B becomes substantial for φ_s approaching φ_b. Thus, to insure low reverse currents and reasonable breakdown voltage, φ_s must be kept close to the interval $\varphi_b<\varphi_s<0$. For high resistivity material, $\varphi_b\rightarrow 0$ and the desired working range becomes small. For devices where current gain is influenced by surface recombination, confining φ_s to this interval tends to exact a further price of lower current gain. (See Fig. 6.) However, for surface sensitive transistors, probably the most satisfactory compromise is a value of φ_s near zero. The experiments reported by Wahl and Kleimack seem to lead to a similar conclusion.

VIII. CONCLUSIONS

Modulation of both low bias saturation current and breakdown voltage of filamentary n^+-p junctions by an electric field applied at the surface is possible. By combining this "junction field effect" with conventional field effect measurements, a filamentary structure has been used to compare surface properties of a free surface with those of an adjacent n^+-p junction. The measurement allows direct comparison of field induced variations in φ_s and S with field induced variations in junction current.

This comparison indicates that junction current variations can be calculated from variations in S measured on the filament, provided the surface conductivity type remains the same as that of the body. When the surface conductivity becomes opposite in type to that of the body, an additional current appears which is roughly calculable in terms of channel growth. However, the variations in junction breakdown voltage are not quantitatively predictable from measured variations in φ_s, at least on the basis of the theory of Garrett and Brattain. These variations are qualitatively predictable, however, in the sense that shifting φ_s in the direction of an inverted surface tends to suppress surface breakdown.

The observed dependence of junction characteristics on surface potential indicates that, for many surface sensitive devices, an optimum value of surface potential can be specified.

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APPENDIX

A. Filamentary Junction Currents

(1) *Dark Current*

The rectangular geometry of the filamentary diode is illustrated in Fig. 10. The shaded boundary at $x=0$

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[25] Similar results have been reported by Bardeen, Coovert, Morrison, Schrieffer, and Sun, Phys. Rev. **104**, 47 (1956).

[26] deMars, Statz, and Davis, Phys. Rev. **98**, 540 (1955).

[27] R. H. Kingston, Phys. Rev. **98**, 1766 (1955).

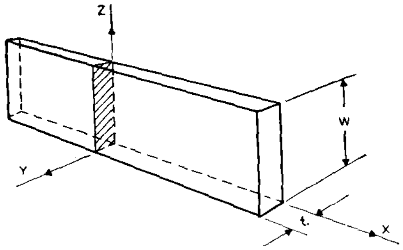

FIG. 10. Geometry for the filamentary junction.

indicates the n^+-p junction, with the n^+ material extending in the negative x direction. The ratios t/w (filament thickness to width) and w/l (width to length) are small. It is, therefore, assumed that the filament is infinite in the z and x directions. We consider only the portion of the filament in the region $x>0$, bounded by the planes $y=0$ and $y=t$, on which the values of surface recombination velocity are S_1 and S_2. Under these conditions, $\Delta n=n-n_0$ must satisfy the boundary conditions,[11]

$$D\frac{\partial\Delta n}{\partial y}=S_1\Delta n, \qquad y=0, \tag{9}$$

$$D\frac{\partial\Delta n}{\partial y}=-S_2\Delta n, \quad y=t. \tag{10}$$

The fractional change in Δn across the filament in the y direction must be less than St/D, where S is the larger of S_1 and S_2. In our experiment, values of S encountered are less than 10^3 cm sec^{-1}, and t is less than 8×10^{-3} cm. Thus St/D is small. Under these conditions the equation for the steady state is, neglecting recombination in the body of the filament,

$$0=-\frac{S_1+S_2}{t}\Delta n(x)+D\frac{d^2\Delta n(x)}{dx^2}. \tag{11}$$

For reverse bias $\gg kT/q$, $\Delta n(0)\simeq-n_0$, the solution of physical interest is

$$\Delta n=-n_0\exp\left[-x\left(\frac{S_1+S_2}{Dt}\right)^{\frac{1}{2}}\right], \tag{12}$$

and the electron current density across the junction at $x=0$ is

$$j_D=qD\left.\frac{dn}{dx}\right|_{x=0}=qn_0(D)^{\frac{1}{2}}\left(\frac{S_1+S_2}{t}\right)^{\frac{1}{2}}. \tag{13}$$

Experimentally, a field effect plate serves to modulate S_2 only. If S_0 is the value of $S_2=S_1$ for zero voltage on the plate and the field produces a change ΔS in S_2, then the reverse dark junction current, I_{JD}, for a junction area A, is given by

$$I_{JD}=Aqn_0(D)^{\frac{1}{2}}\left(\frac{2S_0+\Delta S}{t}\right)^{\frac{1}{2}}. \tag{14}$$

(2) Light Current

We consider the case where the filament is weakly illuminated on the surface $y=0$. For generation of L electron-hole pairs per cm^2 per sec near one surface by an external light source, the continuity equation is, approximately,

$$\frac{L}{t}-\frac{S_1+S_2}{t}\Delta n(x)+D\frac{d^2\Delta n(x)}{dx^2}=0. \tag{15}$$

The important solution is

$$\Delta n=-\left(n_0+\frac{L}{S_1+S_2}\right)\exp\left[-x\left(\frac{S_1+S_2}{Dt}\right)^{\frac{1}{2}}\right]+\frac{L}{S_1+S_2}; \tag{16}$$

the current density is

$$j_L=q\left(n_0+\frac{L}{S_1+S_2}\right)(D)^{\frac{1}{2}}\left(\frac{S_1+S_2}{t}\right)^{\frac{1}{2}}; \tag{17}$$

and if I_{JL} is the junction current with illumination,

$$\Delta I_{JL}=I_{JL}-I_{JD}=Aq\frac{L}{t}\left(\frac{Dt}{S_1+S_2}\right)^{\frac{1}{2}}. \tag{18}$$

The value of ΔI_{JL} produced by a change from 0 voltage on the field effect plate is then

$$\Delta I_{JL}=Aq\frac{L}{t}\left(\frac{Dt}{2S_0+\Delta S}\right)^{\frac{1}{2}}. \tag{19}$$

B. Channel Current

(1) Dark Channel Current

With a large positive voltage on the field effect plate (on the surface $y=t$) $\beta\varphi_s$ is positive, the surface is n-type (see Fig. 11), and an n-p junction is formed on this surface. With reverse bias applied to the n^+-p junction, a current $I(x)$ flows down the inversion layer. The n-p junction is biased to a potential $V(x)$, and will act as a collector of electrons from the p-type filament until $V(x)$, drops to a value $V(l)$ which is insufficient to ensure collection. The distance l is defined as the channel length and depends on the value of I_s, the magnitude of the current density collected by the channel. McWhorter and Kingston[23] have given the following expression for the excess reverse, or channel current, I_{CD}:

$$I_{CD}=I_s^{\frac{1}{2}}P\left(2g_0\ln\frac{V_a}{V(l)}\right)^{\frac{1}{2}}, \tag{20}$$

where P is the perimeter of the junction, and V_a is the voltage applied to the junction. They assume the

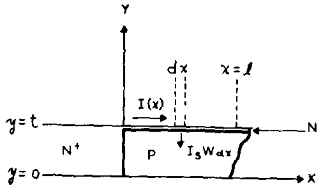

FIG. 11. Channel on the filamentary junction.

channel conductance, G_C, is given by

$$G_C=g_0/V(x). \qquad (21)$$

Garrett and Brattain[6] give an appropriate expression for g_0. With an n surface on p-type germanium this is

$$g_0=\frac{q\mu_n n_0^2 L_d^2}{4\beta l_n n_i}\exp[\beta(\varphi_s-\varphi_b)], \qquad (22)$$

where $L_d=1.4\times10^{-4}$ cm, and l_n is the mean free path for electrons. For our experimental case,

$$g_0\simeq4.5\times10^{-9}\exp(\beta\varphi_s)=K\exp(\beta\varphi_s). \qquad (23)$$

If we make the approximation that all carriers generated at the surfaces are collected by the channel, then

$$I_s=qn_0(S_1+S_2)=qn_0(2S_0+\Delta S), \qquad (24)$$

and for $P=w$

$$I_{CD}=(2S_0+\Delta S)^{\frac{1}{2}}\exp(\beta\varphi_s/2)w\left(qn_0K\ln\frac{V_a}{V(l)}\right)^{\frac{1}{2}}. \qquad (25)$$

Equation (24) can only be accurate for values of channel length l large compared to $(Dt/2S_0+\Delta S)^{\frac{1}{2}}$, a condition not too well fulfilled in our experiments, even when $\beta\varphi_s$ approaches 4 or 5.

(2) Channel Current with Illumination

If the surface $y=0$ is illuminated with nonpenetrating light, the effect is to increase the channel current to a value approximately given by

$$I_{CL}=\left(\frac{I_s+L}{I_s}\right)^{\frac{1}{2}}I_{CD}. \qquad (26)$$

The value of L can be estimated from the measurement of I_J made when $\beta\varphi_s$ is negative and the channel does not exist. Using Eqs. (14) and (19)

$$L=n_0(S_1+S_2)\left(\frac{\Delta I_{JL}}{I_{JD}}\right). \qquad (27)$$