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Minority-carrier injection into semi-insulators

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A previous paper was concerned with the injection of minority carriers into relaxation semiconductors without traps. The present paper considers traps in their dual role as recombination centers and charge-storage localities. It is shown that the presence of traps changes the boundary between majority-carrier depletion ($\Delta n < 0$) and the majority-carrier augmentation ($\Delta n > 0$), moving the system more towards the latter, compared with expectations based on the trap-free case. Trapping of injected minority carriers also leads to an increase of majority-carrier diffusion in opposition to the current, and the containment of this diffusion calls for higher-than-normal electric fields. As a consequence, the injection region can have a higher-than-normal resistance, qualitatively as predicted by Van Roosbroeck, but for quite different reasons. Computed contours show the corresponding charge concentration and field profiles. The resistance enhancement effect is expected to be most prominent in lifetime semiconductors of high trap density; conditions for its appearance (if any) in relaxation semiconductors are discussed. Questions relating to the definition of relaxation semiconductors are also discussed.

I. INTRODUCTION

A previous paper on relaxation semiconductors[1] (i.e., materials for which the dielectric relaxation time exceeds the minority-carrier lifetime) showed that the injection of minority carriers leads to majority-carrier depletion, as originally predicted by Van Roosbroeck,[2] and, for sufficiently high currents, to a recombination front. Contrary to original expectations, majority-carrier depletion did *not* lead to higher-than-normal resistances, nor to a prominent sublinearity of the current-voltage relationship. For simplicity, all these conclusions were derived specifically for a material free of traps and recombination centers; recombination was therefore bimolecular, and associated with a carrier lifetime independent of injection level. Such a model accounts for many essential features of the system, but there are two reasons why the analysis should be extended to more general cases: (a) real materials of high resistivity do contain traps and recombination centers, and their effect on the injection situation calls for qualitative and quantitative assessment; and (b) there are in the literature results obtained on gallium arsenide,[2-4] which indicated that injection does, in fact, increase the resistance of the sample, against normal expectations concerning injection.

In the discussion which follows, the original limitations will be relaxed. This involves two aspects, those associated with the recombination mechanism, and those associated with space-charge storage in traps. It will be shown that the second is actually the more potent factor. The introduction of a recombination lifetime which depends on injection level leads only to quantitative changes in the original picture. In contrast, charge storage in traps leads to a completely new situation, and quite different expectations in terms of total resistance.

The previous calculations[1] have shown that, whatever the injection level, qualitative changes in the behavior of the solutions appear when a certain boundary condition is crossed, for which the neutralization rate equals the recombination rate. For the trap-free case (only), this boundary is given by the condition $A = 1$, where

$$A = \tau_{Dn}/\tau_0(1 + p_e/n_e) \tag{1}$$

and

$$\tau_{Dn} = \epsilon/e\mu_n n_e\,. \tag{2}$$

τ_{Dn} may be considered the dielectric relaxation time arising from majority carriers alone. τ_0 is the carrier lifetime, and p_e, n_e are the equilibrium carrier concentrations. In that sense, one could distinguish between materials for which $A < 1$ (lifetime semiconductors) and those for which $A > 1$ (relaxation semiconductors), as Van Roosbroeck[2] has done. However, in the presence of traps, the boundary condition will be shown to change. The boundary itself is marked by the onset of majority carrier depletion, and the term "relaxation regime" is used below *only* in that sense, i.e., for operational conditions under which majority-carrier depletion appears under the injection conditions here envisaged. Conversely, the term "lifetime regime" is used *only* for the operational conditions which imply majority carrier augmentation. Neither term is intended as an ultimate criterion for the classification of materials as such. By the extension of our previous model to the case with traps, it will be shown be-

low that the increase in specimen resistance can take place without offending against the demands of current continuity.

The new analysis suggests that virtually every kind of electronic, photoelectric, and galvanomagnetic measurement procedure on semi-insulators is due for reexamination. This may lead to new applications as well as to a new understanding of transport processes.

II. MAJORITY-CARRIER DEPLETION BOUNDARY FOR DIFFERENT RECOMBINATION MECHANISMS

It was shown in the previous paper[1] that the transport equations can be written in a normalized form as

$$\frac{\delta N}{\delta t}=\frac{\delta(NE)}{\delta X}+\frac{\delta^2 N}{\delta X^2}-A(NP-P_e)=\frac{\delta J_n}{\delta X}-A(NP-P_e)\,, \tag{3}$$

$$\frac{\delta P}{\delta t}=-\frac{\mu_p}{\mu_n}\left(\frac{\delta(PE)}{\delta X}-\frac{\delta^2 P}{\delta X^2}\right)-A(NP-P_e)=-\frac{\delta J_p}{\delta X}-A(NP-P_e)\,, \tag{4}$$

$$\frac{\delta E}{\delta X}=(P-P_e)-(N-1)\,, \tag{5}$$

where N is the electron concentration normalized to n_e, $N_e=1$; P is the hole concentration normalized to n_e, $P_e=p_e/n_e$; E is the electric field normalized to kT/eL_{Dn} (voltage normalized to kT/e); X is the spatial coordinate normalized to L_{Dn}; J_n and J_p are the electron and hole currents normalized to $eD_n n_e/L_{Dn}$; and t is the time normalized to τ_{Dn}, with

$$L_{Dn}=(kT\epsilon/e^2 n_e)^{1/2}\,. \tag{6}$$

This normalization for currents is somewhat different from that used in the previous paper,[1] and more conveniently adapted to the structure of the equations. Thus current densities are now normalized with respect to $eD_n n_e/L_{Dn}$ instead of $eD_p p_e/L_p$ as previously used, L_p being the diffusion length of holes. This change simplifies the equations but does not affect the solutions.

The parameter A resulted directly from a recombination term (common for electrons and holes) of the form

$$R=(np-n_e p_e)/\tau_0(n_e+p_e)\,, \tag{7}$$

in which the lifetime τ_0 was considered constant (τ_{00}), i.e., independent of departures from equilibrium. As a result, A was also constant (A_0). In real cases, this is no longer true. It will be shown below that, when τ_0 becomes a function of the injection level, the recombination can still be written in the form $A(NP-P_e)$, but the parameter A becomes a function of injection level. For low-injection levels τ_0 becomes constant; accordingly A is also constant and its value can likewise be denoted by A_0.

In the simple case discussed in the previous papers, $A=A_0=1$ corresponds to $\Delta N=N-N_e=0$ everywhere, whatever the value of $\Delta P=P-P_e$. In that situation, there was an exact balance between the rate at which the majority carrier concentration tended to increase in order to ensure neutrality, and the rate at which it tended to decrease due to recombination. Departures from $A=1$ led either to excess majority carriers ($A<1; \Delta N>0$), or to their depletion ($A>1; \Delta N<0$). When A is nonconstant, it cannot be used directly to characterize the response of a material to minority carrier injection. Nevertheless, a situation for which $\Delta N\approx 0$ can still be envisaged, and be regarded as a new depletion boundary, as long as the injection level is reasonably low ($\Delta P<1$). Thus, Eq. (3) can be rewritten in terms of the departures ΔN and ΔP from the equilibrium concentrations and, together with Eq. (5), this yields

$$\frac{\delta \Delta N}{\delta t}=(1+\Delta n)(\Delta P-\Delta N)+E\frac{\delta\Delta N}{\delta X}+\frac{\delta^2\Delta N}{\delta X^2}-A(\Delta P+P_e\Delta N+\Delta P\Delta N)\,. \tag{8}$$

For the special case of $A=1$, this equation becomes

$$\frac{\delta\Delta N}{\delta t}=-\Delta N-(\Delta N)^2+E\frac{\delta\Delta N}{\delta X}+\frac{\delta^2\Delta N}{\delta X^2}-P_e\Delta N\,, \tag{9}$$

which is compatible with the solution $\Delta N=0$ for all values of x and t, as discussed in the previous paper.[1] For the case with traps, we know now that A is no longer a constant. However, if its low-injection value (A_0) is unity, then the equality $A\cong 1$ represents a satisfactory approximation which ensures, for all but very high values of ΔP, that $\Delta N\cong 0$. Thus $A_0=1$ is still an approximate boundary which characterizes the response of the system to minority carrier injection.

Bearing in mind that the principal interest attaches to steady state conditions, the form of Eq. (7) can be maintained, but τ_0 will depend on the nature of the recombination process. By way of example, Shockley-Read recombination (density of recombination centers so low that their space charge can be neglected) will be considered in some detail.

III. STEADY-STATE SOLUTIONS FOR SHOCKLEY-READ RECOMBINATION

For Shockley-Read recombination, we have a recombination rate of the form

$$R=\frac{np-n_e p_e}{\tau_0(n_e+p_e)}=\frac{np-n_e p_e}{\tau_{p0}(n+n_1)+\tau_{n0}(p+p_1)}\,, \tag{10}$$

where τ_{n0}, τ_{p0}, n_1, and p_1 have their usual meaning for this model.[5] For small departures from equilibrium, this becomes

$$R_0=\frac{np-n_e p_e}{\tau_{00}(n_e+p_e)}=\frac{np-n_e p_e}{\tau_{p0}(n_e+n_1)+\tau_{n0}(p_e+p_1)}\,.$$

Consequently, via Eq. (6), we obtain

$$A=A_0\frac{n_e+n_1+(\tau_{n0}/\tau_{p0})(p_e+p_1)}{n+n_1+(\tau_{n0}/\tau_{p0})(p+p_1)}$$

$$=A_0\frac{1+N_1+(\tau_{n0}/\tau_{p0})(P_c+P_1)}{N+N_1+(\tau_{n0}/\tau_{p0})(P+P_1)}\,, \tag{11}$$

where

$$A_0=\frac{\tau_{Dn}}{\tau_{00}(1+P_e)}=\frac{\tau_{Dn}}{\tau_{p0}(1+N_1)+\tau_{n0}(P_e+P_1)} \tag{12}$$

and N_1, P_1 are the normalized (with respect to n_e) values of n_1 and p_1. We see from Eq. (11) that A decreases when N and P increase. If, therefore, we are in a relaxation regime, with majority carrier depletion, the value of A changes so as to enhance the depletion. Whether this has significant consequences can be assessed only by reference to the complete solutions, i.e., computed concentration, field, and recombination rate contours. Such contours have been obtained (for semi-infinite systems) under moderate and deep relaxation conditions. In order to address a concrete example, it was assumed that $\tau_{n0}/\tau_{p0}=1$ and that the recombination centers are in the middle of the band, making $N_1=P_1=N_1$. For the moderate relaxation case, the changes resulting from $\tau_0 \neq \tau_{00}$ are generally insignificant. Majority-carrier depletion is slightly deepened. For the deep relaxation case the changes are also small as regards concentration contours and field, but significant as regards the recombination front. This can be seen on Fig. 1. The recombination front is sharpened.

IV. TRANSPORT EQUATIONS IN THE PRESENCE OF A HIGH DENSITY OF RECOMBINATION CENTERS

The Shockley-Read recombination rate refers explicitly to low densities of recombination centers; for high densities the equations have to be used in their general form.[5] In particular, the time-dependent equations for electrons and holes do not necessarily involve the same recombination term. Also, a space charge is trapped in the recombination centers, and because the concentration of such centers is now substantial, the space charge in them can no longer be neglected.

In the presence of a single, monovalent trapping level at the energy E_t, the conventional transport equations can be written as follows, using normalization procedures similar to those above:

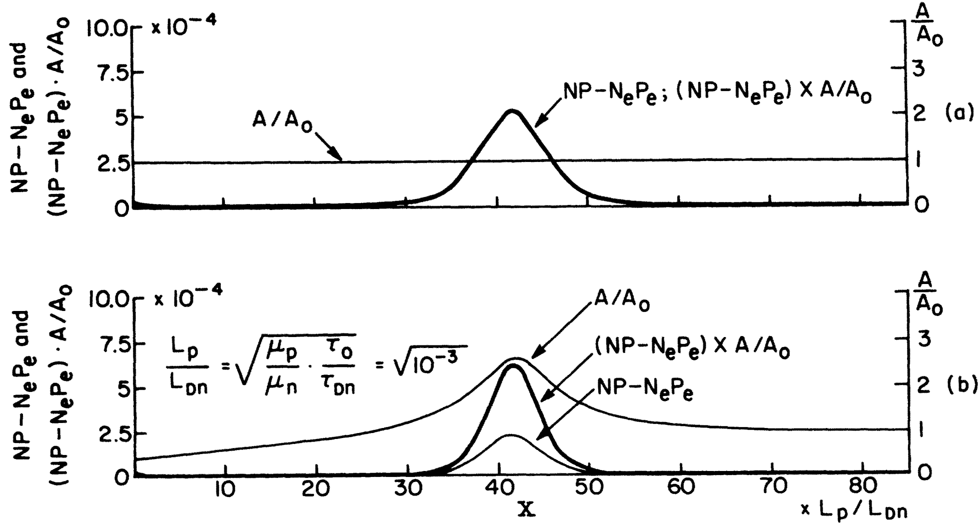


FIG. 1. Effect of injection-level-dependent lifetime on recombination contours. $\tau_0/\tau_{Dn}=10^{-3}$, corresponding to $A \approx 991$; n-type material; $p_e/n_e=10^{-2}$; $\mu_n=\mu_p$; $J=\sqrt{10}$. Recombination rate proportional to $(NP-N_eP_e)(A/A_0)$. (a) Lifetime independent of injection level ($\tau_0=\tau_{00}$; $A=A_0$). (b) Lifetime dependent on injection level according to Shockley-Read model. In this and subsequent figures, the abscissa X is normalized to L_{Dn}, the dielectric relaxation time arising from electrons (only). Thus $X=x/L_{Dn}$, which means that the abscissae are here given in multiples of the diffusion length L_p.

$$\frac{\delta N}{\delta t}=\frac{\delta(NE)}{\delta X}+\frac{\delta^2 N}{\delta X^2}-A_n\left[N\left(1-\frac{M}{M_0}\right)-\frac{M}{M_0}N_1\right]$$

$$=\frac{\delta J_n}{\delta X}-A_n\left[N\left(1-\frac{M}{M_0}\right)-\frac{M}{M_0}N_1\right], \tag{13}$$

$$\frac{\delta P}{\delta t}=-\frac{\mu_p}{\mu_n}\left(\frac{\delta(PE)}{\delta X}-\frac{\delta^2 P}{\delta X^2}\right)-A_p\left[P\frac{M}{M_0}-\left(1-\frac{M}{M_0}\right)P_1\right]$$

$$=-\frac{\delta J_p}{\delta X}-A_p\left[P\frac{M}{M_0}-\left(1-\frac{M}{M_0}\right)P_1\right], \tag{14}$$

$$\frac{\delta M}{\delta t}=A_n\left[N\left(1-\frac{M}{M_0}\right)-\frac{M}{M_0}N_1\right]$$

$$-A_p\left[P\frac{M}{M_0}-\left(1-\frac{M}{M_0}\right)P_1\right], \tag{15}$$

$$\frac{\delta E}{\delta X}=(P-P_e)-(N-1)-(M-M_e), \tag{16}$$

where the new symbols are M_0, the total concentration of traps; M, the concentration of traps filled with electrons; M_e, the equilibrium value of M, all normalized to n_e. Instead of a single A, we now have

$$A_n=\tau_{Dn}/\tau_{n0},\quad A_p=\tau_{Dn}/\tau_{p0}, \tag{17}$$

where τ_{n0} and τ_{p0} are the trapping time-constants for electrons and holes respectively, with their usual definitions.[5] The concentration N_1 is given in terms of the separation of the trapping level E_t and the Fermi level E_F:

$$N_1=n_1/n_e=\exp[-(E_F-E_t)/kT]. \tag{18}$$

As usual, we have

$$P_1=N_i^2/N_1, \tag{19}$$

where N_i is the normalized intrinsic carrier concentration;

$$N_i=\exp[-(E_F-E_{Fi})/kT], \tag{20}$$

in which

$$E_{Fi}=(E_c+E_v)/2+kT\ln(N_c/N_v)^{1/2} \tag{21}$$

is the Fermi level for the intrinsic material. In the steady state, the recombination terms in Eqs. (13) and (14) become equal; they thus have the same form as in the case of zero trapping and can be written as $A(NP-N_eP_e)$, where A is given by Eqs. (11) and (12). Under such conditions, Poisson's equation becomes

$$\frac{dE}{dX}=\Delta P-\Delta N+Q_t, \tag{22}$$

where $\Delta Q_t(=M_e-M)$ stands for the *excess* positive charge stored in traps, which is in fact a function of the excess charge densities ΔN and ΔP. In order to calculate it, we put $\delta M/\delta t=0$ in Eq. (15) and obtain, after some manipulation,

$$\Delta Q_t=M_e-M=M_e\frac{\Delta P(\tau_{n0}/\tau_{p0})-\Delta N[N_1+(\tau_{n0}/\tau_{p0})P_e]/[1+(\tau_{n0}/\tau_{p0})P_1]}{1+N_1+(\tau_{n0}/\tau_{p0})(P_e+P_1)+\Delta N+(\tau_{n0}/\tau_{p0})\Delta P} \tag{23}$$

in which

$$M=M_0\{[N+(\tau_{n0}/\tau_{p0})P_1]/[N+N_1+(\tau_{n0}/\tau_{p0})(P+P_1)]\}. \tag{24}$$

From this equation we may obtain M_e, the equilibrium value of M, by putting $N=N_e=1$ and $P=P_e$:

$$M_e=M_0\{[1+(\tau_{n0}/\tau_{p0})P_1]/[1+N_1+(\tau_{n0}/\tau_{p0})(P_e+P_1)]\}. \tag{25}$$

To sum up we find that in the presence of recombination centers in high concentrations, which imply also notable trapping effects, the transport equations are changed in two ways. The important parameter A becomes a function of ΔN and ΔP, and Poisson's equation includes an extra term ΔQ_t, which likewise depends on excess carrier concentrations. More elaborate models could be envisaged which make a distinction (not made here) between recombination centers in which charge is also trapped, and pure traps which play no role in recombination. Though ΔQ_t would be quantitatively changed, no essential qualitative changes are expected to arise from this situation. The consequences of the modified parameter A are already discussed above; those arising from ΔQ_t will now be considered in some detail.

V. LIFETIME-RELAXATION BOUNDARY FOR DIFFERENT TRAP CONCENTRATIONS

As seen above, the lifetime-relaxation boundary is no longer defined by $A_0=1$, even though $A\approx A_0=1$ remained a useful approximation in the absence of trapped space charge. In the presence of significant charge trapping, this is no longer true. Corresponding to Eq. (8), we now have in the steady state

$$\frac{\delta\Delta N}{\delta t}=(1+\Delta N)(\Delta P-\Delta N+\Delta Q_t)+E\frac{d\Delta N}{dX}$$

$$+\frac{d^2\Delta N}{dX^2}-A(\Delta P+P_e\Delta N+\Delta N\Delta P)=0. \tag{26}$$

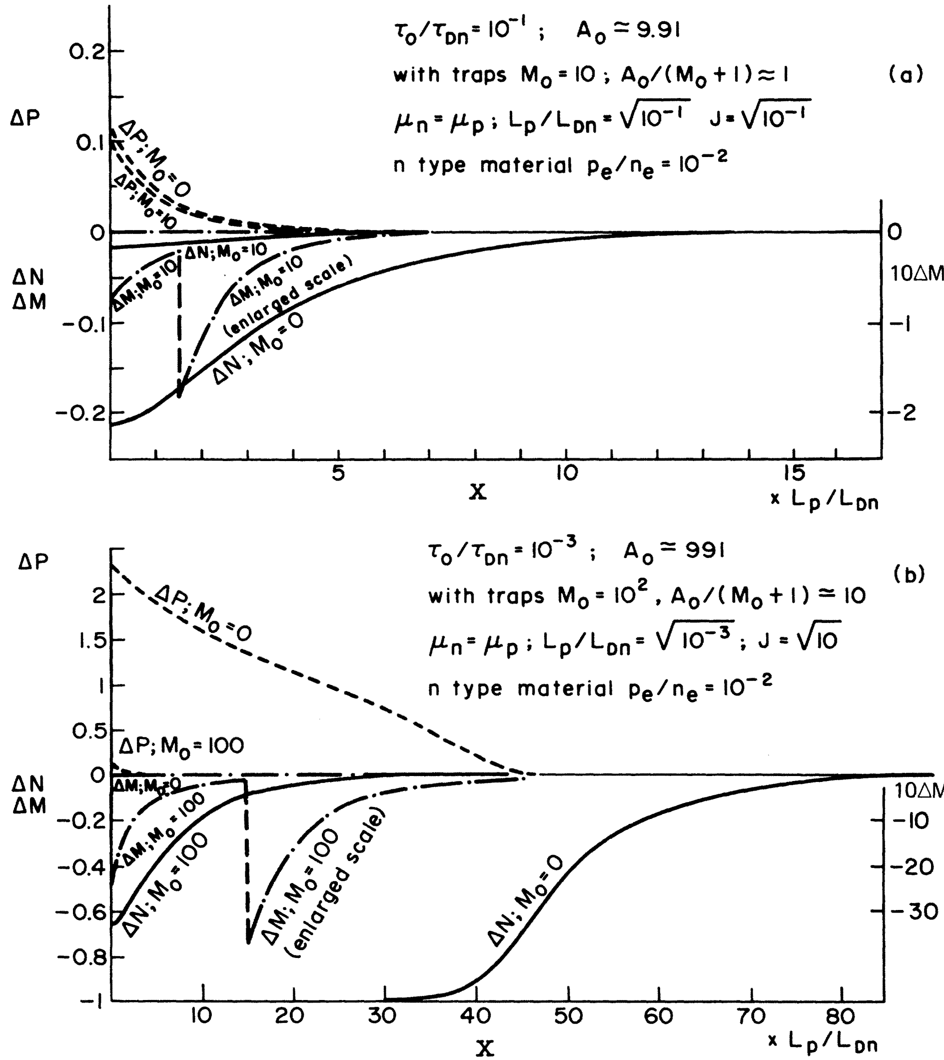


FIG. 2. Effect of trapped space charge on the carrier concentration contours. (a) Moderate-relaxation case. (b) Deep-relaxation case. Note total carrier $(N+P)$ depletion for $M_0 = 100$ up to about $X = 25 L_p/L_{Dn}$. Curves (a) and (b) correspond to normalized currents J so chosen as to keep constant the injection level [defined as $j/(eD_p pe/L_p)$, where j is the *actual* current density]. $\Delta M = M - M_e = -\Delta Q_t$; n-type material, $p_e/n_e = 10^{-2}$; $\mu_n = \mu_p$.

In general, and as long as the traps are not full, one must also expect

$$\Delta Q_t = B \Delta P . \tag{27}$$

The continuity equation for majority carriers then becomes

$$\frac{\delta N}{\delta t} = -\Delta N - (\Delta N)^2 + E\frac{\delta \Delta N}{\delta X} + \frac{\delta^2 \Delta N}{\delta X^2} - (B+1)P_e \Delta N , \tag{28}$$

where B is a constant, given by

$$A \simeq B + 1 . \tag{29}$$

Equation (28) is again compatible with a solution $\Delta N = 0$ for all values of x and t. We see, therefore, that $A \cong B + 1$ which ensures $\Delta N \cong 0$ is a new boundary for the operating regimes, valid for the case with traps in the steady state, and for not-too-high values of ΔP [so that Eq. (27) remains permissible].

The parameter B can be calculated for every particular trapping model. For the single monovalent trapping level envisaged here, Eq. (29) becomes, with Eqs. (11) and (24),

$$A = A_0 \frac{1 + N_1 + (\tau_{n0}/\tau_{p0})(P_e + P_1)}{1 + N_1 + (\tau_{n0}/\tau_{p0})(\Delta P + P_e + P_1)} = M_e \frac{\tau_{n0}/\tau_{p0}}{1 + N_1 + (\tau_{n0}/\tau_{p0})(\Delta P + P_e + P_1)} + 1 . \tag{30}$$

For large concentrations of occupied traps, $M_e \gg 1$, and, under these conditions Eq. (30), and thus the depletion boundary is actually independent of ΔP (injection level). It will be seen that, for any given value of A_0, there will be a particular trap density M_0 which satisfies the above condition. By using Eqs. (12) and (25) it will be seen that this critical trap density is given by

$$\tau_{Dn}/\tau_{n0} \simeq M_e \simeq M_0 \quad \text{for } P_e, N_1, P_1 \ll N_e (\equiv 1), \tag{31}$$

compared with $\tau_{Dn}/\tau_0 = 1$, in the absence of traps.

A computation was carried out along the lines described in the previous paper for the particular trapping system discussed above ($N_1 = P_1 = N_i$ and $\tau_{n0} = \tau_{p0}$). For this case, Eq. (30), via Eq. (25), reduces to $A_0 \approx M_0 + 1$. This means that $A_0/(M_0+1) > 1$ corresponds to the relaxation regime and $A_0/(M_0+1) < 1$ to the lifetime regime. Thus, the nature of this trapping system is assessed, approximately by comparing $A_0/(M_0+1)$ with unity, instead of A_0 in the absence of traps.

Figure 2(a) corresponds to $A_0 = 9.91$, and contrasts the two cases, $M_0 = 0$, which makes $A_0/(M_0+1) \approx 10$ (moderate-relaxation case), and $M_0 = 10$, which makes $A_0/(M_0+1) \approx 1$. It will be seen that majority-carrier depletion is greatly reduced by the presence of traps, in comparison with expectations based on the same value of A_0 in the absence of traps. Indeed, the depletion has become almost negligible. The positive space charge now resides mostly in the traps. Figure 2(b) corresponds to $A_0 = 991$ and contrasts two other cases, $M_0 = 0, [A_0/(M_0+1) \approx 10^3]$, deep relaxation case, and $M_0 = 100, [A_0/(M_0+1) \approx 10]$. Majority carrier depletion which is virtually complete for $M_0 = 0$, is considerably reduced in the presence of traps. It will also be noted that ΔP is likewise strongly reduced; the necessary positive space charge is now provided by the minority carriers in traps. The computations also showed that the disappearance of the majority-carrier depletion region is associated with the disappearance of the recombination front, as one would expect.

The general conclusion is that the effect of traps *for a given value of* A_0 may be considered to amount to a displacement of the depletion boundary, with all its usual consequences. None of the above situations revealed any possibility of higher-than-normal resistances. It remains to be shown what happens when traps in high concentration are present in the material. Under conditions ($A_0 > 1$) which, in the trap free case, imply majority carrier depletion, the presence of traps can make $A_0/(M_0+1) < 1$ and thereby lead to majority-carrier

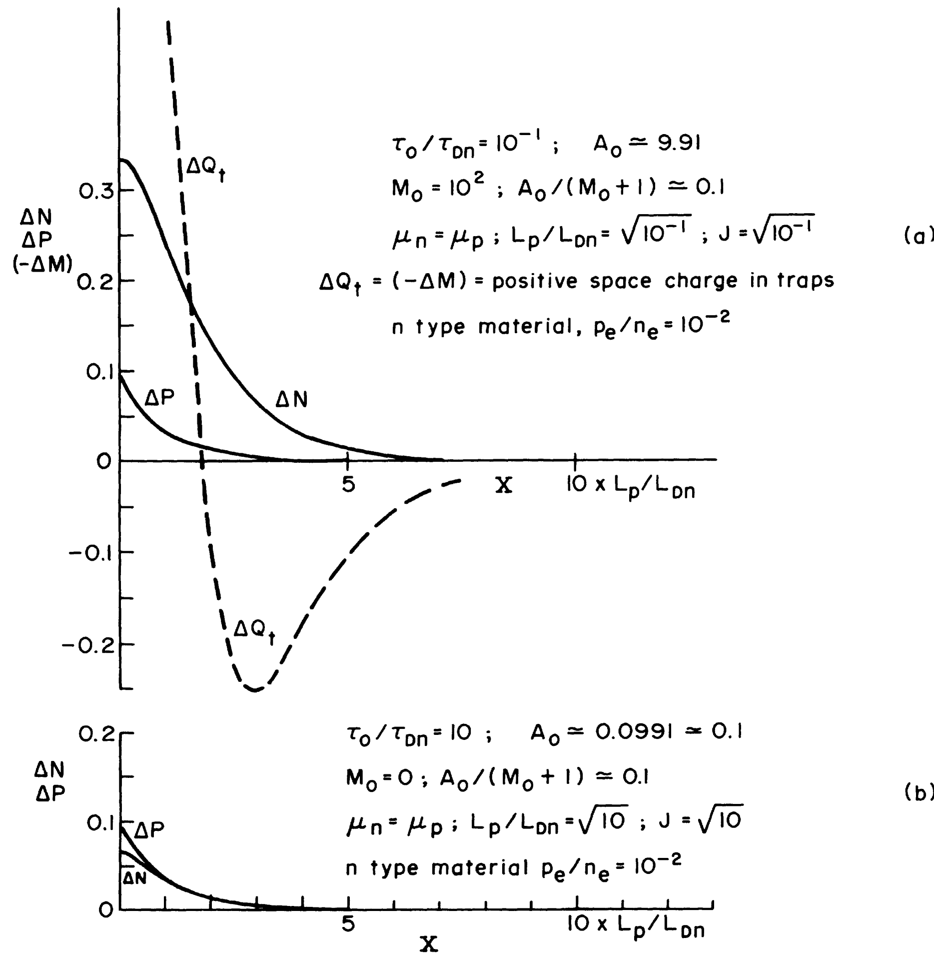


FIG. 3. Carrier concentration contours for a relaxation semiconductor, brought into the lifetime regime by injection in the presence of traps (a); comparison with a trap-free case of equal $A_0/(M_0+1)$ (b). n-type material; $p_e/n_e = 10^{-2}$; $\mu_n = \mu_p$. Currents J so chosen as to keep constant the injection level (defined as $j/(eD_p\, p_e/L_p)$), where j is *actual* current density).

augmentation, as shown below. When dealing with real materials, as opposed to the solutions of equations on paper, it should not be assumed that a high value of M_0 leads automatically to this inequality, since A_0 is in fact dependent on M_0. Indeed, considering the usual definition of τ_{n0} in terms of the capture coefficient C_n, namely, ($\tau_{n0}=1/M_0C_n$) in Eq. (31), the condition $\tau_{Dn}<M_0\tau_{n0}$ reduces to

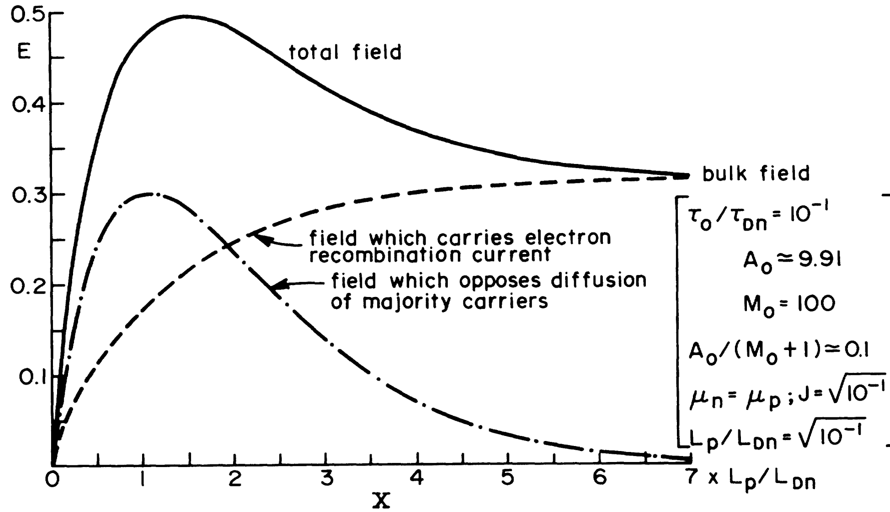
$$C_n<1/n_e\tau_{Dn}=e\mu_n/\epsilon=B \tag{32}$$

and is thus independent of M_0. In other words, the trapping coefficient should be lower than the Langevin recombination coefficient B,[2,6,7] to produce an excess of majority carriers when minority carriers are injected.

VI. PROBLEM OF HIGHER-THAN-NORMAL RESISTANCES

Figure 3(a) shows the carrier concentrations for $A_0/(M_0+1)\approx 0.1$ and should be compared with Fig. 2(a), because it corresponds to the same conditions, except for the greater trap density. One immediately sees that ΔN is now positive. Figure 3(b) shows the carrier concentrations for the same value of $A_0/(M_0+1)$, but in the absence of traps (trap-free lifetime case). The difference is clear: whereas ΔP at $X=0$ is the same (the currents were adjusted so as to ensure this, for simple comparison), ΔN at $X=0$ is very much greater in the presence of traps, and indeed greater than ΔP. $\Delta N_0 \gg \Delta P_0$ is brought about by the fact that the positive charge in traps ΔQ_{t0} must be compensated. With increasing X, the trapped charge ΔQ_t changes sign and, as a consequence, the total space charge changes sign also. This has important consequences for the local field which must now go through a maximum value. There is no equivalent to this in the trap free case.

Figure 4 gives the field contours which correspond to the concentration contours of Fig. 3. In Figs. 4(a) and 4(b), the total computed field is



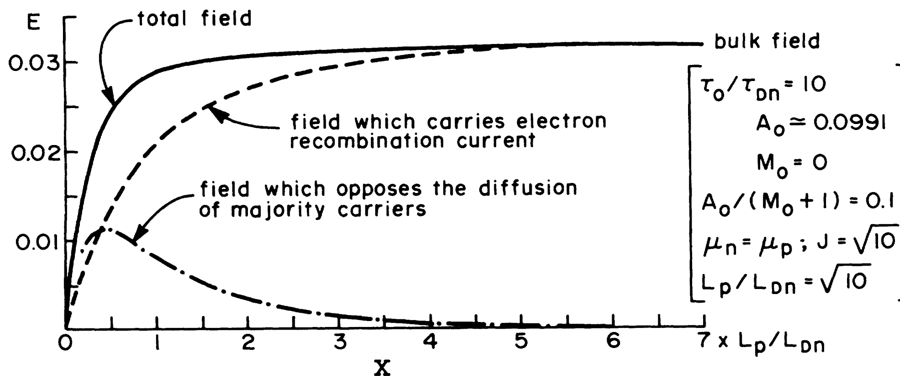


FIG. 4. Field contours for a relaxation semiconductor, brought into the lifetime regime by injection in the presence of traps (a); comparison with trap-free case of equal $A_0/(M_0+1)$ (b). Conditions as for Fig. 3. n-type material; $p_e/n_e=10^{-2}$; $\mu_n=\mu_p$.

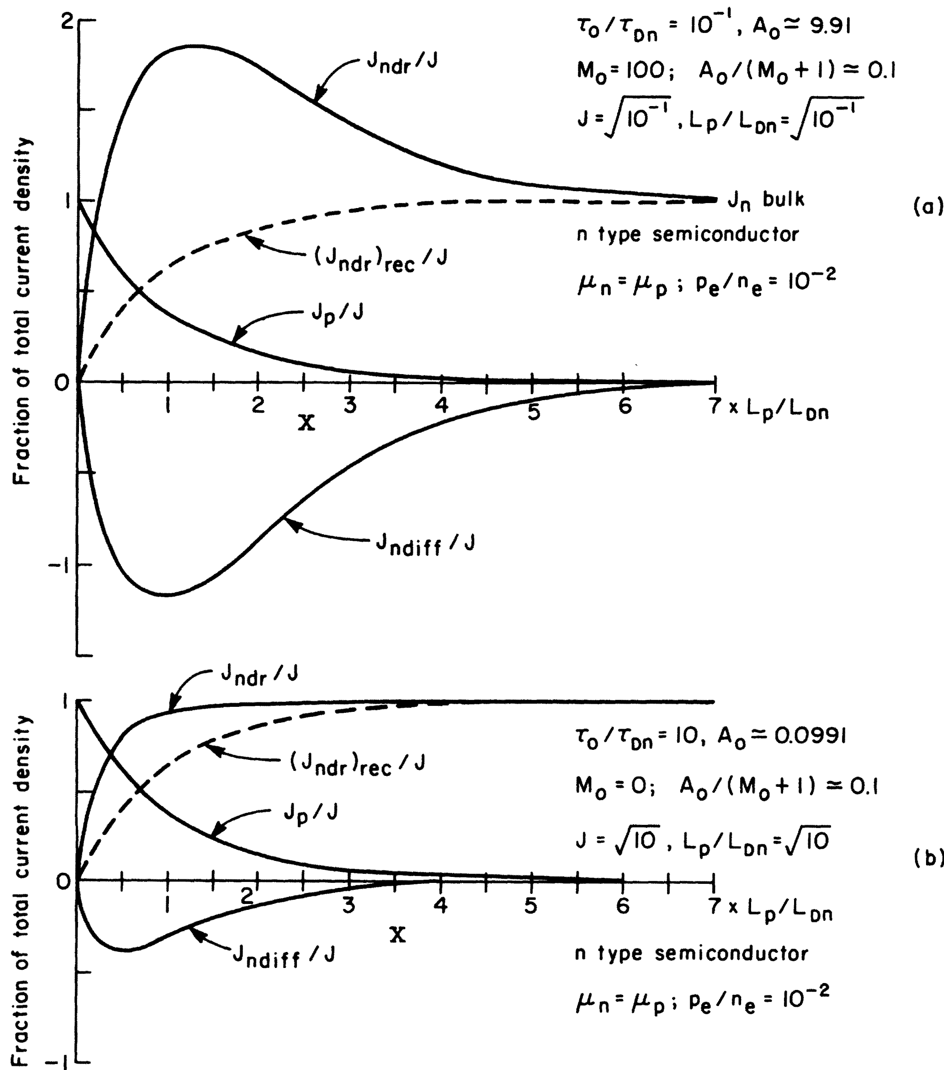


FIG. 5. Current density contours for a relaxation semiconductor, brought into the lifetime regime by injection in the presence of traps (a); comparison with trap-free case of equal $A_0/(M_0+1)$ (b). Conditions as for Figs. 3 and 4. n-type material; $p_e/n_e \approx 10^{-2}$; $\mu_n = \mu_p$.

greater than the field which is necessary to bring electrons into the injection region for recombination (to ensure current continuity). This field is always *lower* than the bulk field. The excess of the total field over this value is used in both cases (a and b) to compensate for electron diffusion. The difference between Figs. 4(a) and 4(b) is, in fact, only a quantitative one, related to the greater electron diffusion gradient which has to be compensated in the presence of traps. In the trap-free lifetime case (b), the sum of the fields is always lower than the bulk field; hence injection lowers the total resistance. In the lifetime case with traps (a), the total field locally exceeds the bulk field; hence injection increases the total resistance. The region of maximum field is associated with the maximum carrier gradient. Figure 5 shows how current continuity is maintained in these circumstances.

The situation described by Figs. 3(a), 4(a), and 5(a) is not restricted to relaxation semiconductors with traps, but can also appear when traps are present in lifetime semiconductors. This is because the only requirement is the negative majority carrier diffusion gradient. Indeed, the ratio between the maximum field and the limit field in the bulk material is even greater in the lifetime case. Thus, for $A_0 \approx 0.1$, and the same injection level and trap density as above, this ratio increases to 3. The highest possible field is given by the highest possible slope of ΔN, and this is determined by the highest slope of ΔQ_t (see Fig. 3). The results show that, in the presence of a high trap density, the conditions $A_0 < 1$ or $A_0 > 1$ no longer imply qualitatively different solutions, the appearance of the reverse majority carrier diffusion gradient being then governed by $A_0/(M_0+1) \approx 1$ or $C_n \approx B$.

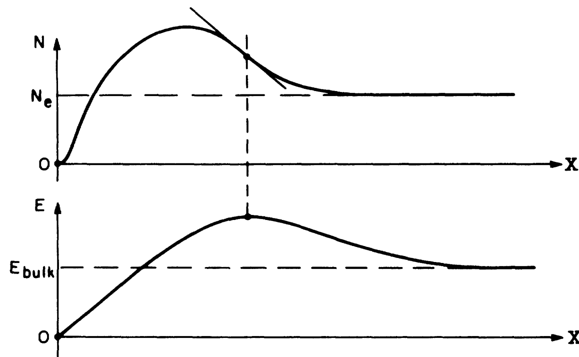


FIG. 6. Speculative conditions for higher-than-normal resistances in the presence of majority-carrier depletion.

The question arises whether higher-than-normal resistances can ever occur in the presence of majority carrier *depletion*, as originally proposed.[2] The present calculations have not revealed such a case, but the results cannot prove that such a resistance augmentation is actually impossible. They do, however, indicate the conditions which would have to be fulfilled. If a higher-than-normal field occurs anywhere, this will not happen in the majority carrier depletion region, but can only be envisaged outside it, at some location where the free majority carriers have a maximum decreasing slope. This situation is shown in Fig. 6. Whether such concentration contours, which begin with electron depletion and develop to an excess, correspond to real solutions remains to be seen.

Lastly, one might ask why observations of higher-than-normal resistances in lifetime semiconductors with traps have not been reported long ago. One answer might be that low values of the capture cross section C_n and high values of the trap density M_0, do not usually go together. However, this combination of parameters is believed to apply in good photoconductors, and the GaAs measurements reported by Casey, Queisser, and Van Roosbroeck[3] and by Ilegems and Queisser[4] may also correspond to just such a case. The present results suggest desirability of a wider investigation.

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