Use of Infrared Absorption in Germanium to Determine Carrier Distributions for Injection and Extraction

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(Received May 14, 1956)

Measurements of the absorption of infrared radiation by the free carriers in germanium have been used to determine carrier distributions due to injection and extraction. The transverse distributions were found to agree with theory and have been used to determine surface recombination velocity. The longitudinal distributions may be put into four classifications. These are injection field-opposed, injection field-aided, extraction field-opposed and extraction field-aided. Some of these distributions have been studied in detail and have been correlated with the ambipolar carrier transport theory of van Roosbroeck. To do this it was necessary to take into account the change in carrier lifetime with carrier density, which was done according to the Shockley-Read theory. Good agreement was thus obtained between experiment and theory for longitudinal carrier distributions.

I. INTRODUCTION

AN excess or deficit of carriers in a semiconductor is distributed in a manner which may be described in terms of recombination, diffusion, mobility, and electric field intensity. Up to the present time, measurements of these distributions have been made by determining local changes in carrier concentration indirectly from changes in reverse current, zero bias conductance or floating potential of a point contact on the surface. A disadvantage of these techniques is that concentrations deep within the bulk cannot be measured; in addition, when contact is made at a different location, the characteristics may not be the same.

Experiments[1–3] have shown that the absorption by a semiconductor of infrared radiation beyond the fundamental absorption edge is due in part, at least, to the free carriers. A more direct approach may thus be used for the measurement of carrier distributions. The absorption of infrared radiation by free carriers has served, in the present experiments, to give information about carrier distributions within the bulk of germanium. A preliminary report[4] has been made of measurements of transverse carrier distributions which were utilized in the evaluation of surface recombination velocity. Longitudinal distributions are of interest because they yield information about carrier lifetime and provide measurements for a test of the ambipolar transport theory[5] for carriers in a semiconductor.

II. EXPERIMENTAL TECHNIQUE

The experimental technique was described briefly in a previous publication[4] where a diagram of the setup was shown. A description of some of the details, however, is in order and will be given with reference to Fig. 1. The source assembly (globar and mirrors) of a Perkin-Elmer Model 12A spectrometer is used to obtain the infrared radiation. An image of the globar is focused on an entrance slit whose dimensions are 0.5×3.5 mm. The sample is placed in the path of the radiation just beyond ($\simeq$2 mm) the slit and just before ($\simeq$ 1 mm) the special Eppley thermopile with a KRS-5 window which serves to detect the radiation transmitted by the sample. A sensitive detector is required which will respond to all radiation beyond 2 microns emitted by the source. It is important to keep the distance between the slit and detector small, since the beam is not collimated. The sample and detector are mounted on separate micromanipulators. The germanium wafer, shown in the previous publication, is no longer used as a filter since the sample acts as its own filter and there is a gain in infrared intensity due to the removal of two highly reflecting surfaces. The sample can be oriented so that the slit image is parallel to the junction for longitudinal carrier distribution measurements or perpendicular to the junction for transverse distributions, as shown in Fig. 1.

The quantities of interest for any position of the sample are the total transmitted radiation, I_T, prior to injection or extraction and the change in transmission, ΔI, due to injection or extraction. I_T may not be the same everywhere; thus it must be measured at each point so that it can be used for the normalization of ΔI. ΔI is usually a small percentage of I_T and hence a high gain is required to measure ΔI accurately. This is achieved as shown by Fig. 1. First the signal, I_T, from the thermopile is balanced off in a bridge; thereafter the change, ΔI, is amplified by a breaker-type amplifier. The signal from the amplifier is passed through electrical filters and then displayed on an oscilloscope. An increase or decrease in transmission of infrared radiation by the sample is observed when carriers are extracted or injected, respectively. It is important to keep the time of injection or extraction short to avoid heating of the sample. On the other hand, it must be comparable to the time constant of the thermopile (about one second).

[1] H. Y. Fan and M. Becker, *Semiconducting Materials* (Butterworths Scientific Publications, Ltd., London, 1951), p. 132.
[2] H. B. Briggs and R. C. Fletcher, Phys. Rev. **91**, 1342 (1953); Roger Newman, Phys. Rev. **91**, 1311 (1953).
[3] A. F. Gibson, Proc. Phys. Soc. (London) **B66**, 588 (1953).
[4] N. J. Harrick, Phys. Rev. **101**, 491 (1956).
[5] W. van Roosbroeck, Phys. Rev. **91**, 282 (1953).

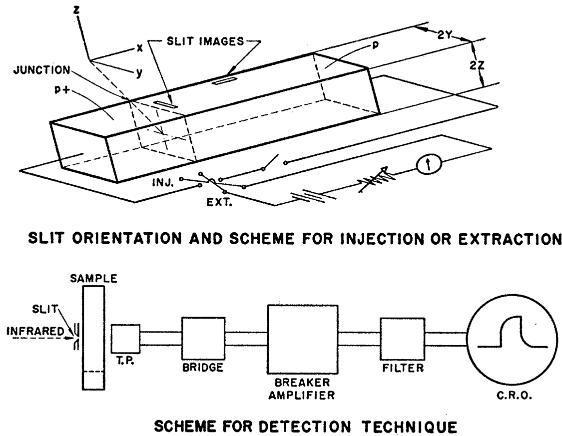

FIG. 1. Experimental setup for carrier distribution measurements.

It should be noted that chopping the beam would not increase the sensitivity. This is because ΔI is only a small percentage of I_T so that it would be difficult to measure ΔI if the whole signal corresponding to $I_T+\Delta I$ were chopped. One scheme which would improve the sensitivity is to use a double infrared beam. One beam would pass through the sample and the other would by-pass it. The signals from these two beams could be balanced against each other and the difference due to injection or extraction, ΔI, could be amplified. This scheme would help to overcome the very bothersome background variations of the infrared radiation.

The sample used for most of the present experiments is a high lifetime p-type germanium bar of dimensions $70\times 9.5\times 9.5$ mm and resistivity of 50 ohm cm at 300°K. It has a highly doped $(p+)$ p region at one end which provides a junction and serves to inject or extract holes. It is necessary to have polished or etched surfaces for the transmission of infrared radiation. A ground surface scatters the infrared beam so that the transmitted intensity is very low.

III. THEORY OF CARRIER DISTRIBUTIONS

It is generally necessary to consider the ambipolar formulation of the carrier transport equations and particularly so for the near intrinsic sample under study. Van Roosbroeck's ambipolar continuity equation (12) of reference 5, may be applied to the present problem (Fig. 1) by putting the electric field components, E_y and E_z, equal to zero. With no loss of generality otherwise, the equation may be written

$$\partial\Delta p/\partial t = D(\partial^2\Delta p/\partial x^2 + \partial^2\Delta p/\partial y^2 + \partial^2\Delta p/\partial z^2) - \mu^* E\partial\Delta p/\partial x - \Delta p/\tau. \quad (1)$$

Here Δp is the departure of the actual carrier concentrations, p and n, from the equilibrium concentrations, p_0 and n_0; $\Delta p = p - p_0 = n - n_0$. The parameters D and μ^* are, respectively, the ambipolar diffusivity and ambipolar mobility and are given by

$$D = \frac{n+p}{n/D_p + p/D_n}, \quad (2)$$

and

$$\mu^* = \frac{N_D - N_A}{n/\mu_p + p/\mu_n}. \quad (3)$$

N_D and N_A are the donor and acceptor densities, respectively. It should be realized that D and μ^* are used to determine carrier distributions and not the motions of the individual particles which are given by the current equations [Eq. (2), reference 5] and ordinary constants (D_p, D_n, μ_p, μ_n). Only in the special case of high doping and low levels of injection do the ambipolar parameters become equal in magnitude to the ordinary constants, since in this case they reduce to the corresponding constants for the minority carrier. Both D and μ^* are concentration dependent. D varies between D_p and D_n, taking on the intermediate value $2D_pD_n/(D_p+D_n)$ for intrinsic material. μ^* varies between $-\mu_n$ and μ_p and becomes zero for intrinsic material.

According to the theory of Shockley and Read,[6] the bulk lifetime, τ, is also concentration-dependent. By assuming $a \ll c$ and $a\Delta p \ll 1$ in their Eq. (6.2), τ is given as

$$\tau = \tau_0(n_0+p_0)/(n_0+p_0+\Delta p). \quad (4)$$

The assumption that $a \ll c$ has been shown, in at least one case,[7] to be correct. In addition, it is in agreement with results from the present experiments. The variation of τ with Δp is a large factor in determining carrier distributions at high injection or extraction levels, particularly in near-intrinsic materials.

Because of the concentration dependence of D, μ^*, and τ, Eq. (1) cannot easily be solved analytically. It has, however, the same form as Eq. (7) of reference 8, for which Shockley has given a solution, assuming the coefficients to be constant. This solution has proven useful in the present investigation. It consists of a series of terms with suitable coefficients,[9] the principal one of which can be written, for the steady state and a bar of semi-infinite length in the x direction, as follows:

$$\Delta p = \pm\Delta p_0 e^{-a(x-x_0)} \cos(by)\cos(cz). \quad (5)$$

The higher modes, which decay faster, are negligible only if the surface recombination velocity has a low value or if measurements are made far from the plane of injection or extraction. If precautions are taken to keep the contribution of the higher modes low, Eq. (5) can be applied within a segment of the bar of

[6] W. Shockley and W. T. Read, Jr., Phys. Rev. **87**, 835 (1952).
[7] R. N. Hall, Proc. Inst. Radio Engrs. **40**, 1512 (1952).
[8] W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950), p. 319.
[9] H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids* (Oxford University Press, New York, 1947), p. 158.

length short enough so that the longitudinal variations in D, μ^*E, and τ can be neglected. Δp_0 is the carrier concentration at the center of the bar and on the segment boundary nearest the junction; i.e., $x=x_0$, $y=z=0$.

The plus sign of Δp refers to injection. It was pointed out by van Roosbroeck[5] that the transport equations apply equally well when Δp is negative. This corresponds to carrier depletion or extraction which has been observed in other experiments.[10,11] For the moderate electric fields used in the present experiments, charge neutrality may be assumed in the bulk. Under these circumstances Δp can be no larger than the carrier density due to thermal generation. Hence only thermal carriers can be extracted from the bulk, for if impurity carriers were extracted, the bulk would become charged due to the ionized immobile atoms. Complete extraction for a sample can occur only when the transit time of the carriers over the length of the sample is less than the effective carrier lifetime in the sample.

The longitudinal decay parameter is given by[12]

$$a=\frac{-\mu^*E+[(\mu^*E)^2+4D/\tau]^{\frac{1}{2}}}{2D}. \tag{6}$$

If μ^*E is zero, the longitudinal decay is obviously governed entirely by diffusion and lifetime. The effect of an applied field will be different depending upon the sign of μ^*E. If μ^*E is negative, the magnitude of a will be increased and the effect of the field will be to displace the distribution toward the junction; if μ^*E is positive a will be decreased and the distribution will be displaced away from the junction. The former may be called field-opposed and the latter field-aided distributions which result in, respectively, a lesser or greater drift length than a diffusion length.

It will be noted that both the magnitude and sign of μ^*E are determined as much by μ^* as by E. E is positive when it is directed away from the junction (Fig. 1) and *vice versa*. In intrinsic material, μ^* is zero and there can be no displacement of the carrier distribution by the field, no matter how large. In n-type material, μ^* is positive, the sign of μ^*E is the same as that of E, and the distribution is displaced by the field in the direction of the field[13]; i.e., if E is directed away from the junction, the distribution is field-aided; toward the junction, field-opposed. On the other hand, in p-type material μ^* is negative and the displacement of the distribution is against the field. These statements reduce to the simple rule that the displacement is always in the direction in which the field moves the minority carriers.[14]

In the neighborhood of a junction, four classifications of longitudinal carrier distributions may thus be distinguished; injection field-*aided*, injection field-*opposed*, extraction field-*aided*, extraction field-*opposed*.[15,16] For configurations similar to that shown in Fig. 1 where the field is applied through the junction (no additional contacts), injection of minority carriers take on field-aided distributions and injection of majority carriers take on field-opposed distributions, while extraction of minority carriers take on field-opposed distributions and extraction of majority carriers take on field-aided distributions.

The transverse hole or electron carrier flows are given at $y=\pm Y$ by

$$J_y/e=\pm s\Delta p=-D\partial\Delta p/\partial y, \tag{7}$$

and at $z=\pm Z$ by

$$J_z/e=\pm s\Delta p=-D\partial\Delta p/\partial z, \tag{8}$$

where the J's are the transverse hole or electron currents. The simple form of the transverse carrier flow equations represented by the last terms on the right of these equations are obtained by expressing the transverse currents in terms of the ambipolar quantity, D rather than D_n or D_p, and noting that the total current is necessarily zero [see Eq. (9) of reference 5]. Equations (7) and (8) lead to the familiar boundary conditions

$$b\tan(by)=s/D, \tag{9}$$

and

$$c\tan(cZ)=s/D. \tag{10}$$

With extraction in place of injection, there is generation instead of annihilation at the surface. It is evident, however, that the same formulas for evaluation of surface recombination velocity apply.

[10] J. B. Arthur *et al.*, Proc. Phys. Soc. (London) **B68**, 43 (1955).
[11] R. Bray, Phys. Rev. **100**, 1047 (1955).
[12] Here the contribution of the surfaces to filament lifetime has been neglected. This may be justified by the large cross section and low value of surface recombination velocity for the sample under investigation.
[13] The sign of μ^* is not uniquely determined in the development of Eq. (1), μ^* might have been taken as the negative of the quantity shown in Eq. (3). This has no effect on the final conclusions but involves the less "elegant" statement that displacement in the direction of the field occurs when μ^* is negative.

[14] Similar statements hold for the time-dependent solutions of Eq. (1). A neutral cloud or pulse of carriers in intrinsic material will not move in an applied field. In n-type material the cloud will drift with the field and in p-type it will drift against the field; i.e., the direction of drift of the cloud is always the same as that of the minority carrier. The latter statements are consistent with the idea introduced in early transistor physics that, in heavily doped material, the motion of a pulse is determined largely by that of the minority carrier.
[15] G. G. E. Low [Proc. Phys. Soc. (London) **B68**, 310 (1955)] has made a similar classification which he has termed injection, accumulation, exclusion, and extraction, respectively. He arrived at these from a consideration of injection ratios and sign of electric field for heavily doped n-type germanium with no reference to μ^*.
[16] W. van Roosbroeck's [Bell System Tech. J. **29**, 560 (1950)] classification of field-aiding and field-opposing solutions considers only the direction of E and not the sign of μ^* and thus is less general; however, it is in agreement with the present classification for n-type material.

IV. DETERMINATION OF CARRIER DISTRIBUTIONS FROM INFRARED ABSORPTION

The mechanism of infrared absorption by germanium has been studied by others.[1,17,18] These studies and other experiments[2–4] have shown that the part of the absorption which is due to free carriers is proportional to the free-carrier density. The absorption coefficients for electrons and holes are different but this does not enter into consideration as charge neutrality requires that the observed changes in transmission from added or extracted carriers are due to hole-electron pairs. The radiation from the source which is effective in the absorption by free carriers is that of wavelength greater than the fundamental absorption edge (1.8 microns). As the absorption coefficient increases with wavelength,[17] the longer wavelengths are more effective. The source temperature must be kept constant to avoid any change in the extinction coefficient due to change in spectral distribution of the radiation.

For monochromatic radiation, the differential of the infrared intensity within the material is given by

$$dI = -I\alpha(z)dz, \tag{11}$$

where $\alpha(z)$ is the local infrared absorption coefficient. It has been found[1] that the reflectivity, R, is constant over a wide range of wavelength and conductivity; thus it is reasonable to assume that the reflectivity remains unchanged after injection or extraction. Considering only a single reflection from each surface, the transmitted radiation prior to injection or extraction is given by

$$I_T = I_0(1-R)^2 e^{-k_0 d}, \tag{12}$$

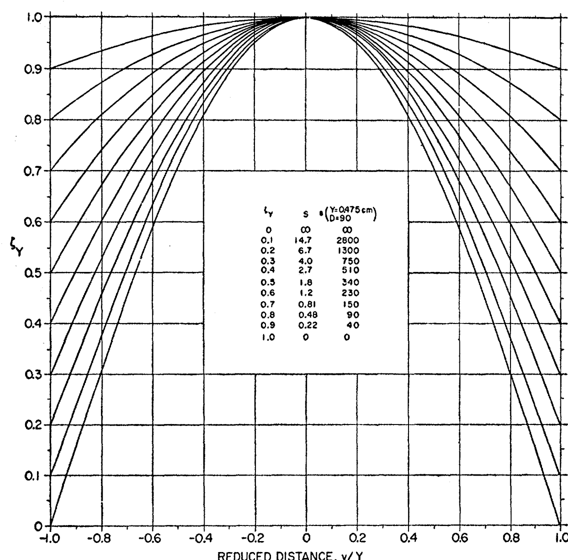

FIG. 2. Plots of $\zeta_y = \cos(by)$ *vs* reduced distance.

[17] Fan, Spitzer, and Collins, Phys. Rev. **101**, 566 (1956).
[18] A. H. Kahn, Phys. Rev. **97**, 1647 (1955).

where $k_0 = d^{-1}\int_0^d \alpha_0(z)dz$ is the average background absorption coefficient which includes absorption due to free carriers generated thermally and carriers due to doping, and also to lattice and impurity absorption,[17] and d is the thickness of the sample. After injection or extraction, the transmitted radiation may be represented by

$$I_T + \Delta I = I_0(1-R)^2 e^{-(k_0+k)d} = I_T e^{-kd}. \tag{13}$$

kd is proportional to the total excess or deficit of carriers in the path of radiation; i.e.,

$$kd \propto \int_{-Z}^{Z} \Delta p_0 e^{-ax}\cos(by)\cos(cz)dz = 2\Delta p_0 c^{-1}\sin(cZ)e^{-ax}\cos(by). \tag{14}$$

Since $\Delta I \ll I_T$ and therefore $kd \ll 1$,

$$\Delta I/I_T \simeq -kd \propto -\Delta p_0 e^{-ax}\cos(by).^{19} \tag{15}$$

In relation (15), the negative of $\Delta I/I_T$ represents carrier distribution due to injection or extraction. It is evident that the transverse measurements will vary as $\cos(by)$ while the longitudinal measurements will vary as e^{-ax}. In the longitudinal measurements the position of the sample is adjusted so that the beam transverses the center of the sample ($y=0$) and $\cos(by)$ equals one.

V. TRANSVERSE DISTRIBUTIONS AND SURFACE RECOMBINATION VELOCITY

Conditions which must be satisfied for the transverse distributions to follow a cosine law are: the measurements must be made far from the junction so that the higher modes may be neglected; the changes in the transverse carrier concentration must be small so that D and μ^* may be considered constant; and the sample must be homogeneous. It is, of course, assumed that the bulk lifetime is high enough so that the effects of extraction and injection can be measured at a distance from the junction. In addition, the effects of trapping and channels are not considered in the present treatment.

For the evaluation of surface recombination velocity, s, it is necessary to determine the constant b. This may be done for a chosen value of x as follows:

$$\cos(by) = (\Delta I/I_T)_{y=y}/(\Delta I/I_T)_{y=0} \equiv \zeta_y. \tag{16}$$

[19] The foregoing development holds rigorously only for monochromatic radiation. It can be shown, however, that when the extinction coefficients are small, which is usually the case for semiconductors, this relationship is a good approximation for heterochromatic radiation. On the other hand, the extinction coefficient should not be too small for then the effects of multiple reflection need to be considered. An etched surface is always somewhat nonuniform so that there will be scattering of the beam which further justifies neglecting any contribution from the higher orders of reflection. One should be aware of these limitations although they are not serious for the present measurements.

From which

$$b=y^{-1}\cos^{-1}\zeta_y, \quad (17)$$

and from (9)

$$s=Dy^{-1}\tan(Yy^{-1}\cos^{-1}\zeta_y)\cos^{-1}\zeta_y. \quad (18)$$

For $y=Y$, (20) may be simplified to give

$$s=\frac{D}{Y}\left(\frac{(1-\zeta_Y^2)^{\frac{1}{2}}}{\zeta_Y}\right)\cos^{-1}\zeta_Y, \quad (19)$$

which is the expression given in reference 4.

Figure 2 gives plots of the function $\zeta_y=\cos(by)$ *versus* the reduced distance, y/Y, for various values of the reduced surface recombination velocity, $S=sY/D$. These curves can be used to determine s for any sample by inserting the appropriate values of the sample half-width, Y, and the diffusivity, D.

In principle only two values of $\Delta I/I_T$ need be measured to establish the corresponding theoretical curve and identify the value of ζ_Y. The most convenient values would, of course, be at $y=0$ and $y=Y$, but due to the finite width of the infrared beam it is not possible to obtain readings at $y=Y$. A reading at any other value of y will do, giving more accurate values for ζ_Y the nearer the reading is taken to $y=Y$. The accuracy in the evaluation of S is greatest for a midrange value of ζ_Y where it is about one-third of the accuracy of ζ_Y. The accuracy decreases as S increases or decreases being about one-tenth the accuracy of ζ_Y for values of S of 14.7 and 0.218.

If two opposing surfaces have different values of s as may occur for the field effect measurements, the transverse distribution will be asymmetric. This is expressed by the following solution of the continuity equation

$$\Delta p=\Delta p_0 e^{-ax}[\cos(by)+d\sin(by)]\cos(cz). \quad (20)$$

The transverse carrier distribution is given by

$$\zeta_y=\cos(by)+d\sin(by), \quad (21)$$

where

$$b=y^{-1}\cos^{-1}[\tfrac{1}{2}(\zeta_y+\zeta_{-y})], \quad (22)$$

and

$$d=\tfrac{1}{2}(\zeta_y+\zeta_{-y})[1-\tfrac{1}{4}(\zeta_y+\zeta_{-y})^2]^{-\frac{1}{2}}. \quad (23)$$

It should be noted that b and d can be evaluated for any y. For the two surfaces, s may be evaluated from

$$s=Db\frac{\sin(bY)\mp d\cos(bY)}{\cos(bY)\pm d\sin(bY)}. \quad (24)$$

Figure 3 shows some measurements representing the case just discussed. The asymmetry was achieved by grinding one surface while the opposing surface was one which had originally been etched but was subsequently contaminated by handling and exposure to air and water. The measured values of s are calculated to be 1840 and 570 cm/sec for the ground and etched surfaces, respectively. It may be noted that the peak is displaced by -0.056 cm. This displacement is given by $\Delta y=b^{-1}\tan^{-1}d$.

VI. LONGITUDINAL DISTRIBUTIONS

A. Correlation with Theory

Measurements have been made of longitudinal distributions of carriers for different levels of injection and extraction. The experimental results have been compared to the ambipolar theory by evaluating the local decay parameter, a, at a chosen point on an experimental curve and thus obtaining a calculated slope through the corresponding experimental point (hereafter called calculated slope).

It is convenient for the present purpose to express D, μ^*, and τ in terms of the injection or extraction level, Δp; of the carriers contributed by acceptors or donors, N_A or N_D, respectively; and of the carriers which arise by thermal generation from the valence to the conduction band, p_g and n_g ($n_g=p_g$ in the absence of trapping). To evaluate a it is necessary to determine N_A and p_g for the sample in question as well as the local values of Δp, E, and τ.

For the near intrinsic p-type sample used, the donor density, N_D, is taken to be zero and the acceptor density may have one of two values for a given conductivity. N_A can be determined unambiguously, however, by measuring the conductivity under the condition of complete extraction, σ_{ce}, for then $N_A=\sigma_{ce}/(e\mu_p)$. N_A evaluated in this way is found to coincide with one of the values obtained from conductivity measurements and the accepted value for the density of either carrier for intrinsic material,[20] n_i. When N_A is known, $n_g=p_g$ can be evaluated from $np=n_i^2$ and the measured conductivity. (It may be noted that the ratio, N_A/p_g can be determined from infrared and conductivity measurements without a knowledge of the constant n_i.)

The local level of injection or extraction, Δp, is obtained by comparing the corresponding value of $\Delta I/I_T$ to the value of $(\Delta I/I_T)_{ce}$ which corresponds to the case of complete extraction; i.e., when $\Delta p=-p_g$. Thus by reference to Table I,

$$\Delta p=-p_g(\Delta I/I_T)/(\Delta I/I_T)_{ce} \quad (25)$$
$$=-5\times10^{15}(\Delta I/I_T).$$

The local values of the parameters D and μ^* may now be determined from (2) and (3).

The electric field may be determined from Eq. (8) of reference 5,

$$\sigma E=J-e(D_n-D_p)d\Delta p/dx. \quad (26)$$

The conductivity, σ, is calculated from the previously determined (as outlined above) values of the local carrier densities. The term $e(D_n-D_p)d\Delta p/dx$ is negligible for all the extraction curves and injection

[20] F. J. Morin and J. P. Maita, Phys. Rev. 94, 1525 (1954).

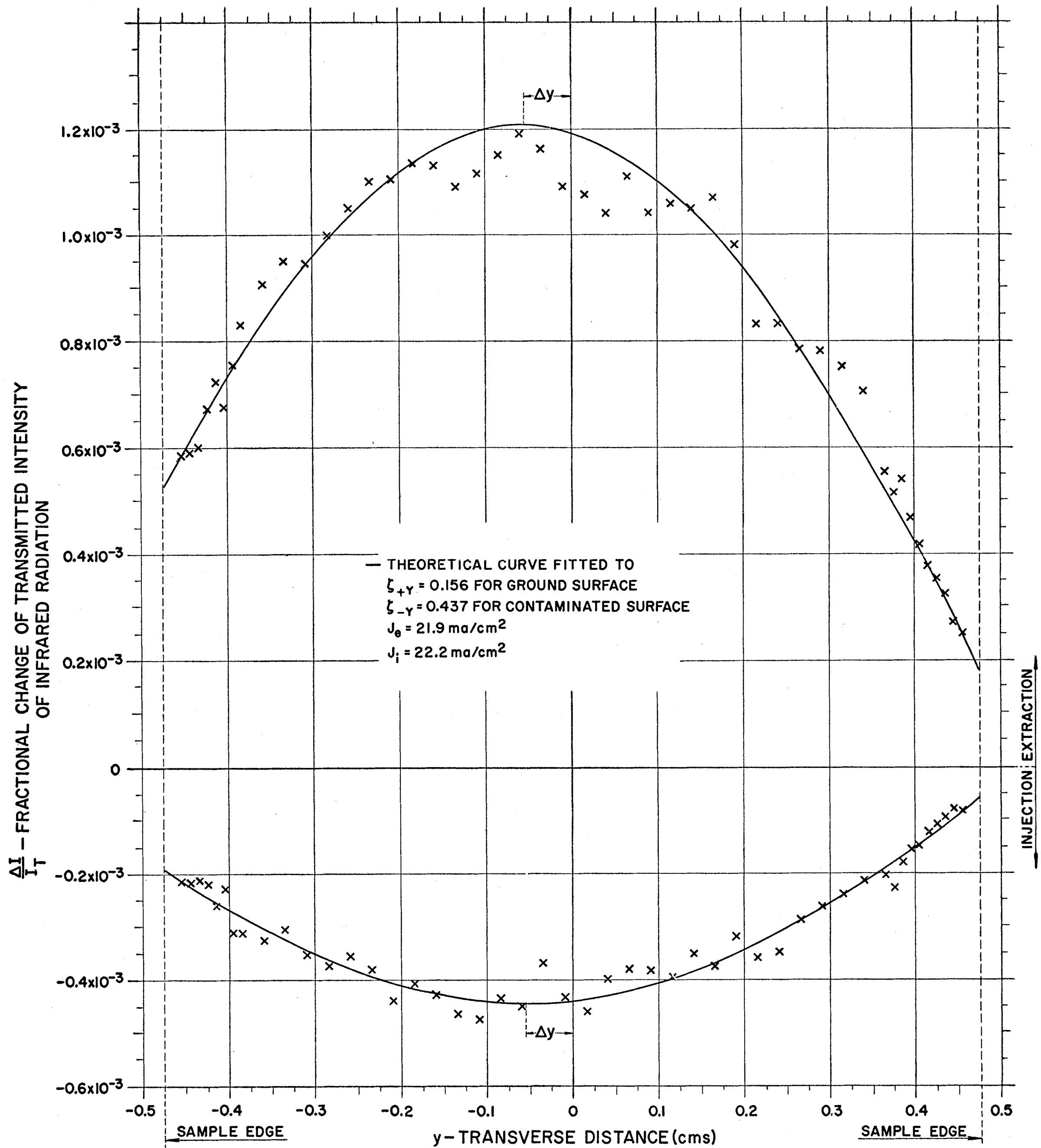

FIG. 3. The fractional change of transmitted infrared radiation intensity due to injection and extraction *vs* transverse distance for ground surface at $y=+Y$ and contaminated surface at $y=-Y$.

curves up to f. For the other curves it has a small but significant contribution to σE where it was determined directly from the experimental slope. This is certainly justified in this case where the gradient term has only a small contribution to σE. Otherwise, a can be evaluated by a series of successive approximations without considering the experimental slope.

If τ_0 is determined from experimental curves for very low levels of injection and extraction, τ may be evaluated at each point from Eq. (4).

Having determined the local constants, it is possible to calculate the local decay parameter from Eq. (6). For the present sample the $p+$ region serves to inject or extract holes. μ^* is negative, and for E positive there results injection field-opposed while for E negative there results extraction field-aided. Both of these

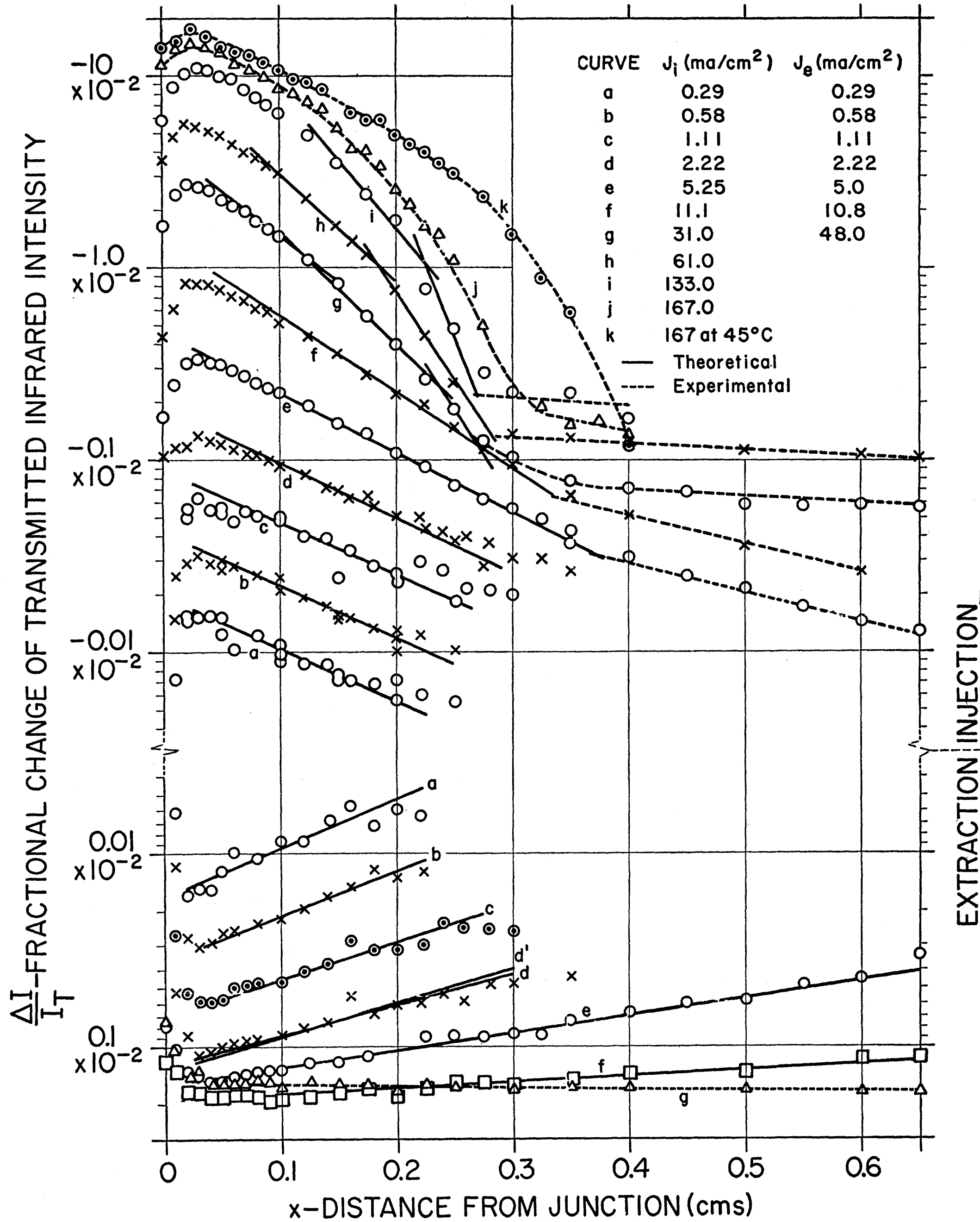

FIG 4. Longitudinal carrier distributions in a p-type germanium bar due to injection and extraction of holes.

effects are demonstrated by the experimental curves of Fig. 4. When there are large changes in concentration it is necessary to evaluate the decay constant for each segment of a curve and thus it is possible to check the validity of the ambipolar theory. Some of the decay parameters and the quantities determined leading to its evaluation as well as the constants of the sample are given in Table I.

B. Discussion of Longitudinal Distributions

The upper set of curves of Fig. 4 corresponds to injection field-opposed. They indicate that there is good agreement between experiment and theory. The change in lifetime with injection level[21] and the field-

[21] A comparison between experiment and theory for greater injection levels than those already made requires a knowledge of the constant a in connection with Eq. (4), where the assumption $a\Delta p \ll 1$ is no longer valid.

TABLE I. Constants and calculated quantities for curves of Fig. 4.

Constants	
General constants at 300°K	Sample constants
$\mu_n=3900$,[a] $D_n=100$[b]	$N_A=3.5\times10^{13}/\text{cm}^3$
$\mu_p=1900$,[a] $D_p=50$[b]	p_g at $300°\text{K}=1.0\times10^{13}/\text{cm}^3$
$n_i=2.2\times10^{13}$[c]	$\tau_0=350$ microseconds
	$\Delta I/I_T$ for complete extraction at 300°K equals 0.2×10^{-2} (see Fig. 4)

Calculated quantities								
Injection curve	x(cm)	$\Delta p\times10^{-13}$	σ(mho)	E(volts cm^{-1})	μ^*	D	τ (μsec)	a (cm^{-1})
g	0.075	9.5	0.108	0.554	380	70.0	128	11.2
g	0.175	3.0	0.048	0.778	875	74.0	226	13.6
g	0.250	0.9	0.028	1.14	1470	79.0	300	22.2
d	0.150	0.35	0.023	0.097	1800	82.0	330	7.30
b	0.150	0.10	0.021	0.027	2000	84.0	343	6.20
Extraction curve								
b	0.1	−0.11	0.019	0.031	2200	86.5	357	5.30
d	0.1	−0.45	0.016	0.142	2630	89.3	390	3.70
f	0.1	−1.00	0.011	1.02	3900	100.0	430	0.60

[a] M. B. Prince, Phys. Rev. **92**, 681 (1953).
[b] See reference 20.
[c] Calculated by using Einstein relationship.

opposed effect are important factors in determining a for fitting the calculated curves. It appears that still better agreement might have been obtained with the choice of a larger value for τ_0. The excellent present agreement, however, demonstrates the validity of the theory adequately. The observed tails on the injection curves are not predicted by theory and will be discussed later. No attempt was made to fit curves for the j and k experimental points. These were taken for the same injection current, with j being taken at room temperature and k at 45°C. The experimental curve k demonstrates how the effect of E decreases as the conductivity increases.

The lower set of curves of Fig. 4 corresponds to extraction field-aided. These also show good agreement between experimental and theory. In the case of extraction Δp is negative and τ should increase rather than decrease with extraction level. According to Eq. (4), the maximum observable increase should be a factor of two for intrinsic material ($N_D=N_A=0$) and complete extraction ($\Delta p=-p_g$). For complete extraction in the present sample, however, the maximum increase in τ should be only 20%. This small change does not have a sensitive effect on the decay parameter; thus it cannot be definitely stated that an increase in τ has been observed. With the exception of d', all the calculations were made assuming an increase of τ with extraction level according to (4). The curve d', where no change in lifetime was taken into account, was included to demonstrate the effect of increase of lifetime.

It may be seen in Fig. 4 that there is some overlapping of the curves for extraction. This occurred because the temperature was not the same for all measurements and p_g is a sensitive function of temperature. An attempt was made to utilize this phenomenon by heating the sample to make it more intrinsic so that larger changes in τ could be observed and the effect

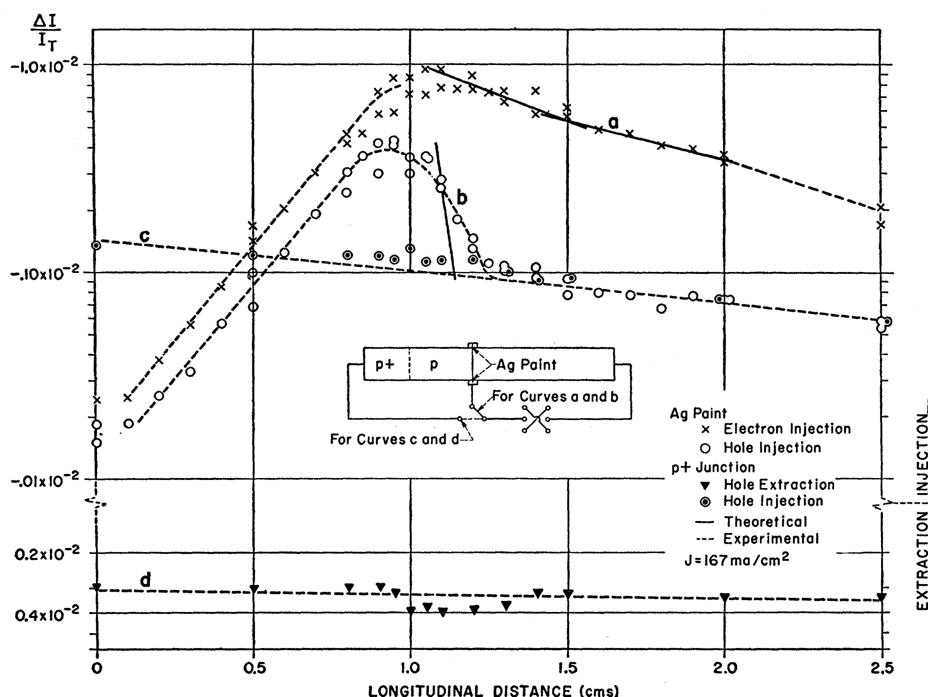

FIG. 5. Curves showing the phenomena of diffusion only, diffusion field-opposed, and diffusion field-aided for the same contact. The position of the silver paint contact corresponds to the peaks of curves a and b.

of E reduced by increasing the conductivity. This works satisfactorily for injection but not for extraction purposes. This is because, in addition to the difficulty of maintaining the temperature at a constant value, the conductivity decreases under extraction to the same value, independent of temperature and determined only by N_A, and the influence of the electric field therefore remains unchanged.

The discussion concerning the extraction and injection curves explains why a larger signal was observed at a distance from the junction for hole extraction than for hole injection. In addition to the field-aiding and field-opposing effect, extraction decreases the conductivity, which further enhances the effect of E, while injection increases the conductivity and thus reduces the effect of the electric field.

VII. FURTHER OBSERVATIONS

In an effort to trace down the origin of the observed tails on the injection curves, a silver paint line contact was made to the sample as shown by the insert of Fig. 5. It was applied on a surface which had been etched but exposed to the atmosphere for weeks. This contact was found to inject regardless of polarity. Holes were injected when it was positive and electrons when it was negative. The portion of the bar between the silver paint contact and the $p+$ region was field free. Thus the curves a and b for electron and hole injection, respectively, in the field free region corresponds to diffusion only and it should be noted that they represent the same diffusion length. The portions of the curves a and b to the right of their peaks represent the field-aided and field-opposed effects for electron and hole injection, respectively. The injection efficiency of the silver paint contact was only 6% for electrons and 3% for holes relative to that of the $(p+)-p$ junction. Because of the low level of injection, there was a strong field opposed effect for hole injection. This was obscured somewhat in the present measurements because of the "averaging" due to the slit width which resulted in the apparent disagreement between experiment and theory for curve b. Curve a, however, shows good agreement between experiment and theory for the field-aided effect. This arrangement thus afforded a good demonstration of the phenomena of diffusion only, injection field-aided, and injection field-opposed even though the cause of the tails on the injection curves were still not understood.

The origin of the tails was finally traced down by investigating the carrier distribution on a slab cut from the same ingot as the present sample. Almost ohmic contacts, although they injected electrons slightly, were prepared by applying silver paint to a freshly etched surface. They were arranged as shown by the

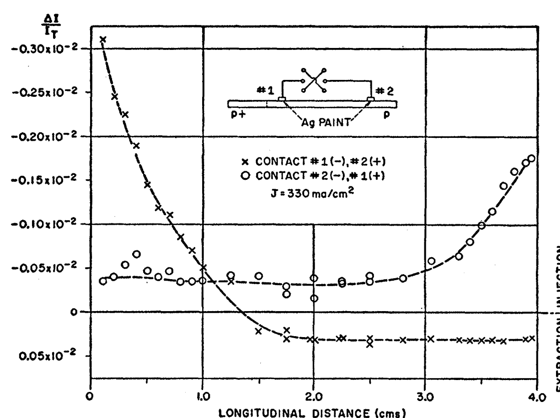

Fig. 6. Injection and extraction by the action of an electric field on a sample with a built-in minority carrier concentration gradient. Contacts No. 1 and No. 2 correspond to the longitudinal position of 0 and 4 cm, respectively.

insert of Fig. 6. Even though no extraction and only slight electron injection could be attributed to the contacts, the bulk showed injection or extraction depending on the sign of the electric field as shown by Fig. 6. This provided sufficient evidence to attribute this excess or deficit of carriers in the bulk to the action of the electric field on a built-in minority carrier concentration gradient. This explanation is in agreement with all other observations as for example from Fig. 5: curve d, which represents complete extraction for the sample, shows an increase in the magnitude of extraction with distance from the junction and this implies that the minority carrier density increases with distance from the junction; curves a and b show no tail in the field free region; the tail of curve b coincides with curve c, which implies that the tail is independent of the nature of the contact. When hole injection takes place at the $p+$ region, the excess of minority carriers is drawn towards the junction which results in an increased bulk conductivity. Similarly when the field is reversed, extraction occurs in the bulk resulting in decreased bulk conductivity. The field-aided extraction due to the $p+$ region was so complete that this additional extraction went unobserved until poorly extracting contacts were prepared as in Fig. 6.

ACKNOWLEDGMENTS

The samples used in the present experiment were cut from an ingot which was kindly furnished by Dr. W. L. Brown of the Bell Telephone Laboratories. The author wishes to acknowledge the help of Dr. F. K. du Pré, Dr. N. C. Jamison, and Dr. E. S. Rittner throughout the course of this work. He is particularly grateful to Dr. P. H. Dowling for many suggestions and critical discussions.